NASA Technical Memorandum 104278

An Electronic Workshop on the Performance Seeking Control and Propulsion Controlled Aircraft Results of the F-15 Highly Integrated Digital Electronic Control Flight Research Program

Proceedings of the Electronic Workshop

Compiled by: Sheryll Goecke Powers

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National Aeronautics and
Space Administration

Dryden Flight Research Center
Edwards, California 93523-0273

CONTENTS

PREFACE

In the early 1980's, the NASA Dryden Flight Research Center began conducting propulsion control flight research using the Dryden F-15 airplane. The flight research began with the Digital Electronic Engine Control (DEEC) program. The DEEC system provided a platform and an opportunity to study advanced engine control modes. The capabilities of the DEEC led to the series of experiments conducted under the program name Highly Integrated Digital Electronic Control (HIDEC). The final two experiments in the HIDEC program were Performance Seeking Control (PSC) and Propulsion Controlled Aircraft (PCA). In September 1994, the results of these two experiments were presented in an electronic workshop.

The electronic workshop was accessible to anyone with a suitable computer, World Wide Web (WWW) access, and an appropriate browser such as Mosaic. The "on-line" feature of the workshop occurred during September, 1994. During this on-line time, the authors responded to questions and comments. After September, the workshop, including questions and responses, was available as an archived workshop accessible through the Dryden WWW home page and as a compact disk (CD). The uniform resource locator (URL) address through the NASA Dryden home page is:

http://www.dfrc.nasa.gov/dryden.html

For those without an appropriate browser, the workshop papers were accessed using an anonymous file transfer protocol (FTP) server at:

ftp.dfrc.nasa.gov, in the directory pub/workshop/HIDEC

The file README.1st explained what was available.

The electronic workshop had an overview paper, a session for the PSC experiment, and a session for the PCA experiment. The overview summarized the experiments that were conducted on the Dryden F-15 airplane during the last 12 years of its flight history. A bibliography of all papers and reports from the F-15 project is included. The workshop papers in the PSC and PCA sessions describe the design, development, and flight test results. The PCA session also included four videos that showed a Manual Throttles-Only Approach; the First PCA-Controlled Landing; an Upset, PCA Recovery and Descent; and a PCA Final Approach.

The papers for the electronic workshop were prepared in the same manner as for a typical workshop but were then converted to an electronic format. In the electronic format, each page of a paper was in a separate file. Each file included the "page" for that paper inserted into a standardized template. Template information included the paper title, page title, information on how to navigate around the workshop, and the author's name and e-mail address. When printed, a file usually required two sheets of paper. Two different electronic presentation formats were tried. For presentation Format1, the graphics (data figures, block diagrams, drawings, photographs, etc.) and descriptive text for that graphics were converted as one unit (or page) into a GIF graphic format. This meant that when viewed and printed, the graphics and descriptive text were treated as one unit. For presentation Format2, the graphics portion of each page was converted into the GIF graphic format and the descriptive text into an electronic text format. This meant that when viewed and printed, the graphics were treated as a unit and the descriptive text was treated as regular text. The reason for the above explanation is that the print quality of a graphics file is very dependent on the resolution of the monitor and the printer. This is particularly apparent for the descriptive text which is treated as graphics in Format1. Because a page was prepared and converted as a unit for Format1, pages prepared for Format1 were easy to print in the pre-converted version. The print quality of the text and graphics was very good for the pre-converted version.

The pages that were prepared for the electronic workshop using Format1 are printed from pre-converted version pages. The pages prepared using Format2 are printed using pages printed from the electronic workshop. Because of the standardized template, most of the pages that used Format2 required two sheets of paper. Some of these second sheets only listed the author and/or e-mail address. These sheets are not included in this paper version of the TM. The videos in the PCA session are included on the CD but not in this paper version of the TM.

ABSTRACT

Flight research for the F-15 HIDEC (Highly Integrated Digital Electronic Control) program was completed at NASA Dryden Flight Research Center in the fall of 1993. The flight research conducted during the last two years of the HIDEC program included two principal experiments: (1) Performance Seeking Control (PSC); an adaptive, real-time, on-board optimization of engine, inlet, and horizontal tail position on the F-15, and (2) Propulsion Controlled Aircraft (PCA); an augmented flight control system developed for landings as well as up-and-away flight that used only engine thrust (flight controls locked) for flight control. In September 1994, the background details and results of the PSC and PCA experiments were presented in an electronic workshop. An overview paper that summarized the experiments conducted on the Dryden F-15 airplane during the last 12 years of the F-15 flight research program was also included. The PCA session also included four videos that showed a Manual Throttles-Only Approach; the First PCA-Controlled Landing; an Upset, PCA Recovery and Descent; and a PCA Final Approach. After September, the workshop, including questions and responses, was available as an archived workshop accessible through the Dryden World Wide Web (WWW) home page and as a compact disk (CD). The uniform resource locator (URL) address through the NASA Dryden home page is:

http://www.dfrc.nasa.gov/dryden.html

NOMENCLATURE

ACTIVE	Advanced Control Technology for Integrated Vehicles
AdAPT	Adaptive Aircraft Performance Technology
ADECS	Advanced Digital Engine Controls System
AICS	air inlet control computer
AJ	exhaust nozzle position
AOA	angle of attack
CC	central computer
CG	center of gravity
CEM	compact engine model
CIVV	compressor inlet variable vanes
DEEC	Digital Electronic Engine Control
DEFCS	Digital Electronic Flight Control System
DFRC	Dryden Flight Research Center, Edwards, CA
EAIC	electronic air inlet controller
EEL	extended engine life

EMD	engine model derivative
EPR	engine pressure ratio
FFT	fast Fourier transform
FNP	net propulsive force
FTIT	fan turbine inlet temperature
FTP	file transfer protocol
GE	ground effects
HIDEC	Highly Integrated Digital Electronic Control
HISTEC	HIgh STability Engine Control
HUD	heads up display
IAR	idle area reset
IFIM	in-flight integrity management
IMPACT	Integrated Methodology for Propulsion and Airframe Control Technology
LP	linear programming
M	Mach number
NCI	navigation control indicator
N1	fan rotor speed sensors
N1C2	low rotor speed
N2	core rotor speed sensors
OFP	operations flight program
PATAL	PSC asymmetric thrust alleviation
PB	burner pressure
PCA	Propulsion Controlled Aircraft
PIO	pilot-induced oscillation
PLA	power level angle
PSC	Performance Seeking Control
PSD	power spectral density
PS2	fan inlet static pressure
PT6	turbine discharge total pressure
RCVV	rear compressor variable vanes
RDM	rapid deceleration mode
SDR	shock displacement ratio
SEC	secondary engine control
SOAPP	Pratt &Whitney State of the Art Performance Program
SRFCS	Self-Repairing Flight Control System
SSVM	steady-state variable model
TCP	thumbwheel controller panel
TSFC	thrust specific fuel consumption
TT2	fan inlet total temperature
URL	uniform resource locator
VMSC	Vehicle Management System Computer
WF	fuel flow
WFAB	augmentor fuel flow
WFGG	gas-generator fuel flow
WOW	weight on wheels
WWW	World Wide Web

NASA Dryden Flight Research Center

"An Overview of Integrated Flight–Propulsion Controls Flight Research on the NASA F–15 Research Airplane"

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Author: Frank W. Burcham Jr.
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3126
Fax: 805–258–3744
Address: M. S. D2033, P. O. Box 273, Edwards, CA 93523–0273
e–mail: Bill_Burcham@QMGATE.DFRF.NASA.GOV

Author: Donald H. Gatlin
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3166
Fax: 805–258–2134
Address: M. S. D2071, P. O. Box 273, Edwards, CA 93523–0273
e–mail: Donald_Gatlin@QMGATE.DFRF.NASA.GOV

Author: James F. Stewart
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3162
Address: M. S. D2071, P. O. Box 273, Edwards, CA 93523–0273
e–mail: Jim_Stewart@QMGATE.DFRF.NASA.GOV

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Frank W. Burcham
Donald L. Gatlin
James F. Stewart
NASA Dryden Flight Research Center
Edwards, CA

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The NASA Dryden Flight Research Center has been conducting integrated flight-propulsion control flight research using the NASA F-15 airplane for the past 12 years. The research began with the digital electronic engine control (DEEC) project, followed by the F100 Engine Model Derivative (EMD). HIDEC (Highly Integrated Digital Electronic Control) became the umbrella name for a series of experiments including: the Advanced Digital Engine Controls System (ADECS), a twin jet acoustics flight experiment, self-repairing flight control system (SRFCS), performance-seeking control (PSC), and propulsion controlled aircraft (PCA). The upcoming F-15 project is ACTIVE (Advanced Control Technology for Integrated Vehicles) This paper provides a brief summary of these activities and provides background for the PCA and PSC papers, and includes a bibliography

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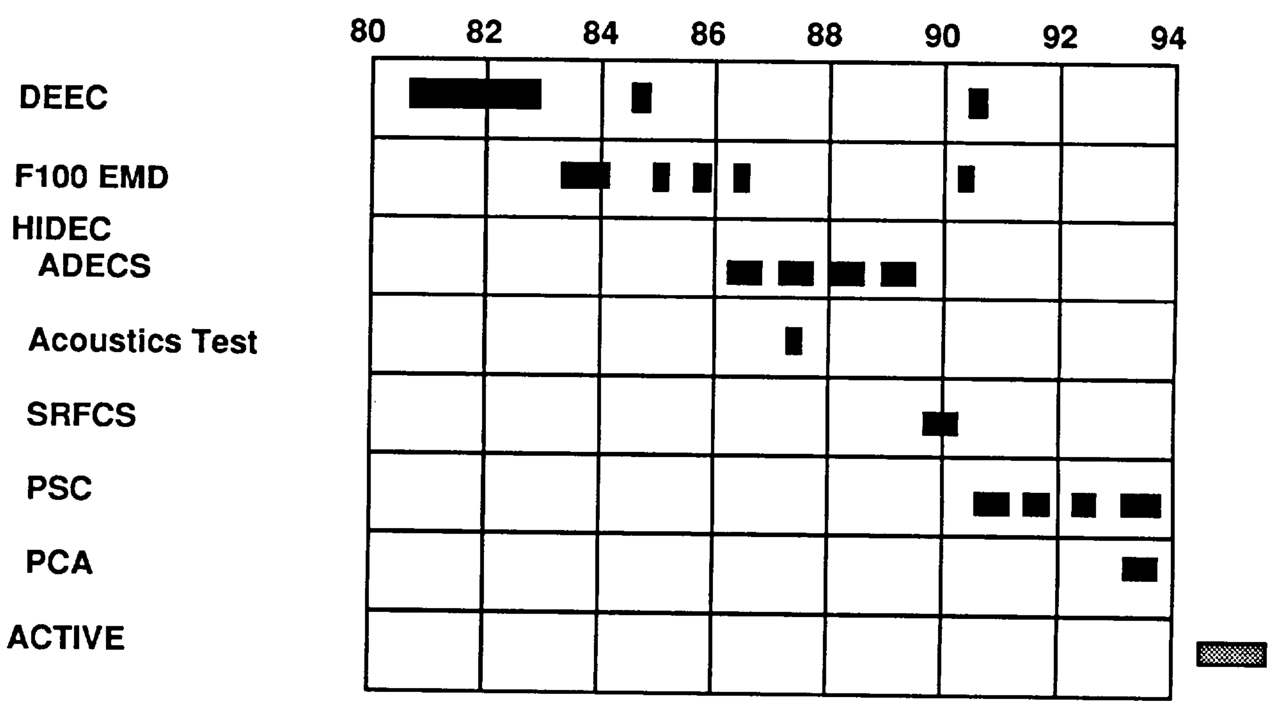
The NASA Dryden Flight Research Center has been conducting integrated flight-propulsion control flight research using the NASA F-15 airplane for the past 12 years. The research began with the digital electronic engine control (DEEC) project, followed by the F100 Engine Model Derivative (EMD). HIDEC (Highly Integrated Digital Electronic Control) became the umbrella name for a series of experiments including: the Advanced Digital Engine Controls System (ADECS), a twin jet acoustics flight experiment, self-repairing flight control system (SRFCS), performance-seeking control (PSC), and propulsion controlled aircraft (PCA). The upcoming F-15 project is ACTIVE (Advanced Control Technology for Integrated Vehicles) This paper provides a brief summary of these activities and provides background for the PCA and PSC papers, and includes a bibliography of all papers and reports from the NASA F-15 project.

F-15 Research Flight Periods



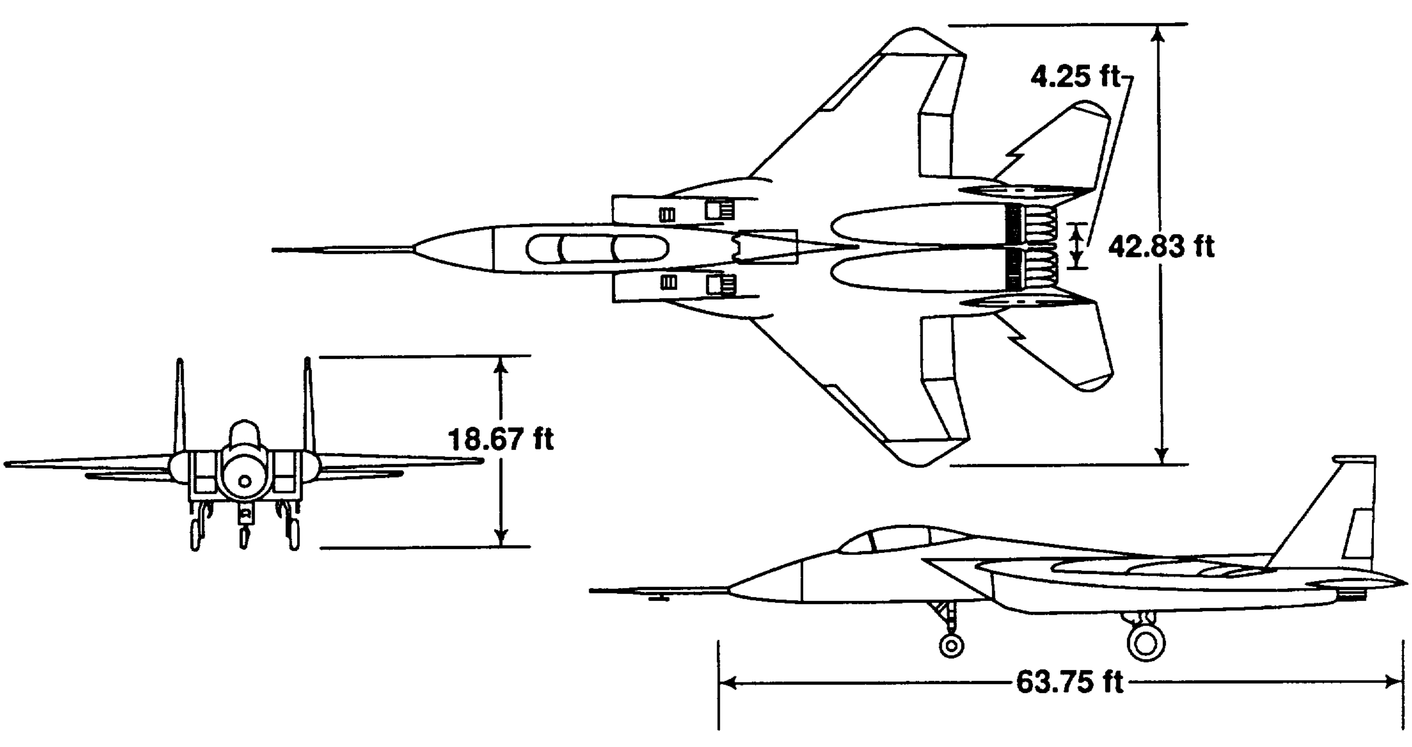
NASA F-15 Research Airplane

The NASA F-15 research airplane (USAF S/N 71-0287) was originally the 8th pre-production F-15 in the USAF test program. It, along with F-15 #2, (S/N 71-0281) came to Dryden in 1976, and was involved in a series of research programs, including flying qualities, buffet, and was the carrier airplane for the 10 deg cone flight experiment, ref 1. In 1980, propulsion experiments were begun on F-15 #8 and in 1985, it received NASA tail number 835.

The NASA F-15 is a single place air-superiority fighter airplane with excellent transonic maneuverability and a maximum Mach number of 2.5. The high-mounted low aspect ratio wing has a 45 deg leading edge sweep and conical camber. Reference wing area is 608 sq. ft. There are twin vertical tails and large all-moving horizontal stabilators. The F-15 propulsion system consists of variable-geometry horizontal ramp inlets on the forward fuselage each feeding afterburning turbofan engines located in the aft fuselage.

The NASA F-15 zero fuel weight is approximately 30,000 lb, and fuel capacity is 11,600 lb. It is equippped with a HUD video camera, and a data system that records digital and analog parameters on an on-board tape recorder, and also telemeters this data to the ground.

NASA F-15 Research Airplane



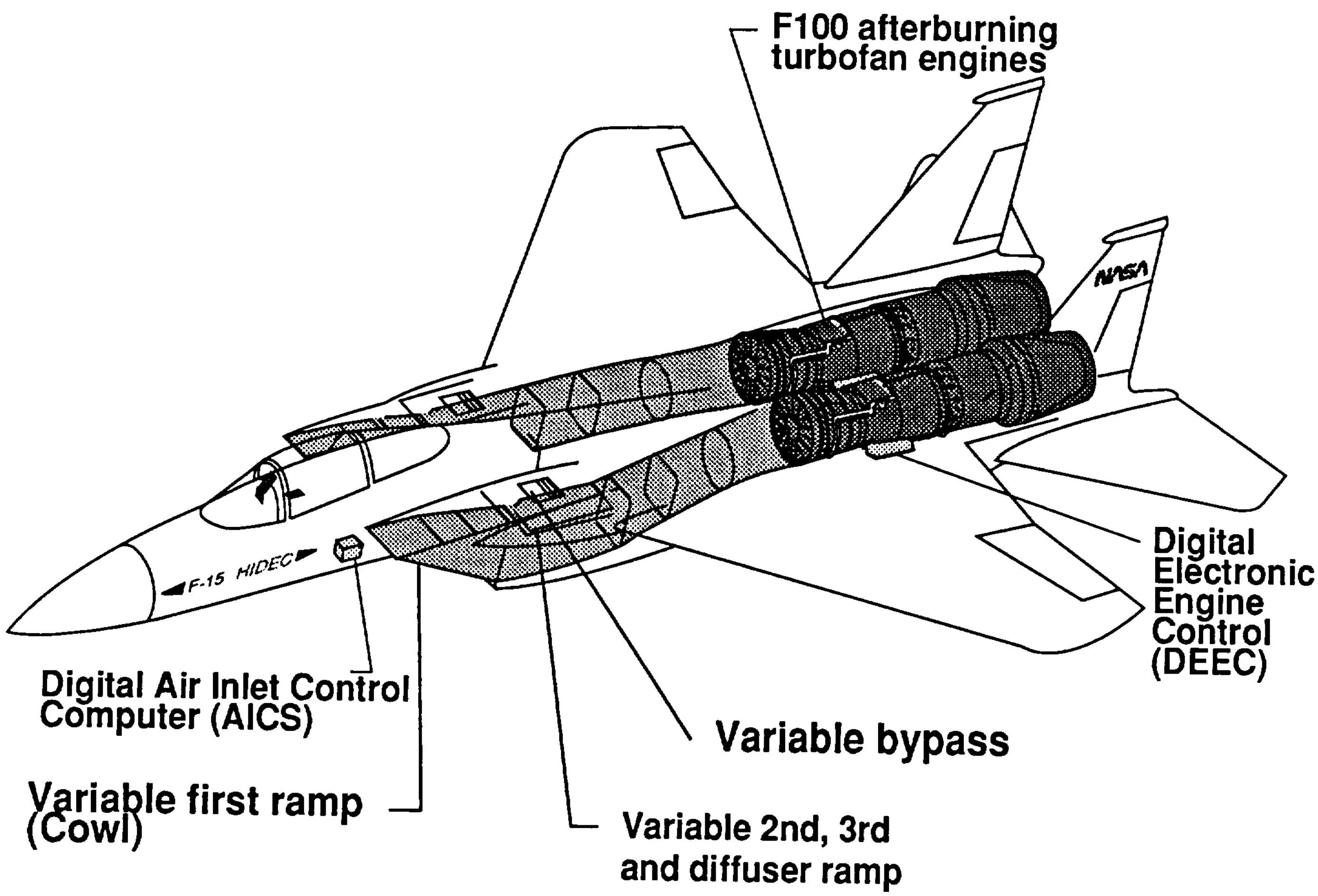
Propulsion System of the NASA F-15

The propulsion system of the F-15 is a highly integrated design consisting of two horizontal ramp inlets each feeding afterburning turbofan engines located in the aft fuselage.

As shown below, the inlets are mounted on the forward fuselage and are of the variable geometry external compression type. The first ramp is pivoted near the cowl lip and provides a variable capture capability to reduce spill drag as angle-of-attack increases. The second and third ramp and diffuser ramp are linked to provide proper compression at supersonic speeds. A bypass door is located on the upper inlet surface for proper airflow matching at supersonic speeds. A digital air inlet control system is provided to position the variable geometry.

The ducts, which are approximately seven diameters long, provide air to Pratt and Whitney F100 afterburning turbofan engines. These engines are low bypass ratio (approximately 0.5) and have a high thrust-to-weigh-ratio of approximately 8. For most tests, these engines were controlled by digital electronic engine control (DEEC) systems.

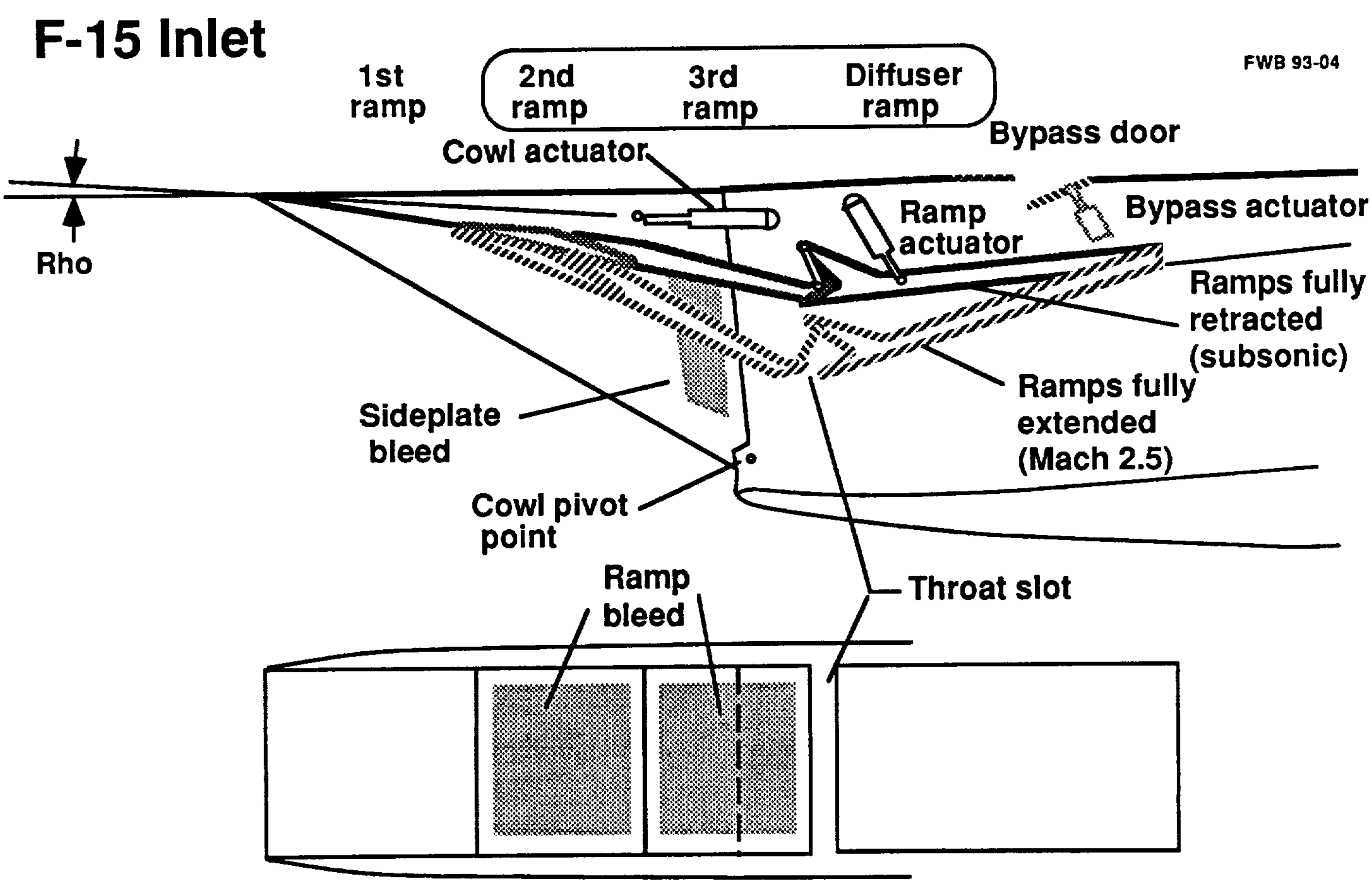
NASA F-15 Propulsion Sytem



F-15 Inlet

The F-15 variable geometry two-dimensional, external compression horizontal ramp inlet system is designed to provide high recovery, low distortion, and low spillage drag over the F-15 flight envelope. The variable first ramp, or cowl, rotates around a pivot located near the lower cowl lip to provide variable capture, and prevent excess inlet spillage drag at high angles of attack. The variable 2nd, 3rd, and diffuser ramps are linked to provide efficient compression at supersonic speeds. Boundary layer bleed is provided to improve recovery, distortion, and stability, using porous surfaces on the ramps, and the sideplates; and at the throat by a flush slot . A bypass door is provided to improve performance and provide airflow matching at Mach numbers above 1.6.

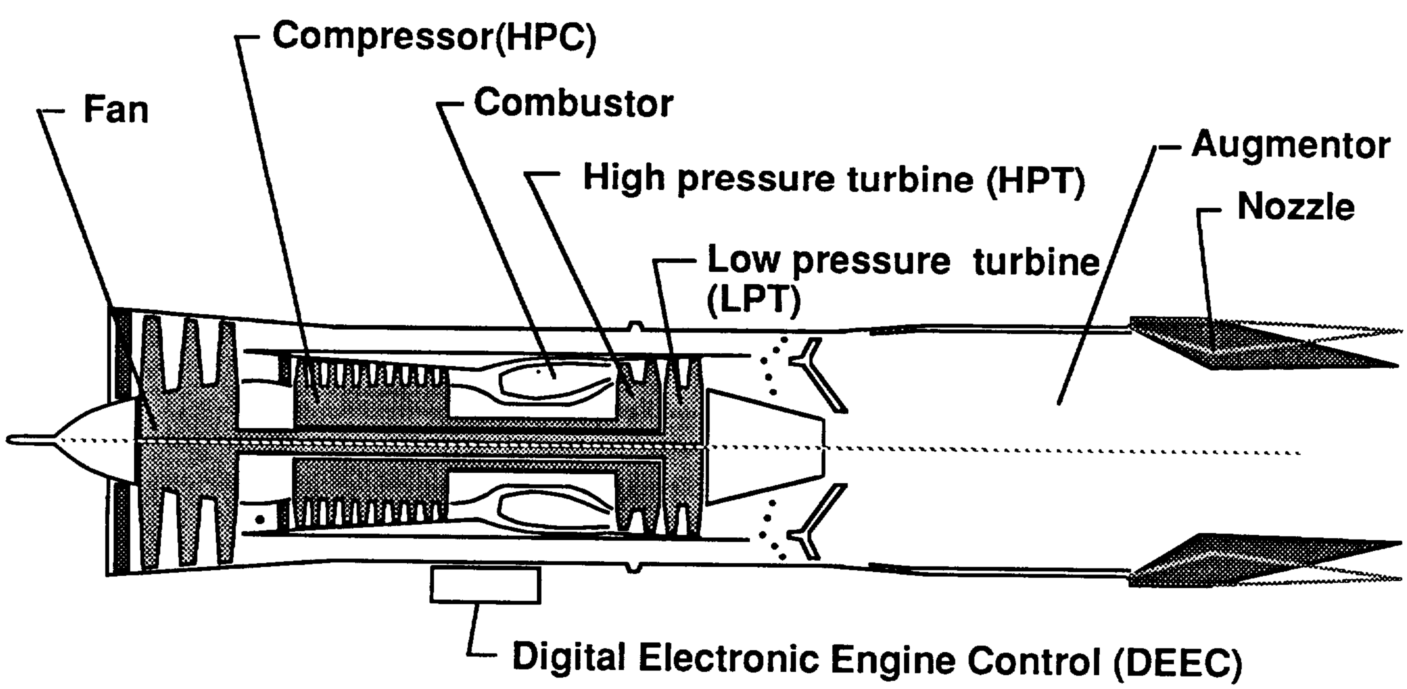
A digital control system positions the cowl, bypass and ramps as a function of local Mach number, local angle of attack, total temperature, and throat total and static pressure. The geometry is positioned by hydraulic actuators; if hydraulic pressure should be lost, the cowl and ramps drift to the full-up (emergency) position. In case of a malfunction, the pilot may also select the emergency position with a cockpit switch. At subsonic speeds, the ramps are fully up and the cowl schedules as a function of angle of attack. At supersonic speeds, the ramps extend primarily as a function of Mach number.



F100 engine

The F100 engine, shown below, is a low-bypass ratio, twin-spool, augmented turbofan engine. The three-stage fan is driven by a two-stage, low-pressure turbine. The 10-stage, high-pressure compressor is driven by a two-stage cooled turbine. The engine incorporates variable geometry (shown in red); compressor inlet variable vanes (CIVV) and 4 stages of rear compressor variable vanes (RCVV) to achieve high performance over a wide range of power settings; a compressor bleed is used only for starting. Continuously variable thrust augmentation is provided by a mixed flow augmentor and a variable area convergent-divergent balanced-beam nozzle. For the DEEC tests, an F100(3) engine, (P&W S/N- 680063) was used. This engine was later modified to the PW1128 configuration. For all PSC and PCA testing, F100 Engine Model Derivative (EMD) engines were used. These engines had a company designation of PW1128, and were development engines for the F100-PW-229 engines. The PW1128 was derived from the F100-PW-220, and features an increased airflow 248 lb/sec fan, single-crystal blades and vanes in the high pressure turbine, a 16 segment augmentor, and an improved DEEC.

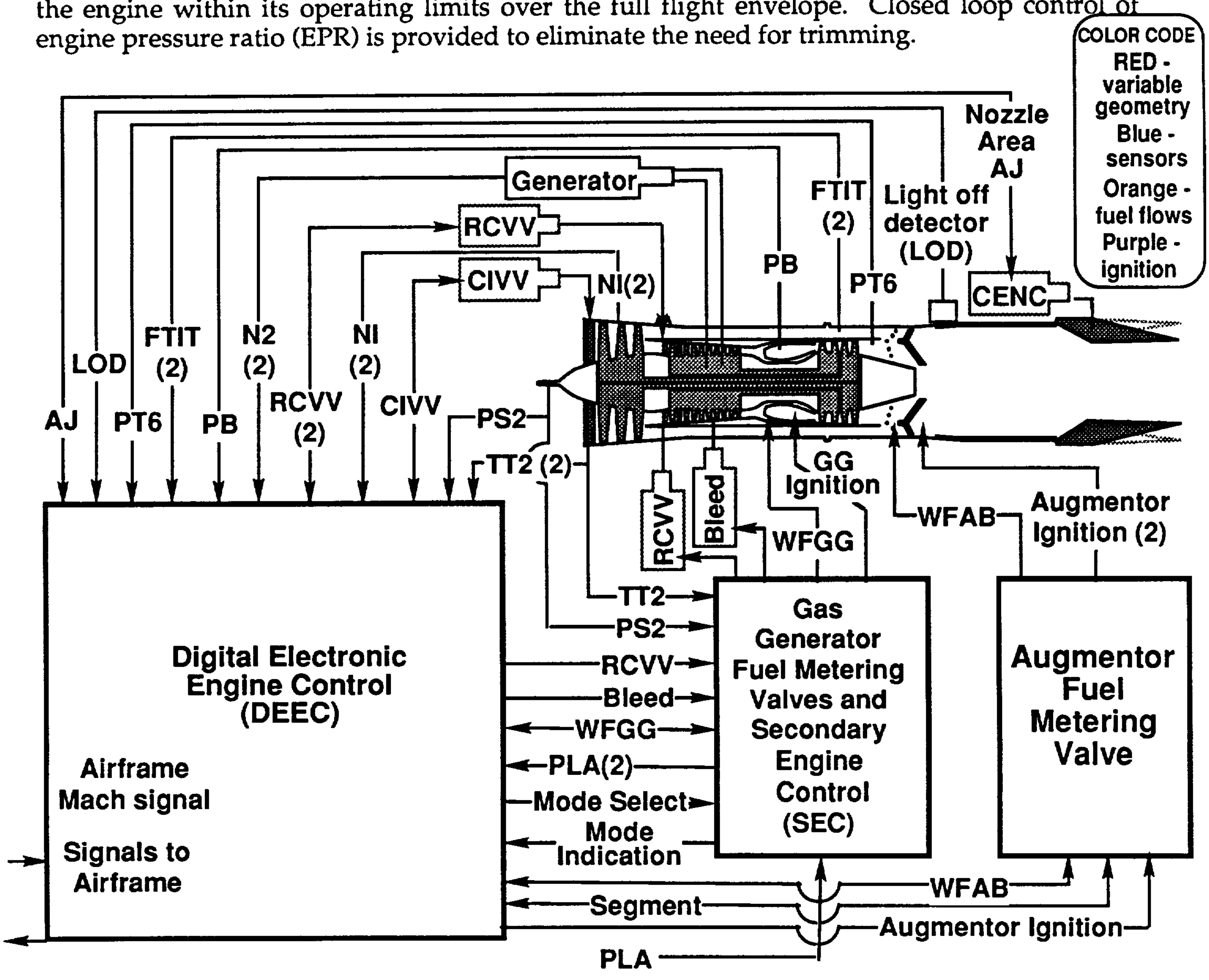
Cutaway view of the F100 engine



Digital Electronic Engine Control (DEEC)

The first full authority production-like digital engine control system flown was the P&W DEEC. It controls the major controlled variables on the engine, and replaces standard F100 engine control system. The DEEC is engine-mounted, and fuel-cooled, and consists of a single-channel digital controller with selective input-output redundancy, and a simple hydromechanical secondary engine control (SEC)

The DEEC system is functionally illustrated below. It receives inputs from the airframe through the power lever angle (PLA) and Mach number (M). Engine inputs are received from pressure sensors; fan inlet static pressure, (PS2), burner pressure, (PB), and turbine discharge total pressure, (PT6); temperature sensors, fan inlet total temperature, (TT2), and fan turbine inlet temperature, (FTIT), fan rotor speed sensors (N1) and core rotor speed sensors, (N2). It also receives feedbacks from the controlled variables through position feedback transducers indicating variable vane (CIVV and RCVV) positions, metering valve positions for gas-generator fuel flow (WFGG), augmentor fuel flow(WFAB), augmentor segment-sequence valve position, and exhaust nozzle position (AJ). The input information is processed by the DEEC computer to schedule the variable vanes (CIVV and RCVV), position the compressor start bleeds, control WFGG and WFAB, position the augmentor segment-sequence valve, and control the exhaust nozzle area. This logic provides linear thrust with PLA, rapid and stable throttle response, protection from fan and compressor stalls, and keeps the engine within its operating limits over the full flight envelope. Closed loop control of engine pressure ratio (EPR) is provided to eliminate the need for trimming.

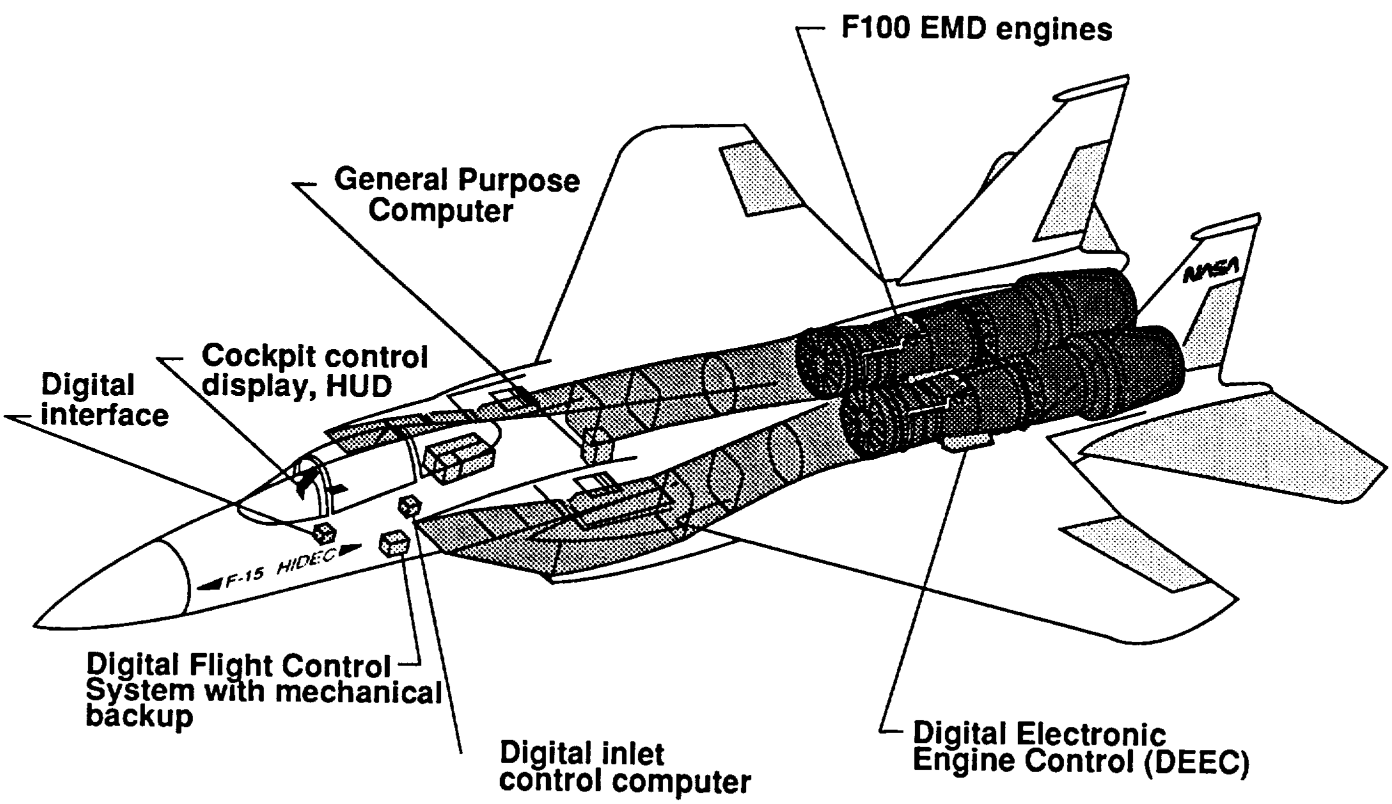


Integrated Control Features of the NASA F-15

The F-15 HIDEC airplane configuration has evolved over the years and is well-suited for integrated controls flight experiments. The features, shown below, include the F100 EMD engines with DEECs, the digital electronic flight control system (DEFCS), the digital inlet control computers, and an interface to allow these systems to communicate. Initially, control laws were hosted in the DEFCS, this configuration is shown on next page. Later, the general-purpose computer was added, and hosted the control laws for more complex integrated control algorithms, For the last tests, the vehicle management system computer replaced the DEFCS, and hosted the digital flight control system. The cockpit interfaces included the navigation control panel for inputs and the HUD for displays.

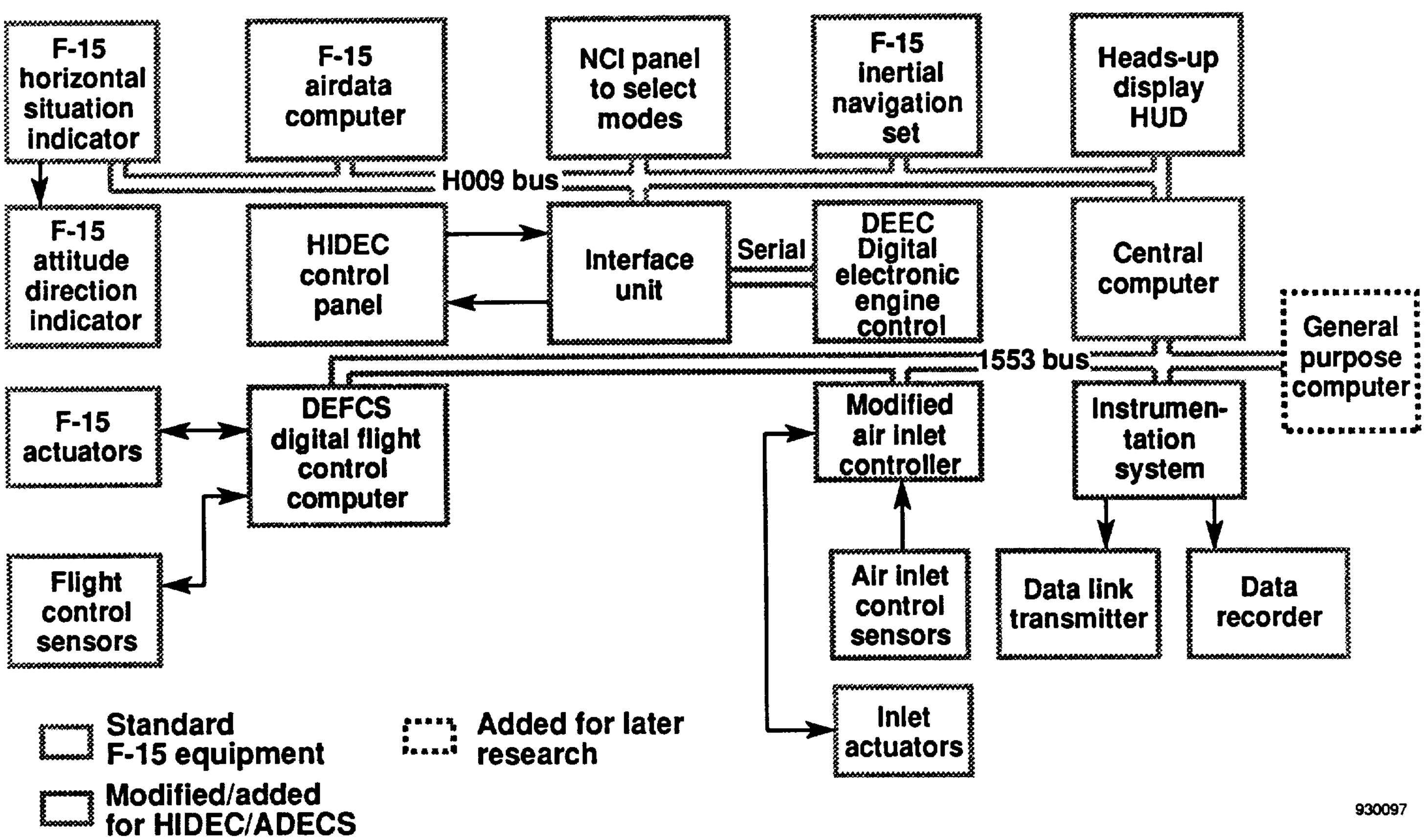
The digital flight control system, and the DEEC included backup dissimilar mechanical controllers so that the digital system software was not flight-safety critical, thus simplifying the software verification and validation process, and allowing research effort to be concentrated on control law research.

F-15 HIDEC Integrated Control Features



HIDEC System Architecture

The HIDEC system architecture is shown below, as it was arranged for the ADECS research with the inlet included. A key avionics box added was the interface unit that allowed the DEECs to communicate with the other F-15 systems and the Digital Electronic Flight Control System (DEFCS) that had excess capacity for research control laws. The various avionics units communicated with each other via H009 and 1553 digital data buses. Digital inputs were received from the digital flight control system, the inertial navigation set, the air data computer, the digital engine controls, commands were sent to the DEECs and inlets during ADECS operation. Later, the general purpose computer was added to accommodate more complex control laws programmed in FORTRAN.



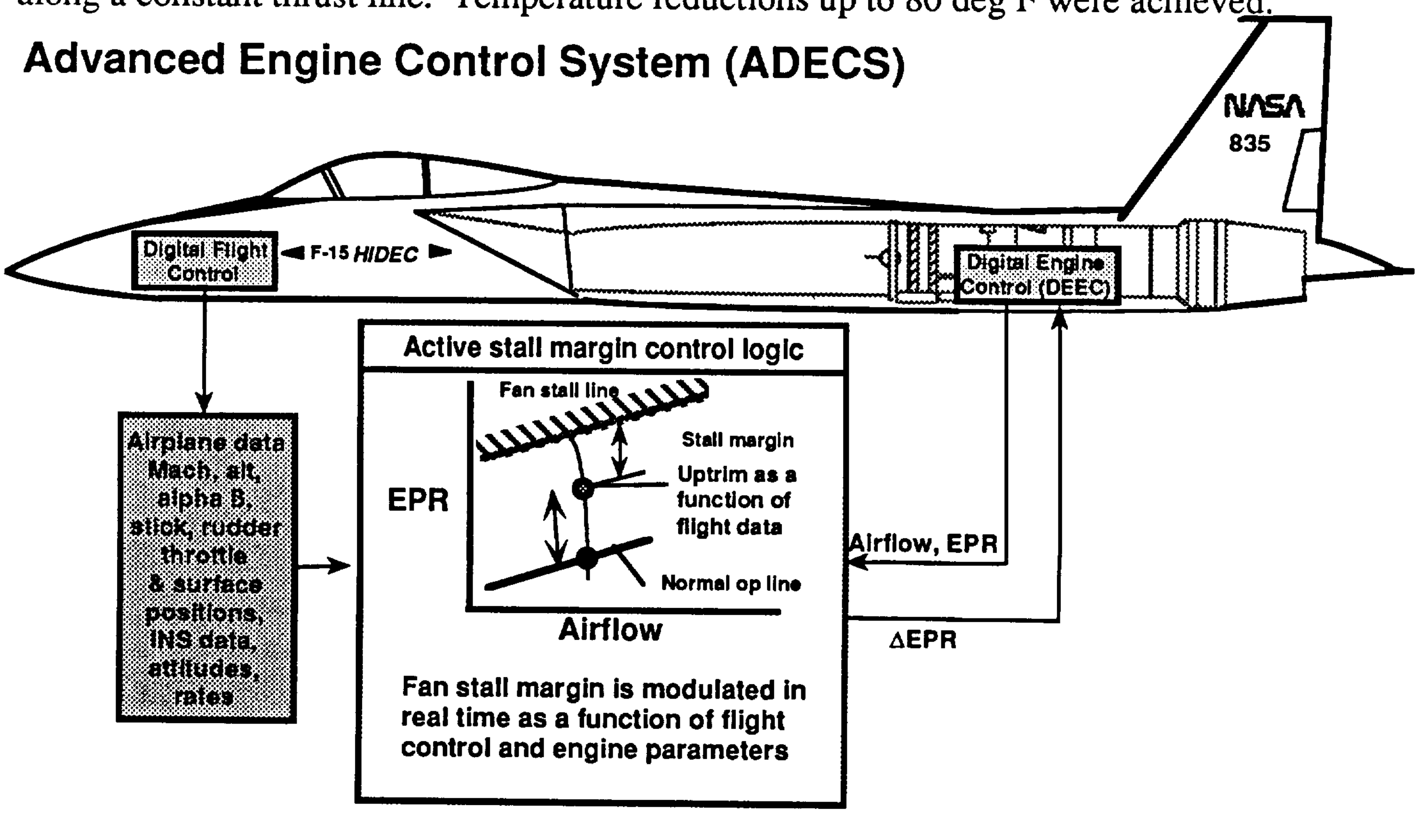
Advanced Engine Control System (ADECS)

As part of the HIDEC program, an advanced engine control system (ADECS) mode was incorporated on the F-15 airplane. McDonnell Douglas, USAF, and Pratt and Whitney assisted NASA in developing and testing ADECS. In ADECS, shown below, airframe and engine information is used to allow the engine to operate at higher performance levels at times when the inlet distortion is low and the full engine stall margin is not required. The ADECS mode increased thrust levels as shown in the fan map by increasing EPR at constant airflow (EPR uptrim). Fuel flow reductions could also be obtained by holding thrust constant as EPR was increased. In essence, ADECS traded unneeded stall margin for thrust. Schedules of EPR uptrim as a function of engine conditions, angle-of-attack, sideslip, and pilot's stick position were stored in the on-board research computer and the uptrims were computed and sent to the DEECs 4 times per second.

In the flight evaluation, the ADECS system was evaluated on the F100 EMD engines on the F-15. Significant performance improvements were demonstrated. Thrust improvements and constant-thrust fuel flow reductions were determined, and compared to predictions. The ability of the ADECS to accommodate rapid aircraft maneuvers and throttle transients was also demonstrated. Intentional stalls were also conducted to validate the stability audit procedures used to develop the ADECS logic.

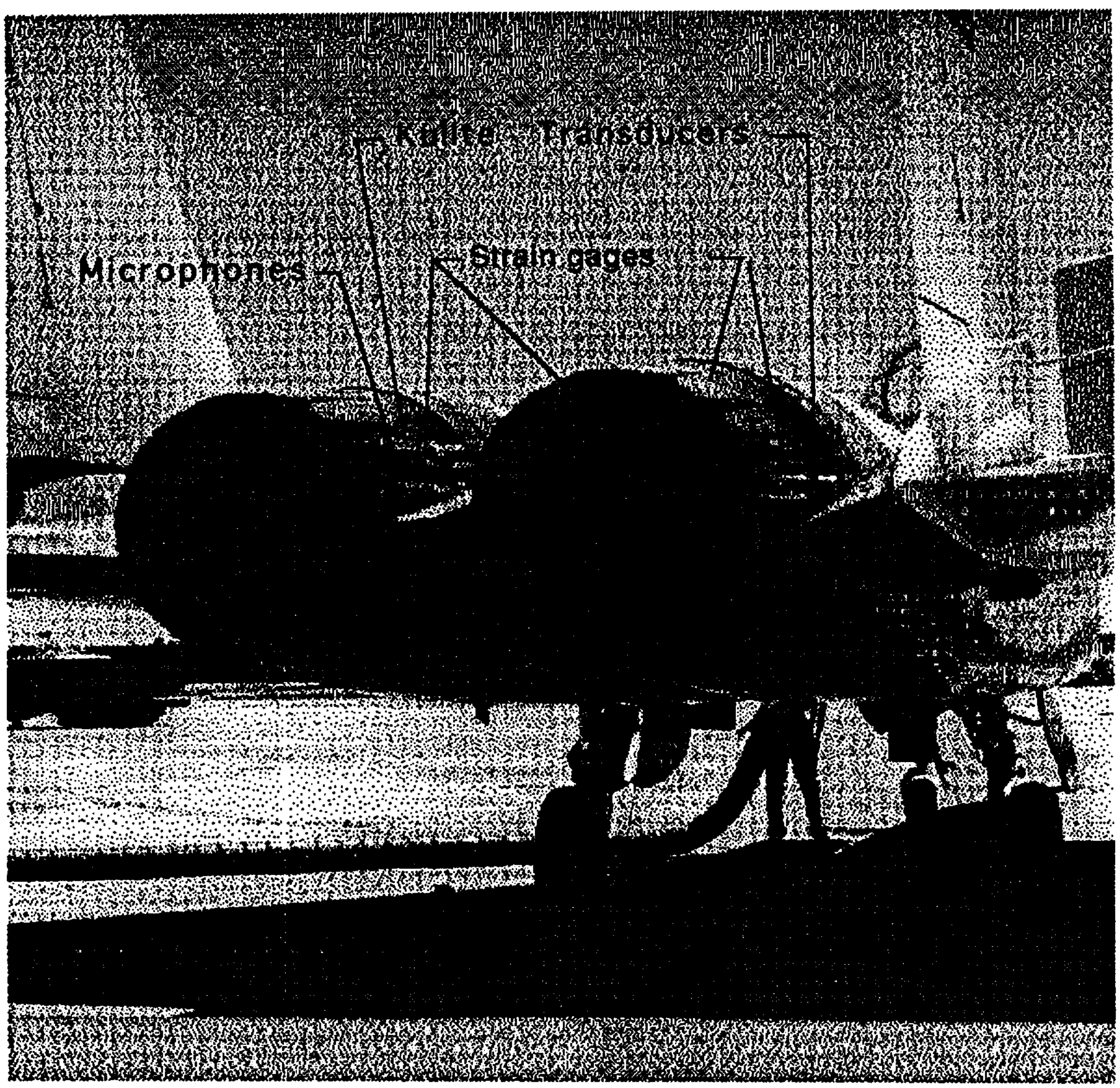
Typical results for an altitude of 30,000 ft. showed increases of 8 to 10 percent in thrust at intermediate power. Fuel flow reductions of 7 to 17 percent were obtained at maximum thrust with the PLA reduced to hold thrust constant. These engine performance improvements resulted in airplane performance improvements (rate of climb, specific excess power) of 10 to 25 percent.

Stall margin could also be traded for reduced temperature, resulting in extended engine life (EEL). EEL was accomplished by increasing EPR and reducing airflow along a constant thrust line. Temperature reductions up to 80 deg F were achieved.



Twin-Jet Acoustic Interactions

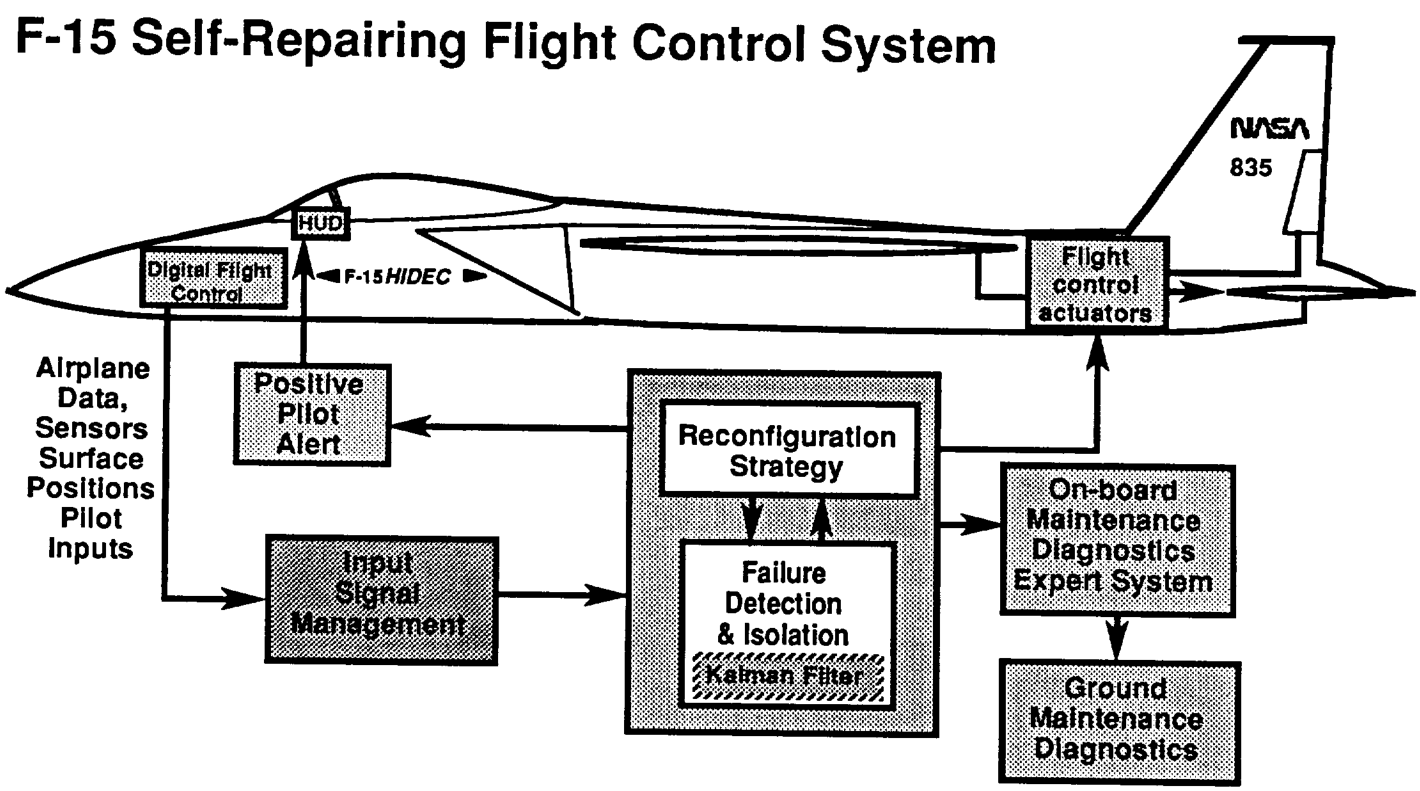
During the ADECS project, NASA Langley requested that Dryden join with them in an acoustics research program to investigate twin jet acoustic interactions. The F-15 and B-1 installations, with close-spaced engines, had both experienced cracked outer nozzle flaps, whereas similar engines running in a single-engine installation in the F-16 did not crack. Dryden installed about 25 high frequency microphones, pressure transducers, and strain gages on the nozzle flaps and interfairing areas. The photo below shows F100 EMD engine P085 on the left and P063 both with the instrumented external flaps installed in the F-15. The HIDEC ADECS system provided an added capability for this test. Langley's desire to match nozzle pressure ratios closely at the same power setting was satisfied by the ability of the ADECS system to increase EPR on one engine until it matched the other. Flights varied Mach number and altitude as well as power setting. Langley analyzed the acoustics data while Dryden provided the exhaust conditions. The results were correlated with small scale cold jet test data and are presented in the references.



Self-Repairing Flight Control System (SRFCS)

NASA Dryden, in conjunction with the USAF, MDA, GE and other contractors, flew a self-repairing flight control system on the NASA F-15. The system, shown below, used a Kalman filter for fault detection and isolation for locked and floating surfaces and partial surface loss. Upon detecting a failure, the control laws were reconfigured to use the remaining surfaces. The pilot was provided with an alert on his HUD, along with an indication of the remaining maneuver capability after the reconfiguration. There was also an on-board expert system for maintenance diagnostics, which fed into the ground diagnostics capability. Most of this system was installed in the on-board general-purpose Rolm Hawk research computer. Simulated failures could be introduced into the system through pilot commands.

The SRFCS was flown in a 25 flight program beginning in late 1989. Forty-three hours of data was accumulated, and quality data was excellent. All of the reconfiguration tests were successful. Most of the induced failures were detected, although some of the partial surface failures were not correctly identified. The flying qualities in the reconfigured system were generally good except for fine tracking. Most impressive was the lack of any false alarms.

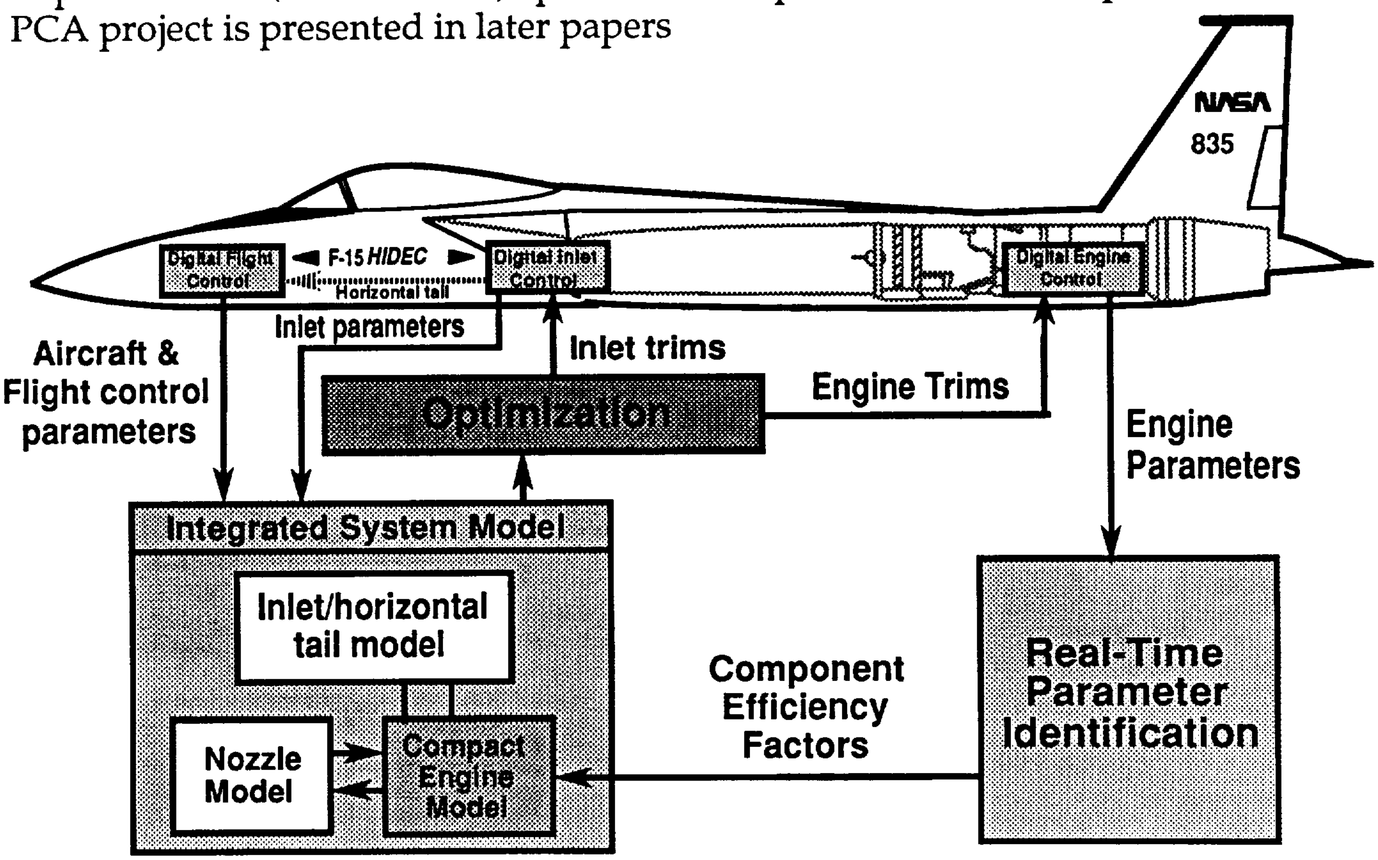


Performance-Seeking Control (PSC)

After the success of the ADECS tests, which was a schedule-based optimization of a single parameter (EPR) for an average engine, it was desired to perform a more sophisticated optimization. The Performance-Seeking Control (PSC) project selected a model-based approach, and performed an adaptive optimization of the propulsion system parameters on the F-15. McDonnell Douglas and Pratt and Whitney assisted NASA in developing and testing the PSC system. Several modes were implemented in the on-board research computer, including maximum thrust, minimum fuel flow at constant thrust, minimum temperature at constant thrust, and minimum supersonic thrust for rapid supersonic deceleration.

In the flight evaluation, the PSC system was evaluated on the F100 EMD engines on the F-15. Significant performance improvements were demonstrated. Thrust improvements and constant thrust temperature reductions and fuel flow reductions were determined, and compared to predictions. Various levels of engine degradation were also tested. Intentional engine stalls were conducted to validate the stability audit procedures.

Typical results for an altitude of 30,000 ft. showed increases of 10 to 14 percent in thrust at intermediate power. Fuel flow reductions of 7 to 17 percent were obtained in the afterburning range with thrust held constant. These engine performance improvements resulted in airplane performance improvements (rate of climb, specific excess power) of 10 to 25 percent. The PCA project is presented in later papers

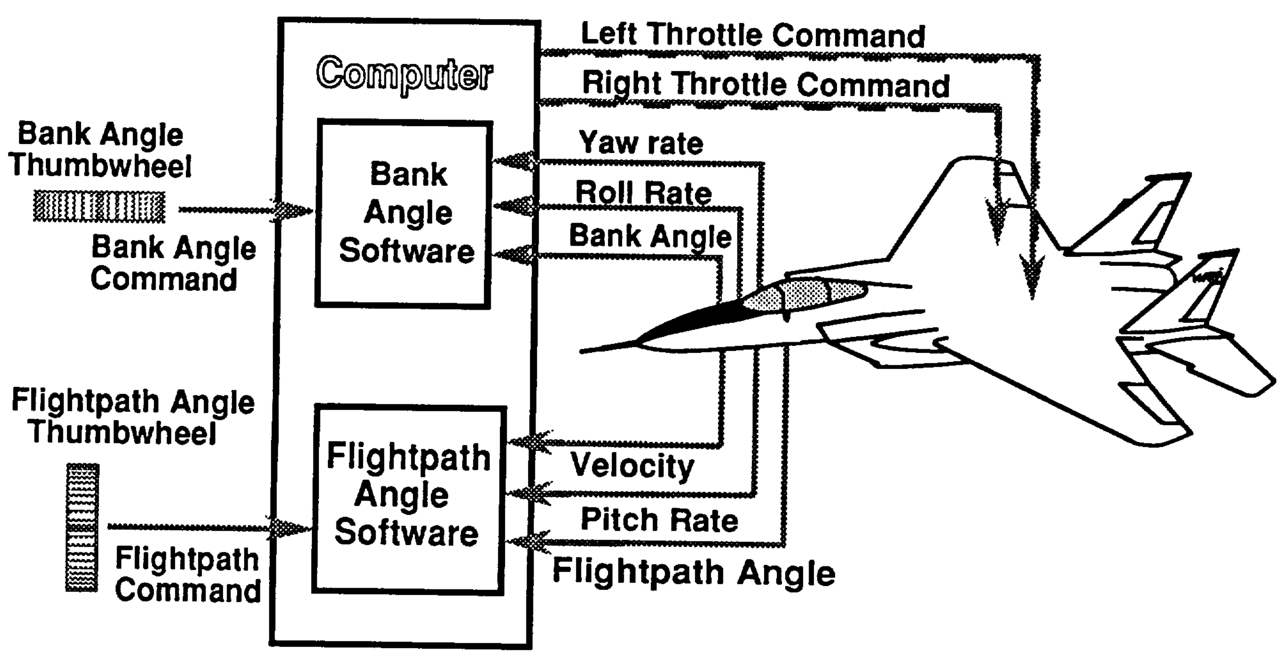


Propulsion Controlled Aircraft (PCA)

As a result of several accidents in which all or major parts of the flight control system was lost, NASA Dryden investigated the capability for a "Propulsion Controlled Aircraft" (PCA), using only engine thrust for flight control.

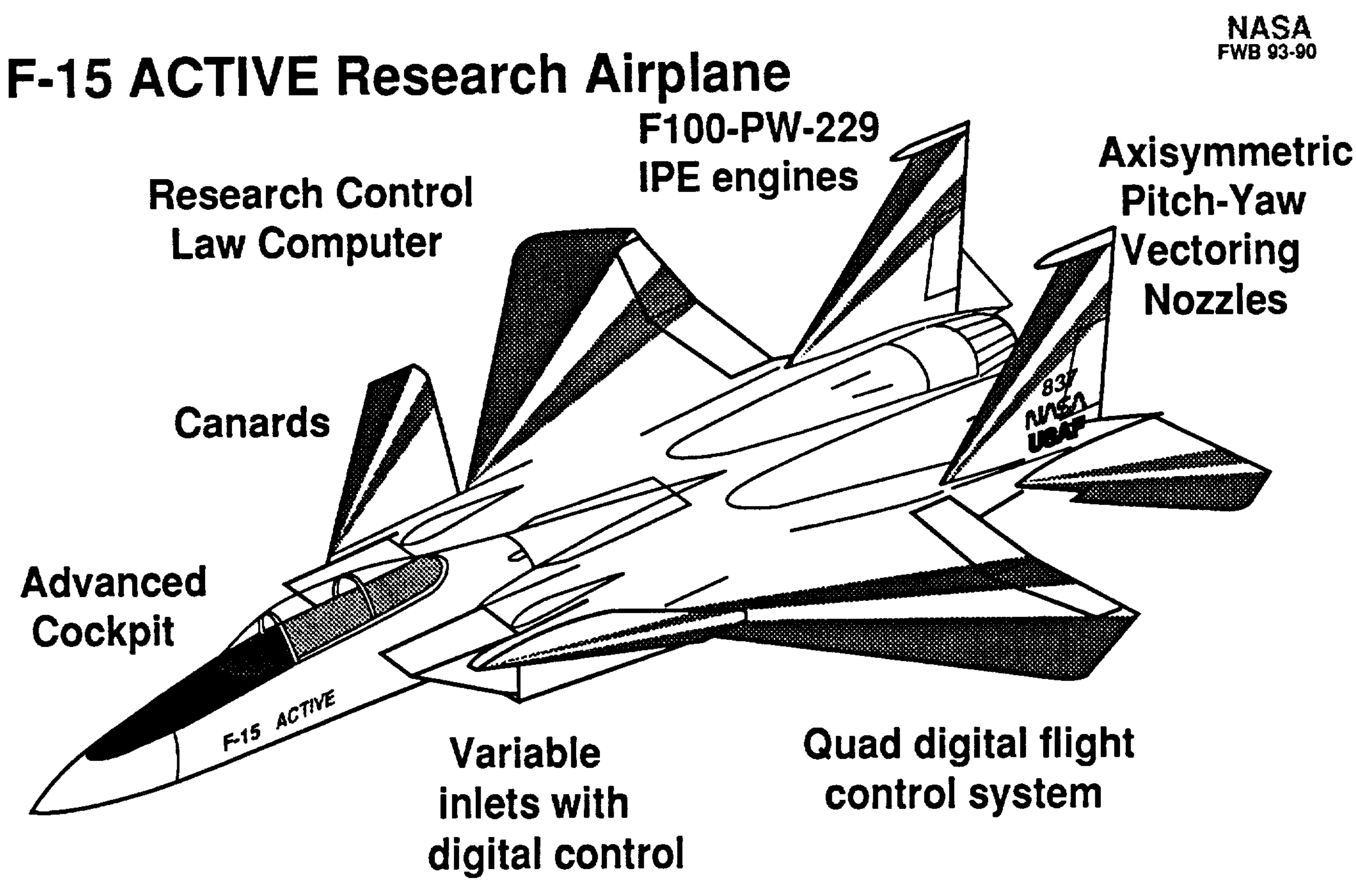
Initial flight studies with the pilot manually controlling the throttles and all flight controls locked in the NASA F-15 showed that it was possible to maintain gross control. For instance, a climb could be initiated by adding an equal amount of power to both engines. Bank control could be achieved by adding power to one engine and reducing power to the opposite engine. Using these techniques, altitude could be maintained within a few hundred feet and heading to within a few degrees. These same flights showed that it was extremely difficult to land on a runway. This was due to the small control forces and moments of engine thrust, difficulty in controlling the phugoid oscillations, and difficulty in compensating for the slow engine response. Studies in flight simulators at Dryden and at McDonnell Douglas were able to duplicate the flight results. These simulators also established the feasibility of a PCA mode, shown below, using feedback of parameters such as flight path angle and bank angle to augment the throttle control capability and to stabilize the airplane.

The NASA F-15 was an ideal testbed airplane for this research. It incorporated digital engine controls, digital flight controls, had a general-purpose computer and data bus architecture that permitted these digital systems to communicate with each other. The only equipment added to the airplane was a control panel containing 2 thumbwheels, one for flightpath command, and the other for bank angle command. Later papers will describe the design, development, and flight test results.



F-15 ACTIVE Research Airplane

The integrated controls flight research program from the HIDEC airplane will be continued on the F-15 ACTIVE (Advanced Control Technology for Integrated VEhicles) airplane. This F-15 airplane was transferred to NASA following the USAF STOL/Maneuver Technology Demonstrator program. Features are shown below. The airplane has independently actuated canards, a quad redundant digital flight control system, an advanced (F-15E) cockpit, F100-PW-229 engines with improved DEECs, and will be equipped with Pratt and Whitney axisymmetric thrust vectoring nozzles. The research computer will be transferred from the HIDEC airplane, as will the digital inlet control system. This program is discussed in the ACTIVE Plans paper.



F-15 Reseach Program References

Airplane Performance

Haering, E. A., Jr.; and Burcham, F. W., Jr.: Minimum Time and Fuel Flight Profiles for an F-15 Airplane with a Highly Integrated Digital Electronic Control System. NASA TM-86042, 1984

Orme, John S., Digital Performance Simulation Models of the F-15, F-16XL, F-18, F-104, TACT F-111, X-29, and Hypersonic Research Vehicle, NASA TM-104244, 1992.

Advanced Control Technology for Integrated Vehicles (ACTIVE)

Hreha, Mark A., Gerard S. Schkolnik, and John S. Orme, "An Approach to Performance Optimization Using Thrust Vectoring," AIAA-94-3361, June 1994.

Doane, Paul, Roger Bursey, and Gerard S. Schkolnik, "F-15 ACTIVE: A Flexible Propulsion Integration Testbed," AIAA-94-3360, June 1994.

Airframe-Propulsion Integration, Inlet and Nozzle

Nugent, J.; Taillon, N. V.; and Pendergraft, O. C., Jr.: Status of a Nozzle-Airframe Study of A Highly Maneuverable Fighter. AIAA 78-990, July 1978.

Webb, L. D.; Whitmore, S. A.; and Janssen, R. L.: Preliminary Flight and Wind Tunnel Comparisons of the Inlet/Airframe Interaction of the F-15 Airplane. AIAA 79-0102, Jan 1979

Stevens, C. H.; Spong, E. D.; Nugent, J.; and Neumann, H.E.: Reynolds Number Scale and Frequency Content Effects on F-15 Instantaneous Distortion. AIAA 79-0109, Jan 1979

Webb, L. D.; and Nugent, J: Results of the F-15 Propulsion Interactions Program. AIAA 82-1041, June 1982

Nugent, J.; Plant, T. J.; Davis, R. A.; and Taillon, N. V.: Pressures Measured In Flight On the Aft Fuselage and External Nozzle of A Twin-Jet Fighter. NASA TP-2017, May 1983

Pendergraft, O. C., Jr.; and Carson, G. T., Jr.: Fuselage and Nozzle Pressure Distributions of a 1/12-Scale F-15 Propulsion Model at Transonic Speeds. NASA TP 2333, Aug 1984

Pendergraft, O. C., Jr.; and Nugent, J.: Results of a Wind Tunnel/Flight Test Program to Compare Afterbody/Nozzle Pressures on a 1/12 Scale Model and a F-15 Aircraft. SAE-841543, Oct 1984

Webb, L. D.; Andriyich-Varda, Dom; and Whitmore, S. A.: Flight and Wind Tunnel Comparisons of the Inlet/Airframe Interaction of the F-15 Airplane.
NASA TP-2374, Nov 1984

Nugent, J.; and Pendergraft, O. C., Jr.: Comparison of Afterbody/Nozzle Pressures From Wind Tunnel and Flight Tests of a Twin-Jet Fighter At Transonic Speeds. NASA TP 2588, Mar 1987.

F-15 Reseach Program References (Continued)

Aerodynamics and 10 deg Cone Experiments

Lorincz, Dale J.; and Friend, Edward L.: Water Tunnel Visualization of the Vortex Flows of the F-15. AIAA Paper 79-1649, Aug 1979

Dougherty, N. S., Jr.; and Fisher, D. F.: Boundary-Layer Transition on a 10 Degree Cone: Wind Tunnel/Flight Correlation. AIAA 80-0154, Jan 1980

McRae, D. S.; Peake, D. J.; and Fisher, D. F.: A Computational and Experimental Study of High Reynolds Number Viscous/Inviscid Interaction About A Cone At High Angle of Attack. AIAA 80-1422, July 1980

Peake, D. J.; Fisher, D. F.; and McRae, D. S.: Flight Experiments With a Slender Cone at Angle of Attack. AIAA 81-0337, Jan 1981

Meyer, Robert. R., Jr., Jarvis, Calvin R., and Barneburg, Jack: In-Flight Aerodynamic Load Testing Of the Shuttle Thermal Protection System. AIAA 81-2468, Nov 1981

Saltzman, Edwin J.; and Ayers, T. G.: A Review of Flight-to-Wind Tunnel Drag Correlation. AIAA 81-2475, 1981

Dougherty, N. S., Jr.; and Fisher, D. F.: Boundary-Layer Transition Correlation On a Slender Cone in Wind Tunnels and Flight For Indications of Flow Quality. NASA TM-84732 or AEDC TR-81-26, Feb 82

Fisher, D. F.; and Dougherty, N. S., Jr.: In-Flight Transition Measurements on a 10 Degree Cone at Mach Numbers from 0.5 to 2.0. NASA TP-1971, June 1982

Peake, D. J.; Fisher, D. F.; and McRae, D. S.: Flight, Wind Tunnel and Numerical Experiments with a Slender Cone at Incidence. AIAA Journal, Vol. 20, No. 10, Oct 1982

Fisher, D. F.; and Dougherty, N. S., Jr.: Flight and Wing-Tunnel Correlation of Boundary-Layer Transition on the AEDC Transition Cone. AGARD CP-339, Oct 1982

Fisher, D. F.; and Dougherty, N. S., Jr.: Flight and Wind-Tunnel Correlation of Boundary-Layer Transition on the AEDC Transition Cone. NASA TM-84902, Nov 1982

Duke, Eugene L.; and Antoniewicz, R. F.: Development and Validation of a General Purpose Linearization Program for Rigid Aircraft Models. NASA TM 86737, Aug 1985

Johnson, J. Blair: In-Flight Boundary Layer Transition Measurements on a 45 deg Swept Wing at Mach Numbers Between 0.9 and 1.8. NASA TM 100412, Mar 1988

Zeis, J. E., Lambert, H.H., Calico, R. A., and Gleason, D.: Angle of Attack Estimation Using an Inertial Reference Platform. AIAA-88-4351-CP, Aug 1988

Curry, Robert E., and Gilyard, Glenn B.: Flight Evaluation of a Pneumatic System for Unsteady Pressure Measurements Using Conventional Sensors. NASA TM 4131, Aug 1989

Corda, Stephen, Stephenson, Mark T., Burcham, Frank W., and Curry, Robert E.: Dynamic Ground Effects Flight Test of an F-15 Aircraft, NASA TM-4604, 1994

Agility

Sisk, Thomas R. A Technique for the Assessment of Fighter Aircraft Precision Controllability. AIAA 78-1364.

Sisk, Thomas R.; and Matheny, Neil W.: Precision Controllability of the F-15 Airplane. NASA TM-72861, May 1979

Digital Electronic Engine Control (DEEC)

Barrett, W. J.; Rembold, J. P.; Burcham, F. W., Jr.; and Myers, L. P.: Flight Tests of a Full Authority Digital Electronic Engine Control System in an F-15 Aircraft. AIAA 81-1501, July 1981

Myers, L. P.; Mackall, K. G.; Burcham, F. W., Jr.; and Walter, W. A.: Flight Evaluation of a Digital Electronic Engine Control System in an F-15 Airplane. AIAA 82-1080, June 1982

Burcham, F. W., Jr.; Myers, L. P.; and Zeller, J. R.: Flight Evaluation of Modifications to a Digital Electronic Engine Control System in an F-15 Airplane. AIAA 83-0537, Jan 1983

Barrett, W. J.; Rembold, J. P.; Burcham, F. W., Jr.; and Myers, L. P.: Digital Electronic Engine Control System F-15 Flight Test. AIAA Journal of Aircraft 81-1501, Vol 20 no 2, Feb 1983

Licata, S. J.; and Burcham, F. W., Jr.: Airstart Performance of a Digital Electronic Engine Control System in an F-15 Airplane. NASA TM-84908, Apr 1983

Walsh, K. R.; and Burcham, F. W., Jr.: Flight Evaluation of a Hydromechanical Backup Control for the Digital Electronic Engine Control System in an F100 Engine. NASA CP-2298, May 1983

Putnam, T. W.: Digital Electronic Engine Control History. NASA CP-2298, May 1983

Kock, B. M.: Digital Electronic Engine Control F-15 Overview. NASA CP 2298, May 1983

Myers, L. P.: F-15 Digital Electronic Engine Control System Description. NASA CP 2298, May 1983

Werner, R. A.; Willoh, Ross G., Jr.; and Abdelwahab, M.: NASA Lewis F100 Engine Testing. NASA CP 2298, May 1983

Myers, L. P.: Flight Testing the Digital Electronic Engine Control in the F-15 Airplane. NASA CP 2298, May 1983

Baer-Riedhart, J. L.: Digital Electronic Engine Control Fault Detection and Accommodation Flight Evaluation. NASA CP 2298, May 1983

Johnson, J. Blair: Backup Control Airstart Performance on a Digital Electronic Engine Control-Equipped F100 Engine. NASA CP 2298, May 1983

Ray, R. J.; and Myers, L. P.: Real-Time In-Flight Thrust Calculation on a Digital Electronic Engine Control-Equipped F100 Engine in an F-15 Airplane. NASA CP 2298, May, 1983

Putnam, T. W.; Burcham, F. W., Jr.; and Kock, B. M.: Flight Testing The Digital Electronic Engine Control (DEEC) - A Unique Management Experience. SFTE (See SFTE 14th Annual Symposium Proceedings-1983), August 1983

F-15 Research Program References (cont.)

Digital Electronic Engine Control (DEEC) continued

Myers, L. P.; and Burcham, F. W., Jr.: Comparison of Flight Results with Digital Simulation for a Digital Electronic Engine Control in an F-15 Airplane. NASA TM-84903, Oct 1983

Burcham, F. W., Jr.; Myers, L. P.; and Walsh, K. R.: Flight Evaluation Results of a Digital Electronic Engine Control in an F-15 Airplane. AIAA 83-2703, Nov 1983

Johnson, J. Blair: Flight Evaluation of the DEEC Secondary Engine Control Air-Start Capability. NASA TM 84910, Dec 1983

Burcham, F. W., Jr.; Myers, L. P.; and Zeller, J. R.: Flight Evaluation of Modifica-tions to a Digital Electronic Engine Control System in an F-15 Airplane. NASA TM-83088, Jan 1983

Burcham, F. W., Jr.; and Pai, G. D.: Augmentor Transient Capability of an F100 Engine Equipped with a Digital Electronic Engine Control. NASA CP-2298, Mar 1984

Burcham, F. W., Jr.; and Zeller, J. R.: Investigation of a Nozzle Instability on a DEEC Equipped F100 Engine. NASA CP-2298, Mar 1984

Burcham, F. W., Jr.: Air Start Performance of a DEEC Equipped F100 Engine in an F-15 Airplane. NASA CP-2298, Mar 1984

Digital Electronic Engine Control (DEEC) Flight Evaluation in an F-15 Airplane, Symposium Proceedings, NASA CP-2298, Mar 1984

Digital Electronic Engine Controls Examined. Aerospace Engineering, pp34-38, Feb, 1985

Myers, L. P.; Baer-Riedhart, J. L.; and Maxwell, M.: Fault Detection and Accommodation Testing on an F100 Engine in a F-15 Airplane. AIAA 85-1294, July 1985

Burcham, Frank W., Myers, Lawrence P., and Walsh, Kevin R.: Flight Evaluation of a Digital Electronic Engine Control in an F-15 Airplane, Journal Of Aircraft, Vol 22, No. 12, pp. 1072-1078, Dec. 1985.

Engine Tests and Thrust Calculation

Kurtenbach, F. J.: Comparison of Calculated and Altitude-Facility-Measured Thrust and Airflow of Two Prototype F100 Turbofan Engines. NASA TP-1373, 1978

Biesiadny, T. J.; Lee, D.; and Rodriguez, J. R.: Airflow and Thrust Calibration of an F100 Engine, S/N P680059, at Selected Flight Conditions. NASA TP-1069, 1978

Biesiadny, T. J.; Lee, D.; and Rodriguez, J. R.: Altitude Calibration of an F100, S/N P680063, Turbofan Engine. NASA TP-1228, 1978

Kurtenbach, F. J.: Evaluation of a Simplified Gross Thrust Calculation Technique Using Two Prototype F100 Turbofan Engines in an Altitude Facility. NASA TP-1482, 1979

Kurtenbach, F. J.; and Burcham, F. W., Jr.: Flight Evaluation of a Simplified Gross Thrust Calculation Technique Using an F-100 Turbofan Engine in an F-15 Airplane. NASA TP-1782, Jan 1981

Foote, C. H.; and Jaekel, R. J.: Flight Evaluation of an Engine Static Pressure Noseprobe in an F-15 Airplane. NASA CR-163109, Aug 1981

Burcham, F. W., Jr.; Myers, L. P.; Nugent, J.; Lasagna, P.L.; and Webb, L. D.: Recent Propulsion System Flight Tests at the NASA Dryden Flight Research Center. AIAA 81-2438, Nov 1981

Hughes, D. L.; and Mackall, K. G.: Effects of Inlet Distortion on a Static Pressure Probe Mounted on the Engine Hub in an F-15 Airplane. NASA CP-2298, May 1983

Ray, R. J.: In-Flight Thrust Determination on a Real-Time Basis. Graduate Thesis: California Polytechnic University, San Luis Obispo, May 1984

Hughes, D. L.; Myers, L. P.; and Mackall, K. G.: Effects of Inlet Distortion on a Static Pressure Probe Mounted on the Engine Hub in an F-15 Airplane. NASA TP 2411, Apr 1985

Ray, Ronald J., Evaluating the Dynamic Thrust Calculation Techniques During Throttle Transients. NASA TM 4591 and AIAA 94-2115, June 1994

F100 Engine Model Derivative

Myers, L. P.; and Burcham, F. W., Jr.: Preliminary Flight Test Results of the F100 EMD Engine in an F-15 Airplane. AIAA 84-1332, June 1984

Cho, Tony K.; and Burcham, F. W., Jr.: Preliminary Flight Evaluation of F100 Engine Model Derivative Airstart Capability in an F-15 Airplane. TM 86031, July 1984

Crawford, David B.; and Burcham, F. W., Jr.: Effect of Control Logic Modifications on Airstart Performance of F100 Engine Model Derivative Engines in an F-15 Airplane. NASA TM-85900, Aug 84

Ogborn, Stephen: State Variable Dynamic Model of a PW1128 Engine with a DEEC Control. Pratt and Whitney Report FR-18761A, May 1985

Walton, James T.; and Burcham, F. W., Jr.: Augmentor Performance of an F100 Engine Model Derivative Engine in an F-15 Airplane. NASA TM 86745, May 1986

F-15 Research Program References (cont.)

HIDEC/Advanced Engine Control System

Yonke, W. A.: Integrated Flight/Propulsion Control: HIDEC Modes. NAECON Paper C-203, May 1984

Burcham, F. W., Jr.; and Haering, E. A., Jr.: Highly Integrated Digital Engine Control System on an F-15 Airplane.AIAA 84-1259, June 1984

Myers, L. P.; and Burcham, F. W., Jr.: Propulsion Control Experience Used in the Highly Integrated Digital Electronic Control (HIDEC) Program. SAE 841553 or NASA TM-85914, Oct 1984

Burcham, F. W., Jr.; Myers, L. P.; and Ray, R. J.: Predicted Performance Benefits of an Adaptive Digital Engine Control System on an F-15 Airplane. AIAA 85-0255 or NASA TM-85916, Jan 1985

Yonke, W. A.; Terrell, L. A.; and Myers, L. P.: Integrated Flight/Propulsion Control: Adaptive Engine Control System Mode. AIAA 85-1425, July 1985

Putnam, T. W.; and Burcham, F. W, Jr.: Performance Improvements of a Highly Integrated Digital Electronic Control System for an F-15 Airplane. AIAA Paper No. 85-1876 or NASA TM 86748, Aug 1985

Baer-Riedhart, J. L.; and Landy, Robert J.: Highly Integrated Digital Electronic Control - Digital Flight Control, Aircraft Model Identification and Adaptive Engine Control, AIAA 85-1877, Aug 1985

Andries, Mary G, and Terrell, L. A.: Highly Integrated Digital Electronic Control HIDEC Sea Level Test Report for Engine P085-11, Pratt and Whitney Report FR-19248, Jan. 1986.

Ray, Ronald J. and Myers, Lawrence P.: Test and Evaluation of the HIDEC Engine Uptrim Algorithm, AIAA-86-1676, June 1986

Baer-Reidhart, Jennifer L., and Landy, Robert J.: Highly Integrated Digital Electronic Control - Digital Flight Control, Aircraft Model Identification, and Adaptive Engine Control, NASA TM-86793, Mar 1987

Myers, Lawrence P., and Walsh, Kevin R.: Preliminary Flight Evaluation of an Adaptive Engine Control System on an F-15 Airplane, AIAA-87-1847, Jun 1987

Yonke, W. A., Landy, R. J., and Stewart, J. F.: HIDEC Adaptive Engine Control Flight Evaluation Results. ASME 87-GT-257, Jun 1987

Smolka, James: F-15 HIDEC Program Test Results, SETP Symposium Proceedings, ISSN #0742-3705, Sept, 1987

Myers, Lawrence P., and Walsh, Kevin R.: Performance Improvements of an F-15 Airplane with an Integrated Engine-Flight Control System, NASA TM 100431, May 1988. (Also AIAA 88-2175)

Simmons, Carl F., and Brant, Garry: Enhanced Fighter Engine Operability Using Full Authority Digital Electronic Control Systems. AIAA 88-3266, Jul 1988

F-15 Research Program References (cont.)

HIDEC/Advanced Engine Control System

Proceedings of the HIDEC Symposium, NASA CP 3024, 1989

Chisolm, J. D., Nobbs, S. G., and Stewart, J. F.: Development of the HIDEC Inlet Integration Mode, ASME Paper presented at the 1989 Gas Turbine Engine Conference, Sept, 1989

Stewart, James F.: Integrated Flight Propulsion Control Results Using the NASA F-15 HIDEC Flight Research Facility, NASA TM-4394, June 1992 and AIAA-92-4106-CP

Kelly, J. B., and Yuhas, A. J.: PW1128 HIDEC EPR Uptrim Limits Final Report, P&W Report FR-18852, Jan 1985.

Integrated Control Systems

Burcham, F. W., Jr.: Propulsion-Flight Control Integration Technology. AGARD N79-16864 08-08, Nov 1978

Carlin, C. M., and Hastings, W. J.: Propulsion/Flight Control Integration Technology (PROFIT) Design Analysis Status. NASA CR-144875, 1978

Carlin, C. M., and Hastings, W. J.: Propulsion/Flight Control Integration Technology (PROFIT) Software System Definition. NASA CR-144876, Jan 1979

Burcham, F. W., Jr.; and Stewart, J. F.: The Development Process for Integrated Propulsion-Flight Controls. NASA CP-2162, Part 1, Oct 1980

Putnam, Terrill W. and Christiansen, Richard S.: Integrated Controls Payoff, AIAA 89-2704, Jul 1989

Burcham, F. W. Jr., Gilyard, Glenn B., and Gelhausen, Paul A.: Flight-Propulsion Control Integration for a Supersonic Transport, SAE paper 901928, Oct 1990 (Won Manley award) also NASA TM 101728

F-15 Research Program References (cont.)

Performance-Seeking Controls

Luppold, R.H., Roman, J. R. , Gallops, G. W., and Kerr, L. J.: Estimating In-Flight Engine Performance Variations Using Kalman Filter Concepts, AIAA 89-2584, Jul 1989

Smith, R. H., Chisolm, J. D., and Stewart, J. F.: Optimizing Aircraft Performance with Adaptive Integrated Flight/Propulsion Control, ASME 90-GT-252, June 1990

Maine, T., Gilyard, Glenn B., and Lambert, H. H.: A Preliminary Evaluation of an F100 Engine Parameter Estimation Process Using Flight Data, AIAA paper 90-1921, Jul 1990

Alag, Gurbux S., and Gilyard, Glenn B.: A Proposed Kalman Filter Algorithm For Estimation of Unmeasured Output Variables For an F100 Turbofan Engine, AIAA 90-1920, Jul 1990

Lambert, H. H., Gilyard, G. B., Chisolm, J. D., and Kerr, L. J.: Preliminary Flight Evaluation of an Engine Performance Optimization Algorithm, AIAA-91-1998, Jun 1991

Lambert, H. L.: A Simulation Study of Turbofan Engine Deterioration Estimation Using Kalman Filtering Techniques, NASA TM 104233, June 1991

Orme, J., and Gilyard, G.: Subsonic Flight Test Evaluation of a Propulsion System Parameter Estimation Process for the F100 Engine, AIAA92-3745, July 1992

Gilyard, Glenn B., and Orme, John S.: Subsonic Flight Test Evaluation of a Performance Seeking Control Algorithm on an F-15 Airplane, AIAA-92-3743, July 1992

Conners, Timothy R.: Thrust Stand Evaluation of Engine Performance Improvement Algorithms in an F-15 Airplane, AIAA 92-3747 and NASA TM 104252, July 1992

Stewart, James F., Burcham, Frank W. Jr., and Gatlin, Donald H.: Flight Determined Benefits of Integrated Flight-Propulsion Control Systems, NASA TM-4393, June 1992. and 18th ICAS Congress, Beijing, People's Republic of China, September 20-25,1992

Myers, Lawrence P., and Conners, Timothy R.: Flight Evaluation of an Extended Engine Life Mode on an F-15 Airplane, NASA TM-104240, Apr 1992

Gilyard, Glen, and Orme, John: Subsonic Flight Test Evaluation of a Performance Seeking Control Algorithm on an F-15 Airplane. AIAA-92-3743, July 1992

Chisholm, John: In-Flight Optimization of the Total Propulsion System. AIAA-92-3744, July 1992

Orme, John, and Gilyard, Glen: Subsonic Flight Test Evaluation of a Propulsion System Parameter Estimation Process for the F100 Engine. AIAA-92-3745, July 1992

Nobbs, Steve, Jacobs, Steve, and Donahue, Dennis: Development of the Full-Envelope Performance Seeking Control Algorithm. AIAA-92-3748, July 1992

Bushman, M., and Gallops, G. W.: In-Flight Performance Identification Capability of an Adaptive Engine Model. AIAA 92-3746, July 1992

F-15 Research Program References (cont.)

Performance-Seeking Controls

Templeman, W. G., and Gallops, G. W.: Performance Benefits of an Adaptive In-flight Propulsion System Optimization. AIAA 92-3744, July 1992

Orme, John, and Gilyard, Glenn: Preliminary Supersonic Flight Test Evaluation of Performance Seeking Control, AIAA 93-1821, June 1993

Mueller, F.D., Nobbs, S. G., and Stewart, J. F.: Dual Engine Application of the Performance Seeking Control Algorithm. AIAA-93-1822, June 1993

España Martín D., and Glenn Gilyard: On the Estimation of the Off-nominal Behavior in Turbofan Engines. AIAA 93-1823 and NASA TM 1993, Jun 1993

Orme, John and Gilyard, Glenn: Preliminary Supersonic Flight Test Evaluation of Performance Seeking Control, TM 4494, June 1993

Gilyard, Glenn B. and Orme, John S.; Performance-Seeking Control: Program Overview and Future Directions. AIAA 93-3765, Aug 1993

Schkolnik, Gerard S.: Identification of Integrated Airframe-Propulsion Effects on an F-15 Aircraft For Application to Drag Minimization. AIAA 93-3764, Aug 1993

Yonke, William A., and Nobbs, Steven G.: Performance Seeking Control (PSC) Final Report, MDC 94B0003, Jan 1994

Orme, John, and Conners, Tim,: Supersonic Flight Test Results of a Performance Seeking Control Algorithm on a NASA F-15 Aircraft. AIAA 94-3210, June 1994

F-15 Research Program References (cont.)

Propulsion Controlled Aircraft (PCA)

Burcham, F. W., Fullerton, C. G., Gilyard, G., Wolf, T., and Stewart, J.: A Preliminary Investigation of the Use of Throttles for Emergency Flight Control, AIAA-91-2222. June 1991. (also TM 4320, Sept 1991)

Dornheim, Michael A.: "Research Pilot Devises Rules of Thumb for Engine-Only Control of Disabled Aircraft", Aviation Week and Space Technology, June 24, 1991, pp 43.

Burcham, F. W. and Fullerton, C. G.: Controlling Crippled Aircraft - With Throttles, Flight Safety Foundation 44th Air Safety Seminar, Nov 1991, also NASA TM 10423

Burcham, Frank W. Jr, Maine, Trindel, and Wolf, Thomas: Flight Testing and Simulation of an F-15 Airplane Using Throttles For Flight Control, AIAA-92-4109-CP, and NASA TM-104255

Burcham, Frank W. Jr., Maine, Trindel, and Wolf, Thomas: Flight Testing and Simulation of an F-15 Airplane Using Throttles For Flight Control. AIAA-92-4109-CP and NASA TM-104255, July 1992

Schiff, Barry: "Out of Controls", Aircraft Owners and Pilots Association, AOPA, Oct 1992

Burcham, F. W., Maine, Trindel, Fullerton, G., and Wells, E. A.: Preliminary Flight Results of a Fly-By-Throttle Emergency Flight Control System on an F-15 Airplane. AIAA-93-1820, June 1993

Burcham, F. W., Maine, Trindel, Fullerton, G., and Wells, E. A.: Preliminary Flight Results of a Throttles-Only Emergency Flight Control System on an F-15 Airplane. TM 4503, Aug 1993

Fullerton, C Gordon: Propulsion Controlled Aircraft Research, Society of Experimental Test Pilots 37th Symposium Proceedings, Sept. 1993 ISSN#0742-3705

Maine, Trindel: Flight Results of an Augmented Fly-By-Throttle Flight Control System, SAE Aerotech, Sept 93 (Oral)

Stewart, J. F.: "Propulsion Controlled Aircraft - A Survivability Concept. Transport Survivability Conference, Oct 1993 (oral)

Urnes, James and Wells, Edward: "Flight Testing of the Propulsion Controlled Aircraft Flight Control System on an F-15 Aircraft", Transport Survivability Conference, Oct 1993 (oral)

Maine, Trindel; Schaefer, Peter; Burken, John; and Burcham, F. W.: "Design Challenges Encountered in a Propulsion Controlled Aircraft Flight Test Program" AIAA 94-3359, June 1994

Wells, Edward A., and Urnes, James M. Sr.: Design and Flight Test of the Propulsion Controlled Aircraft (PCA) Flight Control System on the NASA F-15 Test Aircraft. MDC 94B0005, Jan 1994, and NASA CR-186028, Feb 1994

Burcham, F. W. Jr., Burken, John, and Maine, Trindel: Flight Testing a Propulsion-Controlled Aircraft Emergency Flight Control System on an F-15 Airplane. AIAA 94-2123, and NASA TM 4590, June 1994

"Power Steering", Popular Science 100 Best Innovations of 1993, Popular Science, Oct 1993

F-15 Research Program References (cont.)

Self-Repairing Flight Control

Urnes, James M., Stewart, James, and Eslinger, Robert: "Flight Demonstration of a Self Repairing Flight Control System in a NASA F-15 Fighter Aircraft, AGARD Guidance and Control Panel 49th Symposium, Oct 1989

Urnes, James M.,Stewart, James F., and Yeager, Robert: Self-repairing Flight Control System (SRFCS) Porgram and Flight Test Demonstration 1990 NAECON Conference paper May 23, 1990

Chandler, P, Weiss, Jerold L., and Wells, Edward A.: Detection and Isolation of Control Element Failures on the NASA HIDEC F-15. 1990 NAECON conference paper, May 23, 1990

Migyanko, Barry F., and Yeager, Robert: Flight Test Reconfiguration Performance and Handling Qualities Results. 1990 NAECON conference paper, May 23 1990

Stewart, James F., and Shuck, Thomas L.: Flight Testing of the Self-Repairing Flight Control System Using the F-15 Highly Integrated Digital Electronic Control Flight Research Facility, AIAA-90-1321, May 1990

Urnes, Jim.: Damage Adaptive Flight Control Systems for Tactical Fighter and Transport Aircraft. Aerospace Digest, June 1993

Stewart, J. F.: "The Application of Advanced Control Technology for Improved Aircraft Survivability. Transport Survivability Conference, Oct 1993 (oral)

Trajectory Guidance

Swann, M. R.; Duke, Eugene L.; Enevoldson, E. K.; and Wolf, T. D.: Experience with Flight Test Trajectory Guidance. AIAA 81-2504, Nov 1981

Walker, R. A.; and Gupta, N. K.: Flight Test Trajectory Control Analysis, NASA CR 170395, Feb 1983

Duke, Eugene L.; Swann, M. R.; Enevoldson, E. K.; and Wolf, T. D.: Experience with Flight Test Trajectory Guidance. Journal of Guidance, Control, and Dynamics, Vol 6 no. 5, Sept-Oct 83, pp 393-398

Walker, R. A.; Gupta, N. K.; Duke, E. L.; and Patterson, B.: Developments In Flight Test Trajectory Control. AIAA 84-0240, Jan 1984

Menon, P. K. A.; Saberi, H. A.; Walker, R. A.; and Duke, Eugene L.: Flight Test Trajectory Controller Synthesis with Constrained Eigenstructure Assignment, 1985 Automatic Control Conference, June 1985

Alag, G. S.; and Duke, Eugene L.: Development of Control Laws for a Flight Test Maneuver Autopilot for an F-15 Aircraft. NASA TM 86736, Aug 1985

Alag, Gurbux S. and Duke, Eugene L.: Development of a Flight Test Maneuver Autopilot for an F-15 Aircraft, NASA TM 86799, 1985

Menon, P.K.A., Badgett, M.E., Walker, R.A.: Nonlinear Maneuver Autopilot for the F-15 Aircraft, NASA CR 179442, June 1989

F-15 Research Program References (cont.)

Twin Jet Acoustics

Seiner, J. M., Manning, J. C., and Ponton, M. K.: Model and Full Scale Study of Twin Supersonic Plume Resonance, AIAA paper 87-0244, Jan 1987

Seiner, J., Manning, J, and Burcham, F.: F-15 Aircraft Engine Nozzle Outer Flap Loads, AIAA 88-3238, July 1988

Partial Pressure Suit

Ashworth, G. R.; Putnam, T. W.; Dana, W.; Enevoldson, E.K.; and Winter, W. R.: Flight Test Evaluation of an RAF High Altitude Partial Pressure Protective Assembly. NASA TM-72864, June 1979

Survey & Summary Papers

Szalai, Kenneth J.: Role of Research Aircraft in Technology Development. AIAA 84-2473, 1984

Burcham, Frank W., Jr., Trippensee, Gary A., Fisher, David and Putnam, Terrill W.: Summary of Results of NASA F-15 Flight Research Program. AIAA-86-9761, April 1986.

Burcham, Frank W. Jr., and Ray, Ronald J.: The Value of Early Flight Evaluation of Propulsion Concepts, AIAA paper 87-2877 and NASA TM 100408, Sept 1987

Burcham, F. W., Gilyard, G. B., and Myers, L. P.: Propulsion System-Flight Control Integration - Flight Evaluation and Technology Transition. AIAA Paper 90-2280, July 1990

PSC Session Information

A model-based, adaptive control algorithm called Performance Seeking Control (PSC) has been flight tested on an F-15 aircraft. The PSC was developed to optimize aircraft propulsion system performance during steady-state engine operation. The multimode algorithm minimizes fuel consumption at cruise conditions; maximizes excess thrust (thrust minus drag) during aircraft accelerations; extends engine life by decreasing Fan Turbine Inlet Temperature (FTIT) during cruise or accelerations; and reduces supersonic deceleration time by minimizing excess thrust. On-board models of the inlet, engine, and nozzle are optimized to compute a set of control trims, which are then applied as increments to the nominal engine and inlet control schedules. The on-board engine model is continuously updated to match the operating characteristics of the actual engine cycle through the use of a Kalman filter, which accounts for unmodeled effects. The PSC algorithm has been flight demonstrated on the NASA F-15 HIDEC test aircraft. This session includes papers which present the key elements of the PSC algorithm, its implementation and integration with the aircraft, and summarizes the flight test results.

Agenda

John S. Orme, "Performance Seeking Control Program Overview"

Mark Bushman, Steven G. Nobbs, "F-15 Propulsion System"

Steven G. Nobbs, "PSC Algorithm Description"

Steven G. Nobbs, "PSC Implementation and Integration"

John S. Orme, Steven G. Nobbs, "Minimum Fuel Mode Evaluation"

John S. Orme, Steven G. Nobbs, "Minimum Fan Turbine Inlet Temperature Mode Evaluation"

John S. Orme, Steven G. Nobbs, "Maximum Thrust Mode Evaluation"

Timothy R. Conners, Steven G. Nobbs, John S. Orme, "Rapid Deceleration Mode Evaluation"

Timothy R. Conners, Steven G. Nobbs, "Thrust Stand Test"

Gerard Schkolnik, "Performance Seeking Control Excitation Mode"

Timothy R. Conners, "PSC Asymmetric Thrust Alleviation Mode"

PSC Session Information (Concluded)

Agenda (Concluded)

John S. Orme, "Summary"

Sesson Chair

Chair: John S. Orme
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3683
Fax: (805)258-3744
Address: P.O. 273, MS D-2033, Edwards, CA 93523
e-mail: orme@alien.dfrf.nasa.gov

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NASA Dryden Flight Research Center

"Performance Seeking Control Program Overview"

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Author: John S. Orme
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3683
Fax: (805)258-3744
Address: P.O. Box 273, MS D-2033, Edwards, CA 93523
e-mail: orme@alien.dfrf.nasa.gov

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"Performance Seeking Control Program Overview", page 1

Abstract

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The Performance Seeking Control (PSC) program evolved from a series of integrated propulsion–flight control research programs flown at NASA Dryden Flight Research Center (DFRC) on an F–15. The first of these was the Digital Electronic Engine Control (DEEC) program and provided digital engine controls suitable for integration. The DEEC and digital electronic flight control system of the NASA F–15 were ideally suited for integrated controls research. The Advanced Engine Control System (ADECS) program proved that integrated engine and aircraft control could improve overall system performance.

The objective of the Performance Seeking Control (PSC) Program was to advance the technology for a fully integrated propulsion flight control system. Whereas ADECS provided single variable control for an average engine, PSC controlled multiple propulsion system variables while adapting to the measured engine performance. PSC was developed as a model–based, adaptive control algorithm and included four optimization modes: minimum fuel flow at constant thrust, minimum turbine temperature at constant thrust, maximum thrust, and minimum thrust. Subsonic and supersonic flight testing were conducted at NASA Dryden covering the four PSC optimization modes and over the full throttle range.

Flight testing of the PSC algorithm, conducted in a series of five flight test phases, has been concluded at NASA Dryden covering all four of the PSC optimization modes. Over a three year period and five flight test phases, 72 research flights were conducted. The primary objective of flight testing was to exercise each PSC optimization mode and quantify the resulting performance improvements.

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Author: John S. Orme
e–mail: orme@alien.dfrf.nasa.gov

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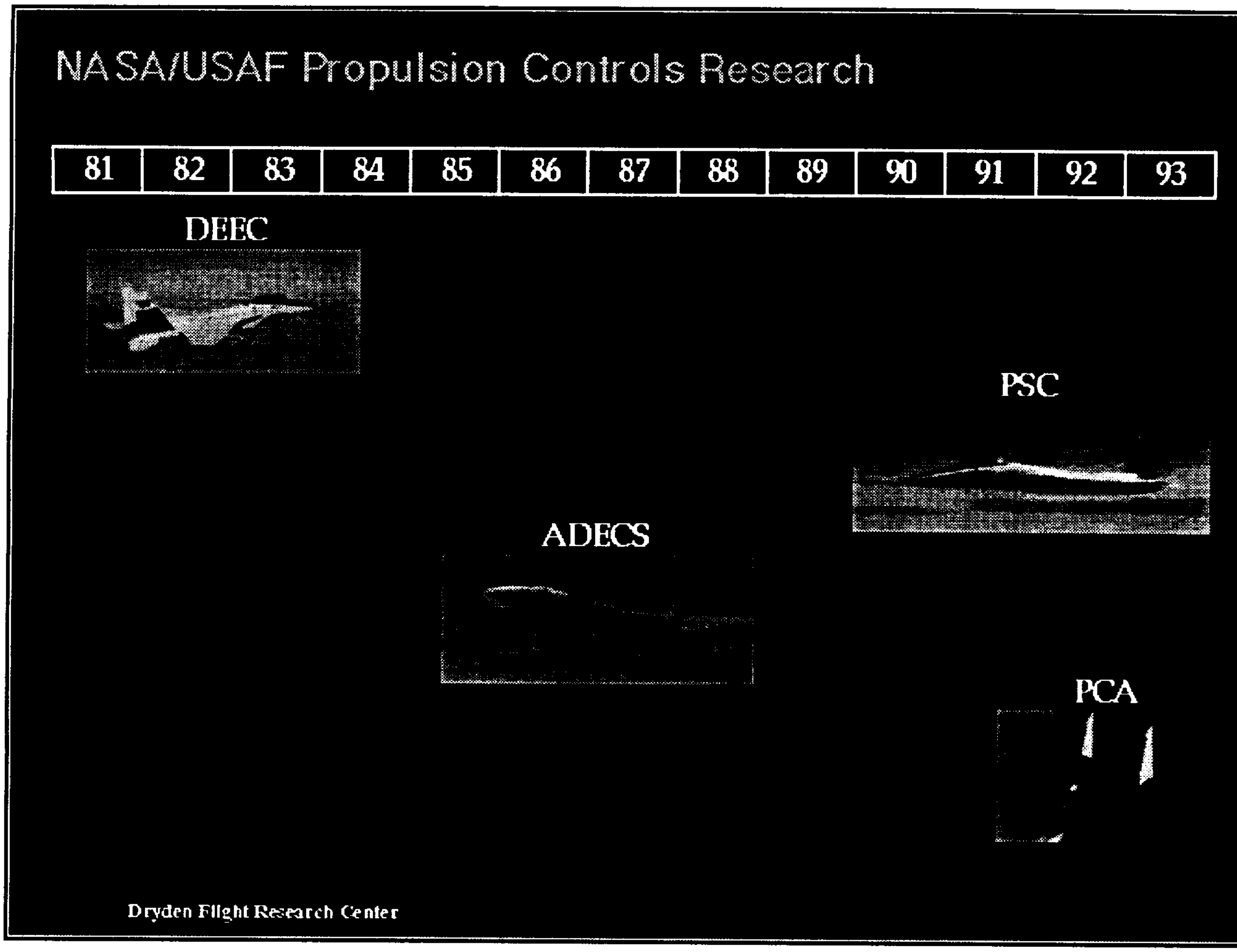

The Performance Seeking Control (PSC) program has evolved from a series of integrated propulsion–flight control research programs flown at NASA Dryden Flight Research Center (DFRC) on an F–15. The first of these was the Digital Electronic Engine Control (DEEC) program which provided digital engine controls suitable for flight control integration. Later, a digital electronic flight control system (DEFCS) was installed and tested. The DEEC and DEFCS enabled propulsion researchers to explore performance gains of an integrated controls approach. For the Advanced Engine Control System (ADECS) program, the DEEC was modified to permit airframe to engine communication and the control software was hosted in the DEFCS computer. Optimum engine pressure ratio (EPR) trims, determined from simulation and scheduled in the DEFCS, were used to demonstrate 5– to 10– percent increases in thrust during ADECS. The ADECS experience proved just how valuable an integrated system testbed was for providing significant performance improvements, but questions remained about applying its scheduled optimum trims to unmatched engines. The next logical step was an adaptive real–time optimization capable of trimming multiple propulsion system elements. Thus, the Performance Seeking Control program concept was proposed, developed, and first flight tested in 1990.

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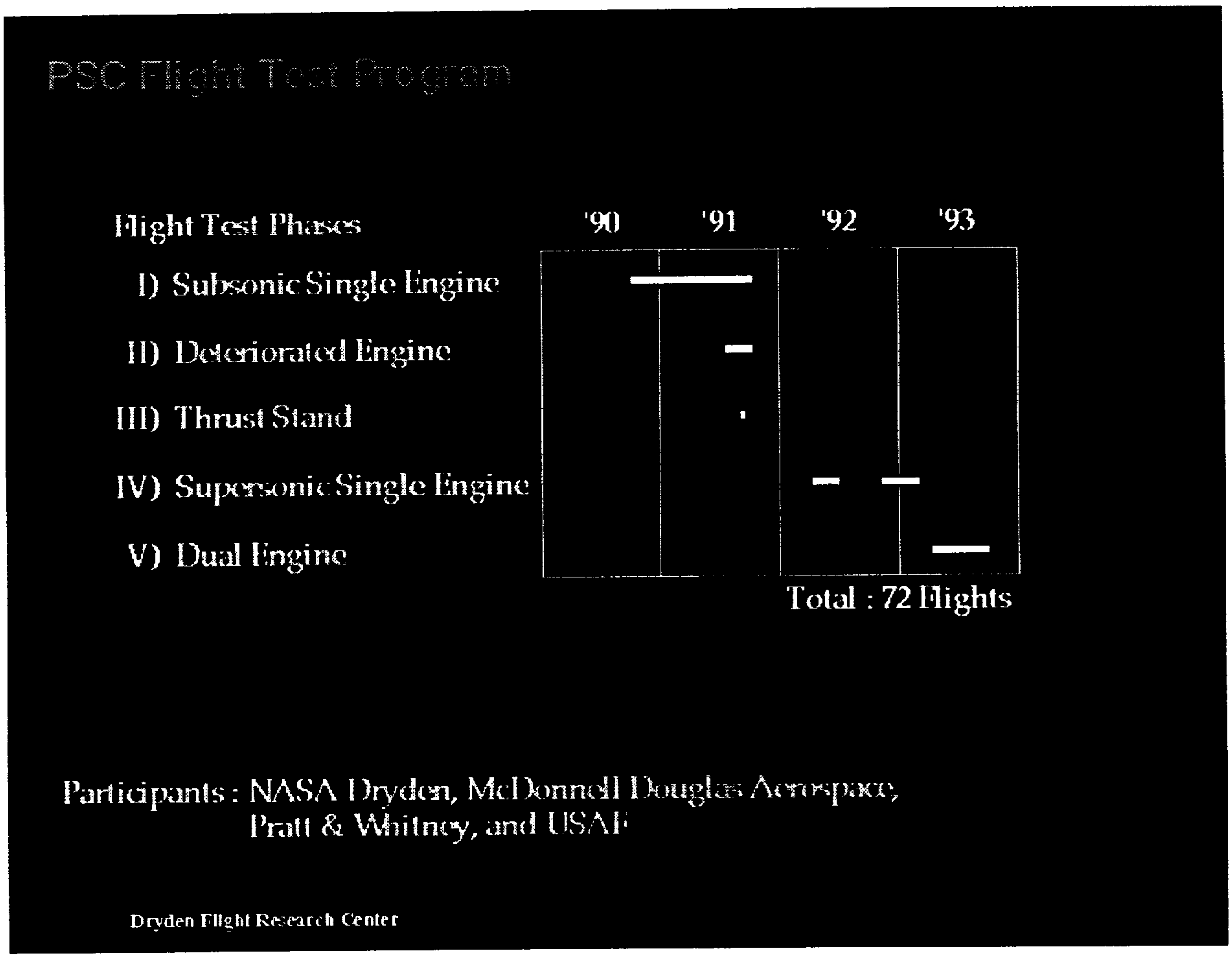
PSC Flight Test Program



The Performance Seeking Control (PSC) program was developed by NASA with McDonnell Douglas Aerospace as the prime PSC contractor and with Pratt and Whitney as subcontractor. The NASA F–15 highly integrated digital electronic control (HIDEC) aircraft and engines were loaned by the U.S. Air Force. The flight test team at NASA Dryden, which is an integrated group composed of Dryden engineering and technical support and on–site engineering support from both McDonnell Douglas Aerospace and Pratt and Whitney, continues to be an effective government and industry team.

The F–15 PSC schedule shows five test phases starting in 1990. Phase I was the implementation and verification of the first flown PSC algorithm. Subsonic testing designed to demonstrate single engine performance benefits was conducted after initial checkout. The ability of the PSC algorithm to adapt to different levels of engine deterioration was tested with an intentionally deteriorated engine during Phase II. Phase III, a two week installed static thrust stand test, was performed in the fall of 1991. Phase IV expanded the single engine envelope of PSC testing out to Mach 2.0 and 45,000 feet. The final flight test phase was a of full envelope demonstration of the dual engine PSC which concluded in October of 1993.

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PSC Objectives

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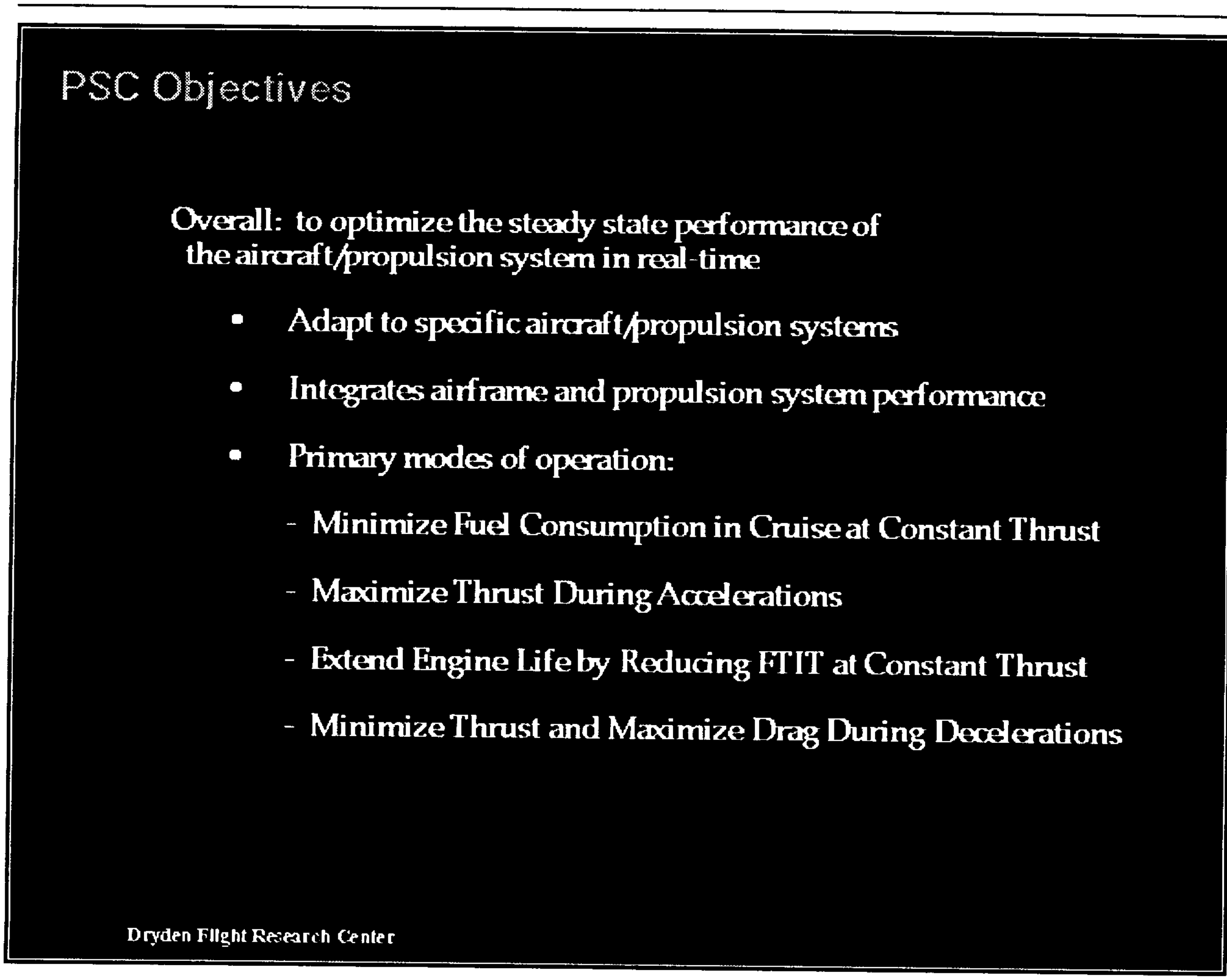

Digital inlet and engine controls and optimal control algorithms enable significant performance improvements of the integrated aircraft–propulsion system. Developing and applying integrated controls technology will contribute to both commercial and military applications by maximizing excess thrust and fuel efficiency and extending engine life. However, conventional scheduled control systems may not recover the full performance potential of the propulsion system because of variations in engine deterioration, engine–to–engine component variations, and non–standard day conditions. The PSC system recovers latent performance from the propulsion system with onboard adaptive engine models.

NASA Dryden, McDonnell Aircraft Company, and Pratt & Whitney have developed and flight tested an adaptive performance seeking control (PSC) system with the objective of demonstrating an onboard adaptive performance optimization. The objective was to optimize the steady state performance of the F–15 propulsion system. The PSC system was developed with the following optimization modes: minimum fuel at constant thrust, maximum thrust, minimum fan turbine temperature at constant thrust, and minimum thrust.

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"F-15 Propulsion System"

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Author: Mark Bushman
Affiliation: Pratt & Whitney Government Products Company
Phone: (407)796-8982
Fax: (407)796-5362
Address: P.O. Box 109600, MS 731-93, West Palm Beach, FL 33410-9600
e-mail: bushmark@pwfl.com

Author: Steven G. Nobbs
Affiliation: McDonnell Douglas Corporation
Phone: (314)232-2717
Fax: (314)232-4141
Address: MC 1069020, P.O. Box 516, St. Louis, MO 63166
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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PW1128 Engine and DEEC

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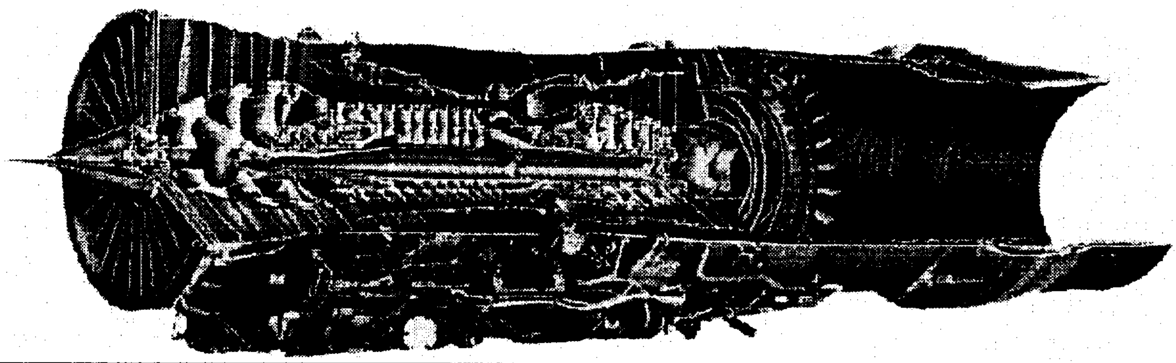
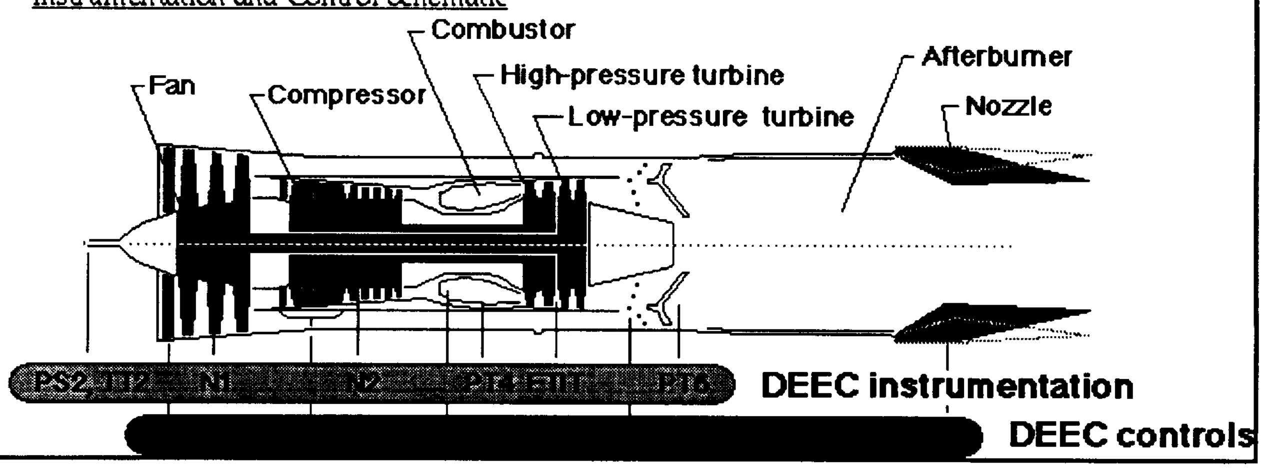
PW1128 Engine and DEEC

Cut-a-way view



Instrumentation and Control Schematic



The F–15 is powered by two PW1128 afterburning turbofans which are growth versions of the F100–PW–100 engine. The above schematic shows the engine control effectors and sensor locations. (further details of the PW1128 engine are contained in Myers, et. al., "Digital Electronic Engine Control (DEEC) Flight Evaluation in an F–15 Airplane", NASA CP–2298, Mar 1984).

The PW1128 is controlled by a full–authority Digital Electronic Engine Control (DEEC). The DEEC schedules and maintains engine operating point through the use of two main control loops; the first regulates the scheduled low rotor speed (N1C2) using main burner fuel flow (WF), the second loop controls engine pressure ratio (EPR) with nozzle throat area (AJ). The

DEEC also schedules compressor variable vanes (CIVV) and rear compressor variable vanes (RCVV). The sensed parameters consist of fan speed, N1; high–pressure compressor speed, N2; engine face total temperature, TT2; fan turbine inlet temperature, FTIT; engine face static pressure, PS2; burner pressure, PT4; and augmentor total pressure, PT6. All pertinent parameters used by the DEEC for engine control are transmitted via a RS422 UART bus to the on–board computers for use by the PSC algorithm.

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Author: Mark Bushman
e–mail: bushmark@pwfl.com

Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

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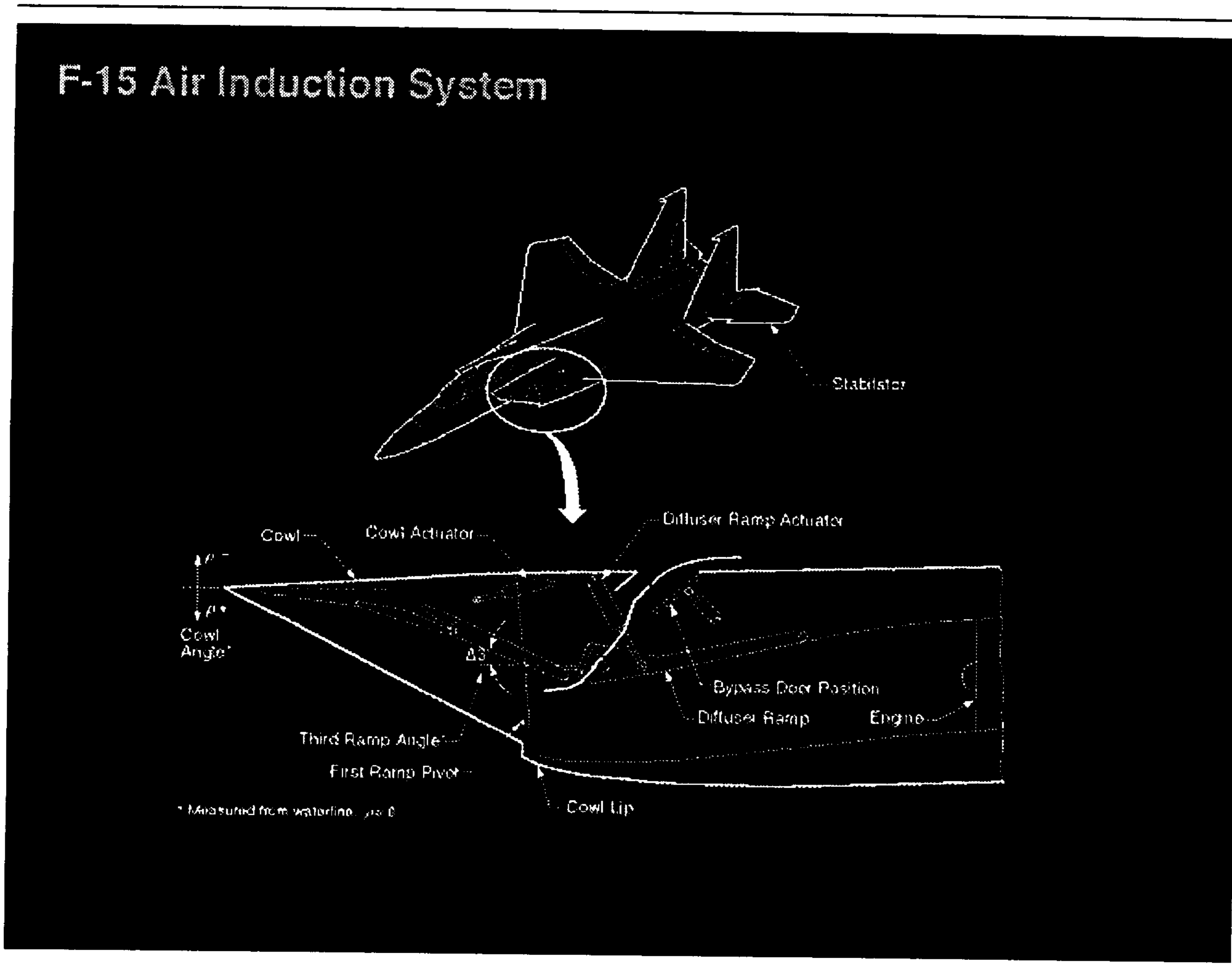
F-15 Air Induction System



The F-15 inlet is a two-dimensional, three-ramp, external compression design with partially cut back side plates. During supersonic operation, compression is accomplished through three oblique shocks and one terminal normal shock. The three compression ramps are all variable. Separate cowl and diffuser ramp actuators provide independent control of the first and third ramps. The second ramp position is dependent on the first and third ramp positions. This approach gives the F-15 inlet a unique variable capture feature that minimizes inlet spill drag. The inlet also incorporates a variable bypass system for inlet/engine matching.

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Author: Mark Bushman
e-mail: bushmark@pwfl.com

Author: Steven G. Nobbs

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Inlet Control System

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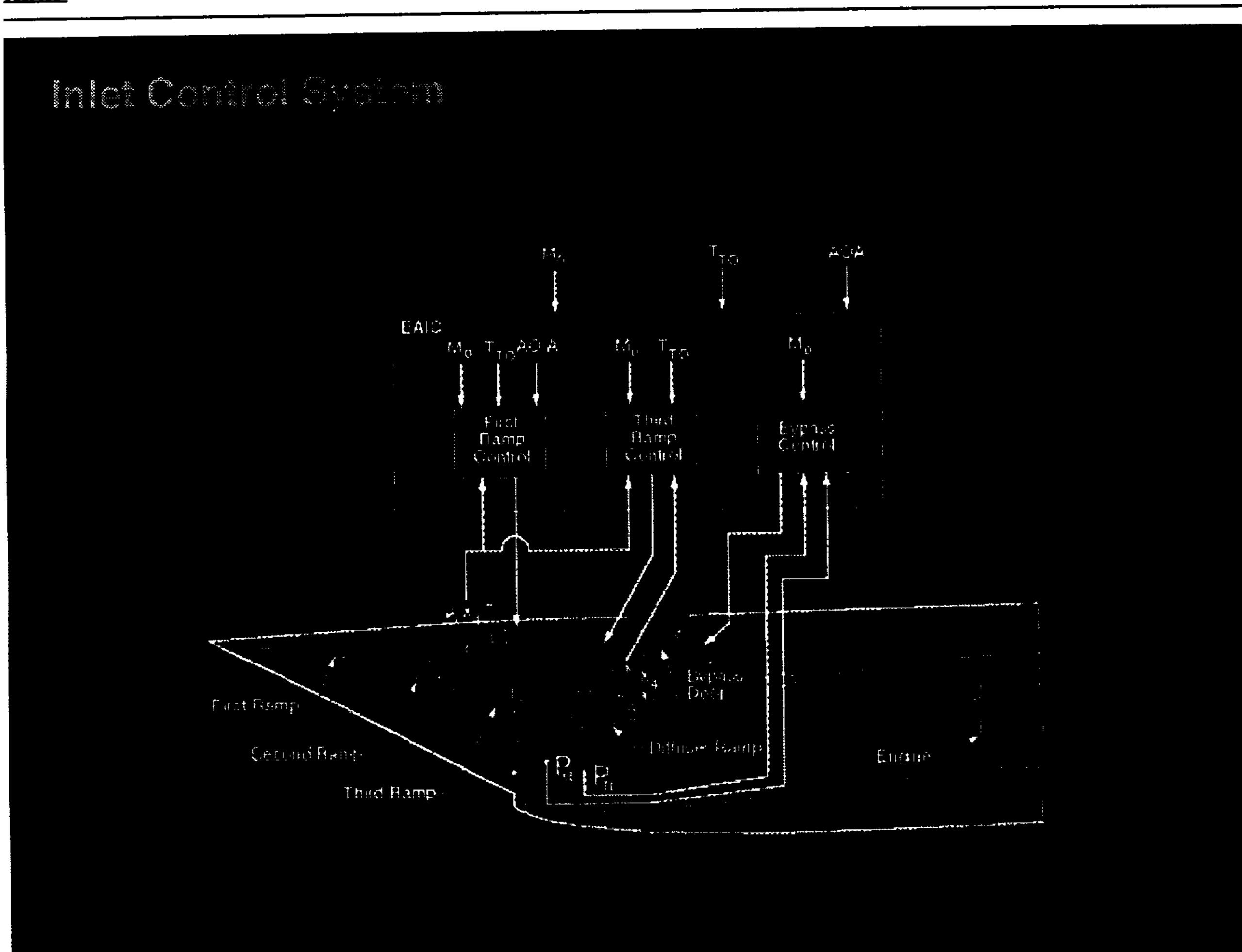

Each inlet is independently controlled by an Electronic Air Inlet Controller (EAIC). The EAIC control logic positions the actuators to yield the scheduled first ramp, third ramp and bypass door positions for the given flight condition and angle of attack (AOA). The first ramp is scheduled with aircraft Mach number, free–stream total temperature and AOA. The third ramp is scheduled with aircraft Mach number and free–stream total temperature. The bypass door is scheduled with free–stream Mach number and inlet duct Mach number. The first and third ramp schedules are designed to maximize inlet and aircraft performance while maintaining stable inlet operation. The bypass door schedule is designed to provide additional inlet stability when it is required.

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Author: Mark Bushman
e–mail: bushmark@pwfl.com

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"PSC Algorithm Description"

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Author: Steven G. Nobbs
Affiliation: McDonnell Douglas Corporation
Phone: (314)232-2717
Fax: (314)232-4141
Address: MC 1069020, P.O. Box 516, St. Louis, MO 63166
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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PSC Algorithm Description

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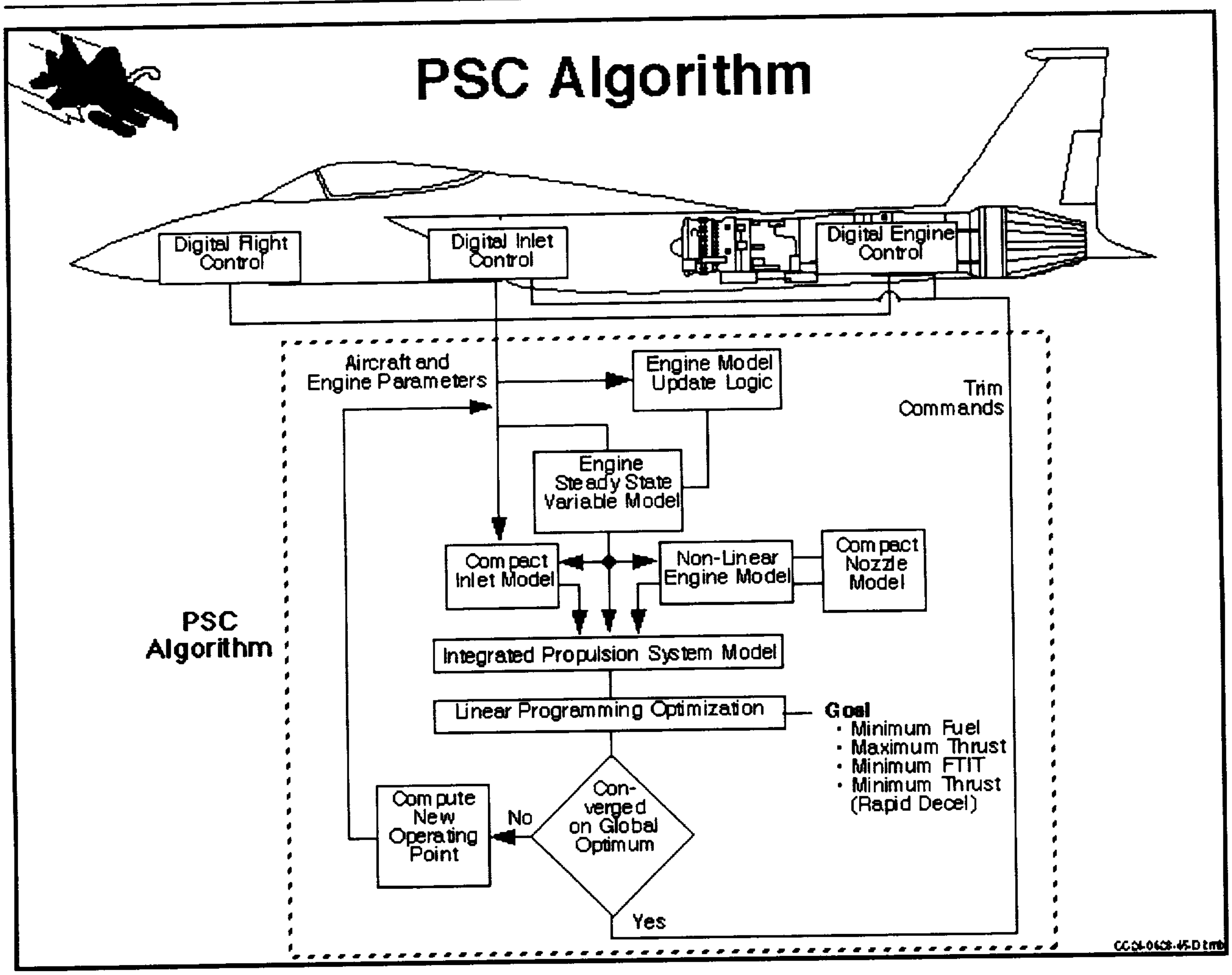

PSC ALGORITHM DESCRIPTION

In this section, an overview of the PSC algorithm and details of the important components of the algorithm are given. The onboard propulsion system models, the linear programming optimization and engine control interface are described.

The PSC algorithm receives inputs from various computers on the aircraft including the digital flight computer, digital engine control, and electronic inlet control.

The PSC algorithm contains compact models of the propulsion system including the inlet, engine, and nozzle. The models compute propulsion system parameters, such as inlet drag and fan stall margin, which are not directly measurable in flight. The compact models also compute sensitivities of the propulsion system parameters to changes in control variables. The engine model consists of a linear steady state variable model (SSVM) and a non–linear model. The SSVM is updated with efficiency factors calculated in the engine model update logic, or Kalman Filter. The efficiency factors are used to adjust the SSVM to match the actual engine.

The propulsion system models are mathematically integrated to form an overall propulsion system model. The propulsion system model is then optimized using a linear programming optimization scheme. The goal of the optimization is determined from the selected PSC mode of operation. The resulting trims are used to compute a new operating point about which the optimization process is repeated. This process is continued until an overall (global) optimum is reached before applying the trims to the controllers.

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Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

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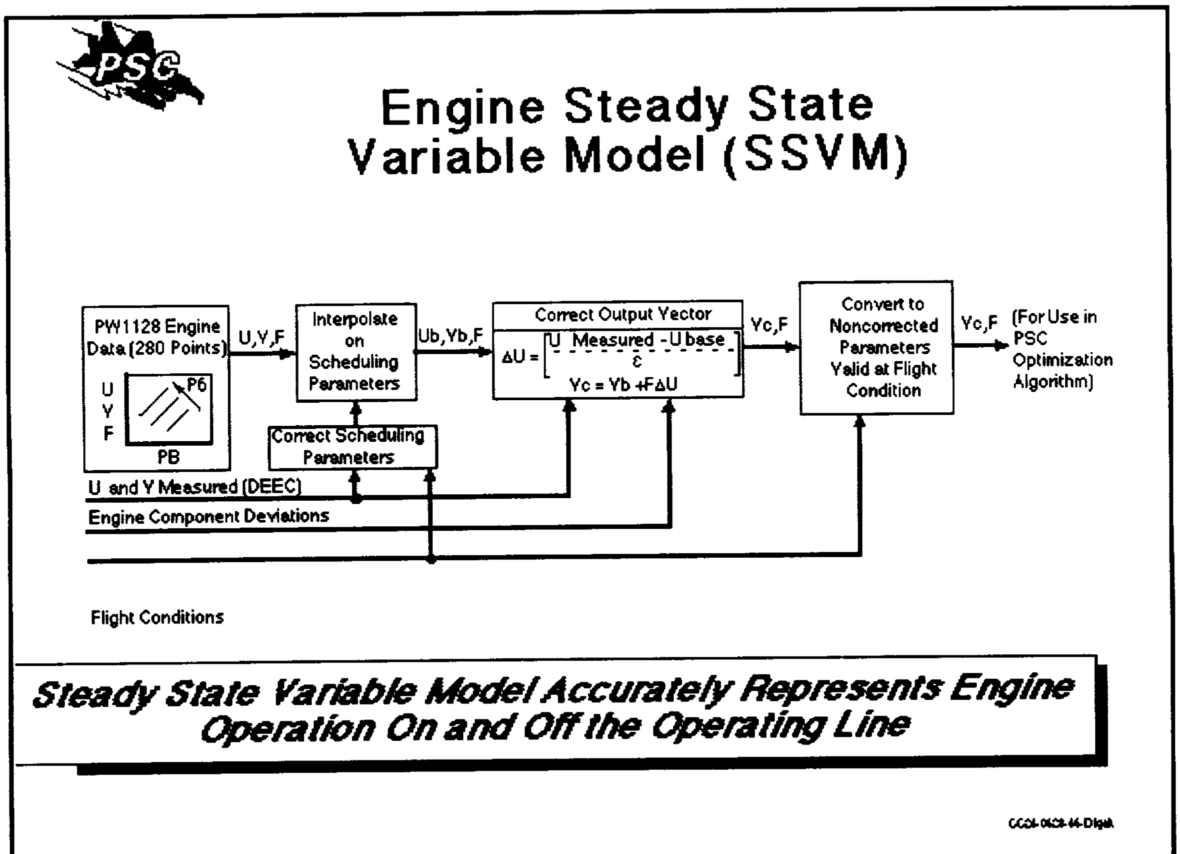
Onboard Propulsion System Models



ONBOARD PROPULSION SYSTEM MODELS

The onboard propulsion system models are the engine, nozzle and inlet models. The engine model consists of the Steady State Variable Model (SSVM), engine model update logic and non–linear engine model. The propulsion models are integrated together to form the Integrated Propulsion System Model.

The SSVM represents engine operation on and off the nominal operating line throughout the entire F–15 flight envelope. Characterizing engine operation off the nominal operating line is essential, since the PSC commands will generally move the engine operating point off the baseline schedules.

The foundation of the SSVM is a set of linear point models located on and off the operating line for a reference flight condition. Full envelope capability is acheived by modeling the engine in terms of corrected parameters. Each point model consists of a basepoint control vector (Ub), a basepoint output vector (Yb), and a sensitivity coefficient matrix (F), which relates changes in control positions to changes in outputs. The point models are scheduled with sensed engine parameters. By interpolating between the models with the scheduling parameters, a single point model (Ub, Yb, and F) to be used for optimization is formed. The output vector is adjusted for control deviations (the difference between the actual control positions and the model basepoint values) and engine component deviations, as identified by the Kalman Filter in the update logic. The output vector and F matrix are then shifted from their corrected values to the current flight condition for the optimization procedure.

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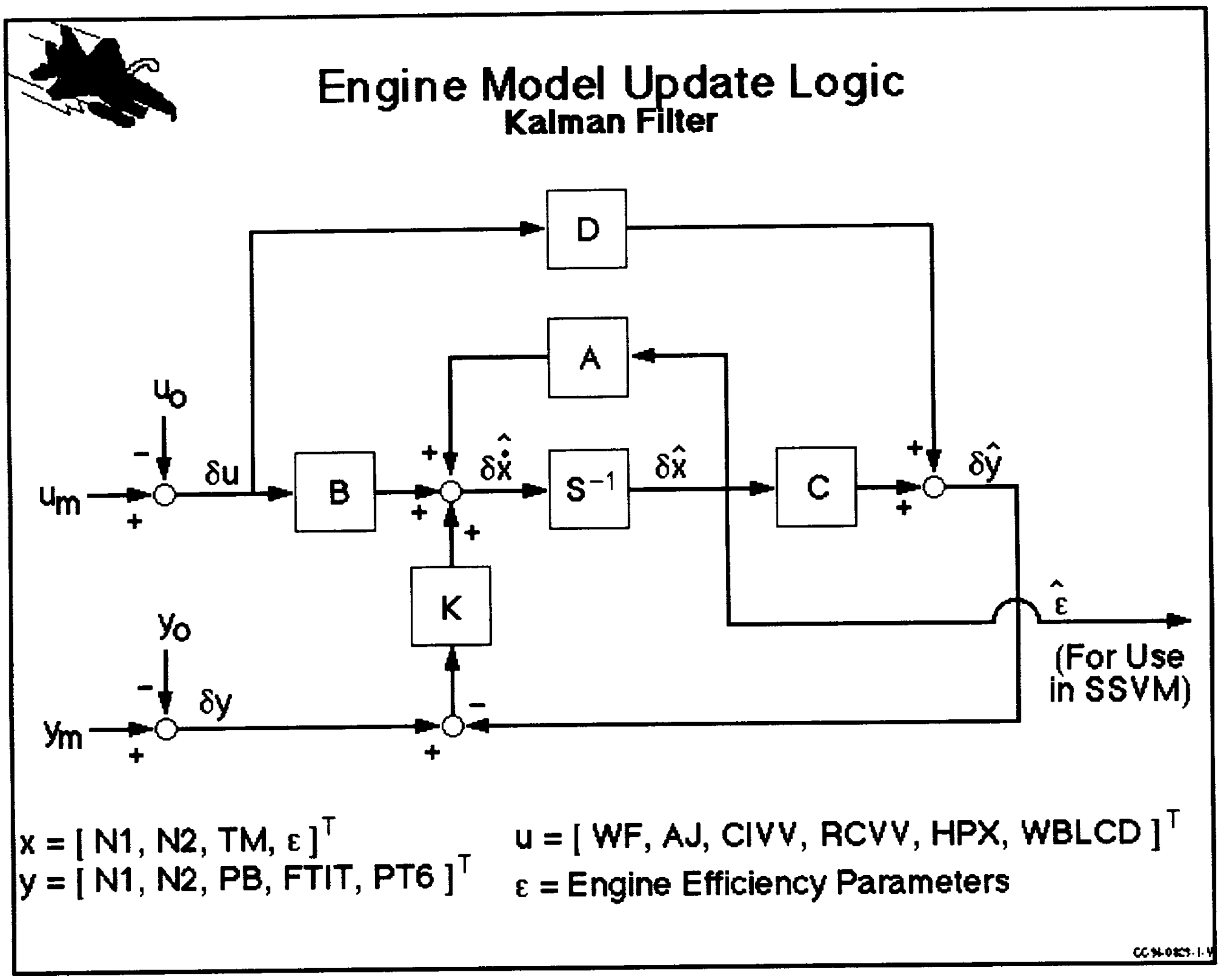
Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

Engine Model Update Logic



ENGINE MODEL UPDATE LOGIC

The goal of the engine model update logic is to match the compact engine model to the operating characteristics of the actual engine. To accomplish this task, a Kalman Filter has been designed to account for anomalous engine performance. The filter estimates five component deviations which fully characterize off–nominal engine performance. The five parameters are low spool efficiency adder, high spool efficiency adder, fan airflow adder, compressor airflow adder, and high turbine area adder. Due to the limited number of sensed engine parameters, isolation of efficiency changes to a specific component is not possible. However, off–nominal performance can be isolated to a particular spool. Changes to the fan and low turbine efficiencies are combined into a low spool adder, while those of the compressor and high turbine are lumped into the high spool adder. This technique has been found to work well within the PSC system and can also be adapted for use in engine monitoring and fault detection.

The component deviation estimates are augmented to the SSVM control vector to improve the accuracy of the compact engine model (CEM) output calculations. Extensive evaluations of the Kalman Filter/CEM tandem have been conducted with nonlinear simulations. Hundreds of flight conditions spanning the F–15 subsonic flight envelope have been analyzed, with several levels of engine deterioration simulated. Results show that, with the engine model update logic, the CEM accuracy in computing steady outputs satisfies the + 2% design goal at nearly all conditions, when compared to a nonlinear aero/thermodynamic engine model (truth model).

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Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

Non–Linear Engine Model

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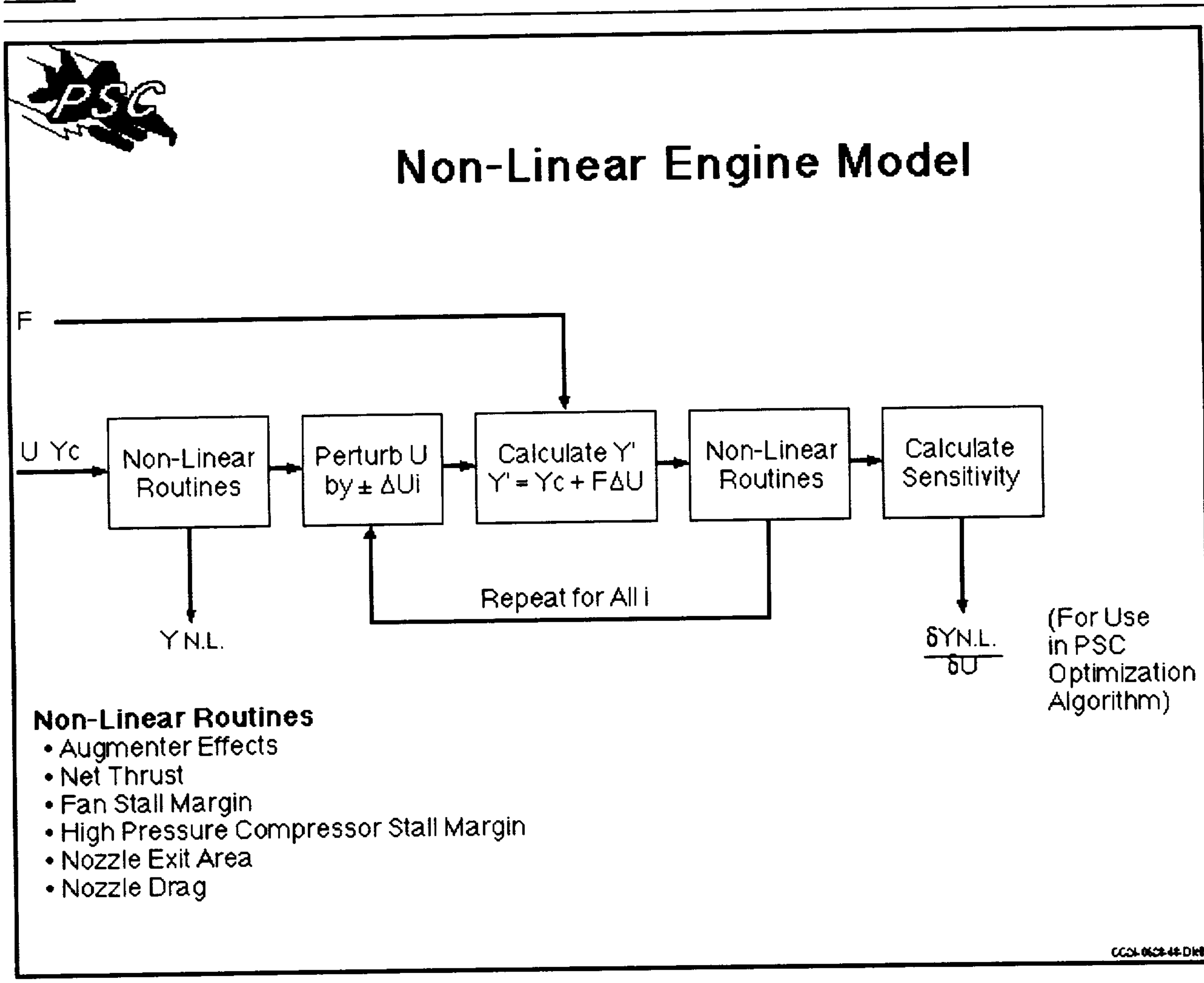

NON–LINEAR ENGINE MODEL

The nonlinear engine model contains those engine effects which cannot be accurately approximated with linear relationships, such as, augmentor operation. This model calculates both the nonlinear parameters and the linear sensitivities of these parameters to changes in controls. The nonlinear parameters are calculated using the measured control settings, Um, and the SSVM output vector, Yc. The sensitivities are determined by mathematically perturbing the elements of the control vector and calculating the resulting changes in the nonlinear parameters.

Compact Nozzle Model

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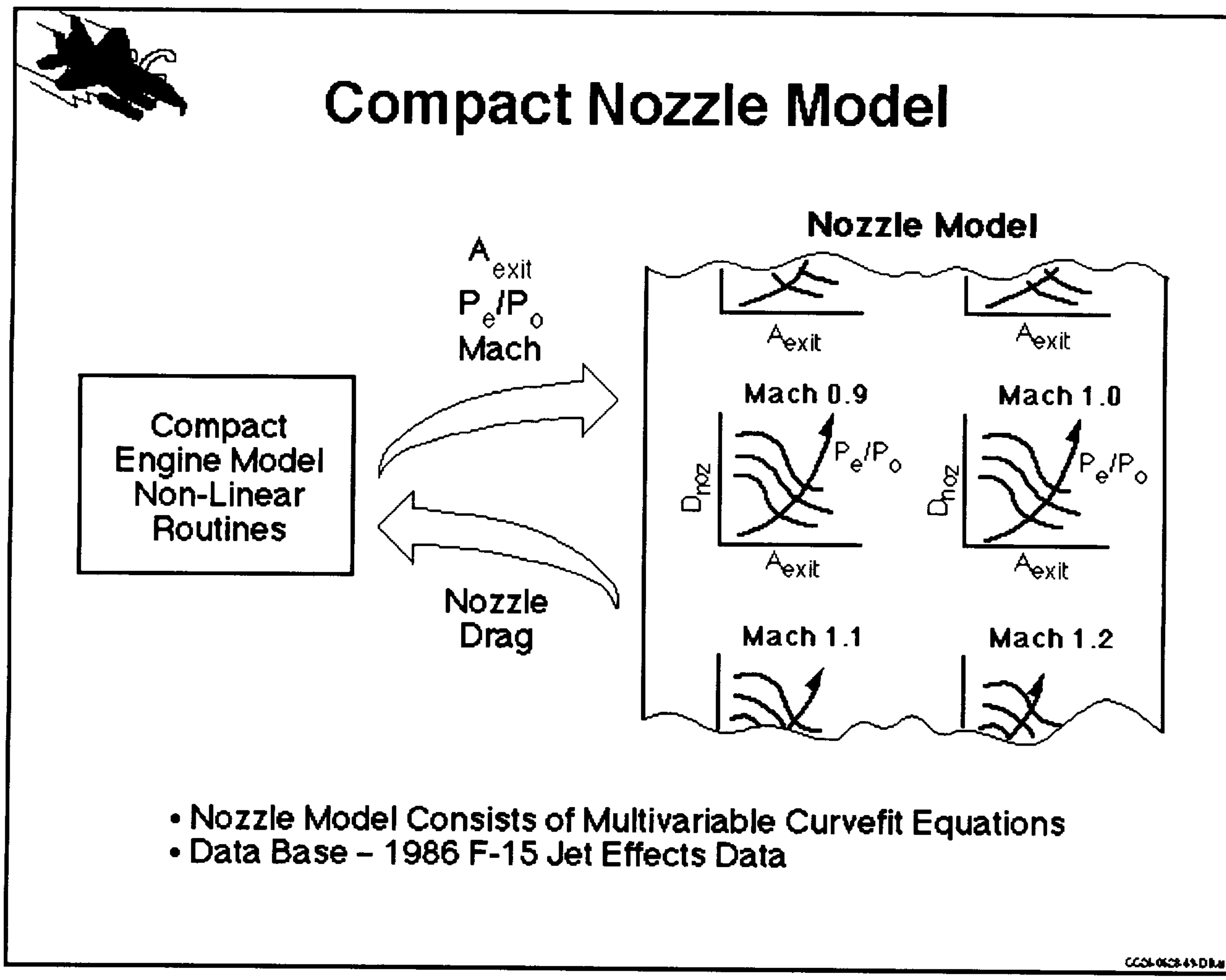

COMPACT NOZZLE MODEL

The PSC nozzle model computes the incremental F–15 aft end drag due to the engine exhaust plume and the external nozzle aerodynamics. The compact nozzle model was designed by curve–fitting wind tunnel jet effects data. The model consists of multivariable equations, each corresponding to a specific freestream Mach number. Each equation expresses nozzle drag as a function of external nozzle exit area and the ratio of exit static pressure to ambient pressure.

The F–15 does not have an actuator for independently controlling the nozzle exit area.

Instead, the exit area is mechanically linked to the nozzle throat area and floats within the bounds provided by the linkage, based on internal and external pressures. Therefore, at a given flight condition, nozzle drag is a function of only the engine control variables, which determine both the exit area and exit static pressure. To optimize overall aircraft performance, it is important to know how nozzle drag changes as the engine controls are varied. The compact nozzle model supplies the PSC optimization with these sensitivities through an on–line linearization procedure similar to that carried out in the nonlinear portion of the compact engine model.

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Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

Compact Inlet Model

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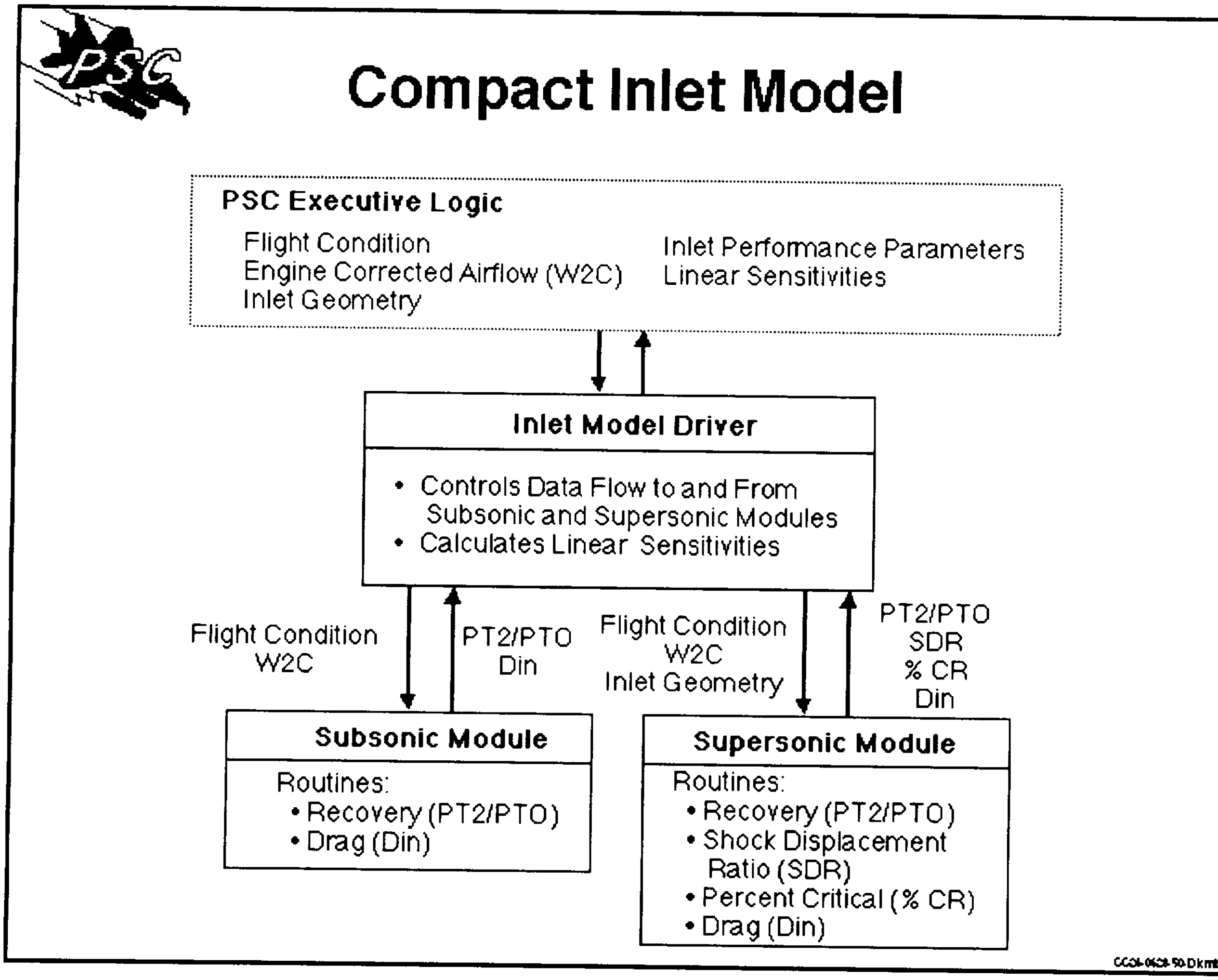

COMPACT INLET MODEL

The compact inlet model calculates inlet performance and sensitivities for the variable three–ramp F–15 inlet . In subsonic operation, inlet performance is calculated in terms of total pressure recovery and inlet drag. In supersonic operation, inlet performance is also calucated in terms of shock displacement ratio and percent critical mass flow. In addition to performance levels, the inlet model also calculates the sensitivity of the performance parameters to changes in the inlet input variables. For PSC, the inlet variables are cowl angle, third ramp angle, and engine corrected airflow. The PSC system will not adjust the bypass door position since it is postioned closed for best performance, as is already done. The inlet controller only opens the bypass door at the onset of inlet flow instabilities.

Subsonically, PSC will not alter the inlet ramp positions. Analysis has shown that the best subsonic inlet performance is obtained with the inlet scheduled wide open, as is currently done. However, the influence of engine corrected airflow on inlet performance must be computed to account for the coupling between the inlet and engine. Therefore, the subsonic portion of the compact inlet model consists of curve–fit equations to calculate total pressure recovery and inlet drag as a function of engine corrected airflow. The curve–fits were generated from McDonnell's best analytical/empirical representation of the F–15 inlet. The inlet sensitivities are calculated by mathematically perturbing the input variables, using a technique similar to that described for the nonlinear engine model.

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Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

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Integrated Propulsion System Model

Compact Model Outputs

Engine/Nozzle

$$\frac{\partial Y_{ENG}}{\partial U_{ENG}} = \begin{bmatrix} F \\ \frac{\partial Y_{N.L.}}{\partial U_E} \end{bmatrix}_{i \times j}$$

Inlet

$$\frac{\partial Y_{INL}}{\partial U_{INL}} = \begin{bmatrix} \frac{\partial PT2}{\partial W2C} & \frac{\partial PT2}{\partial p} & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}_{k \times l}$$

Cross-Coupling Term

$$\Phi = \frac{1}{1 - \left(\frac{\partial W2C}{\partial PT2}\right)_{ENG} * \left(\frac{\partial PT2}{\partial W2C}\right)_{INL}}$$

Combined Propulsion System Model

$$\begin{bmatrix} \Delta Y_{ENG} \\ \Delta Y_{INL} \end{bmatrix} = \underbrace{\begin{bmatrix} \left(\frac{\partial Y_i}{\partial U_j}\right)_{ENG} + \Phi * \left(\frac{\partial Y_i}{\partial PT2}\right)_{ENG} * \left(\frac{\partial PT2}{\partial W2C}\right)_{INL} * \left(\frac{\partial W2C}{\partial U_j}\right)_{ENG} & \Phi * \left(\frac{\partial Y_i}{\partial PT2}\right)_{ENG} * \left(\frac{\partial PT2}{\partial U_l}\right)_{INL} \\ \Phi * \left(\frac{\partial Y_k}{\partial W2C}\right)_{INL} \left(\frac{\partial W2C}{\partial U_j}\right)_{ENG} & \Phi * \left(\frac{\partial Y_k}{\partial W2C}\right)_{INL} * \left(\frac{\partial W2C}{\partial PT2}\right)_{ENG} * \left(\frac{\partial PT2}{\partial U_l}\right)_{INL} + \left(\frac{\partial Y_k}{\partial U_l}\right)_{INL} \end{bmatrix}}_{\text{Propulsion System Matrix Formed From Compact Model Outputs}} \begin{bmatrix} \Delta U_{ENG} \\ \Delta U_{INL} \end{bmatrix}$$

Propulsion System Matrix
Formed From Compact Model Outputs

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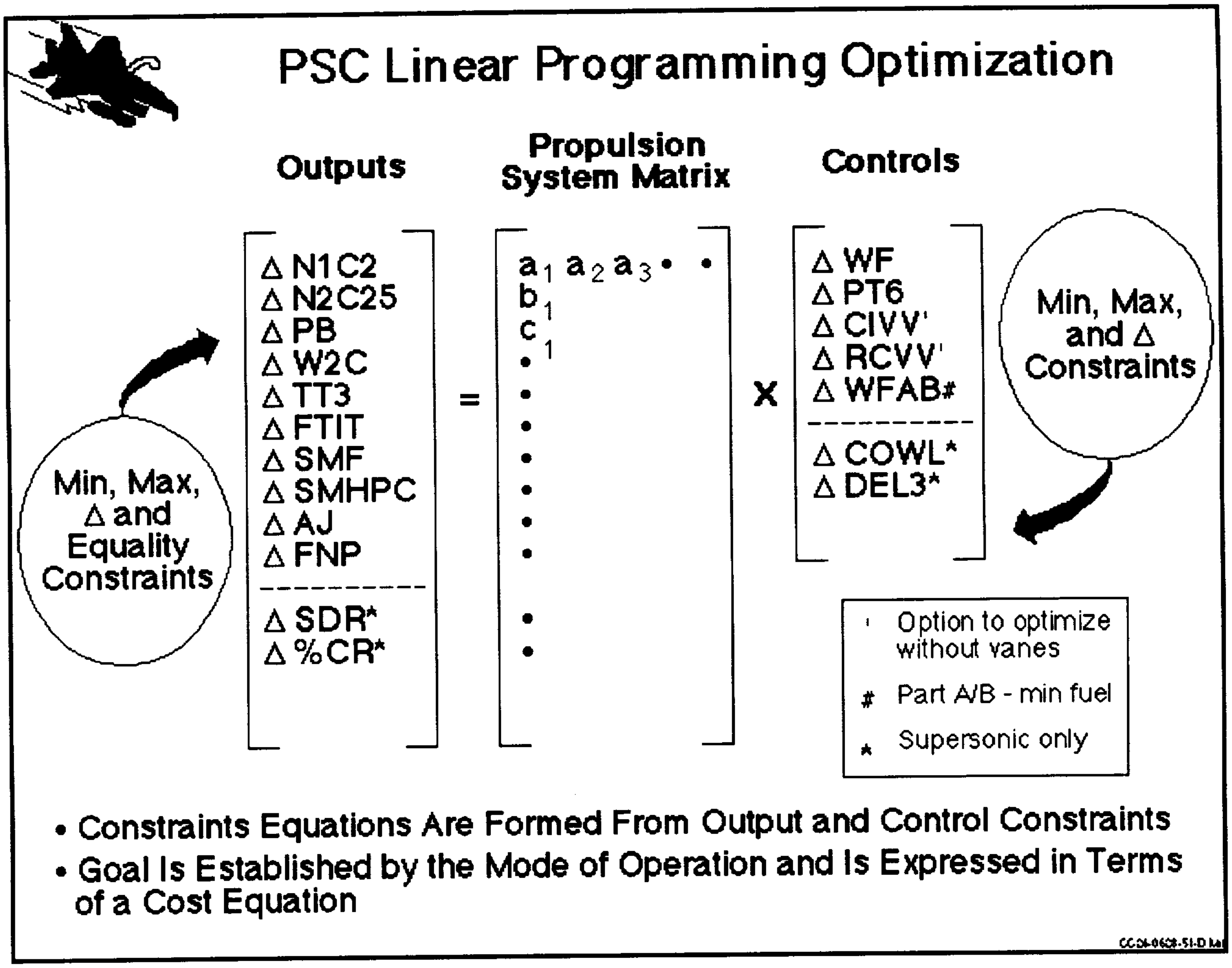
INTEGRATED PROPULSION MODEL

The compact models produce outputs and the sensitivity of those outputs to control changes. The sensitivities from the compact models are then combined to form an overall propulsion system model. The primary goal in this step is to account for the coupling between engine corrected airflow (W2C) and total pressure at the engine face(PT2). Total pressure losses occur in the inlet duct due to diffuser geometry changes and surface friction. The amount of total pressure loss increases with increasing W2C. In the compact engine model, PT2 is modeled as an independent input, which does not vary with engine outputs, such as W2C. To account for this coupling, the engine and inlet sensitivities are mathematically combined to form an overall propulsion system matrix. This matrix relates changes to engine and inlet controls to changes in the propulsion system outputs. Included are relationships, such as the sensitivity of inlet drag to changes in CIVV position, that can only be determined from an integrated model.



LINEAR PROGRAMMING OPTIMIZATION

A linear programming optimization is performed to determine optimal propulsion system control settings.

Determining the global optimum at each operating point requires solving a constrained nonlinear programming problem. The PSC appraoch to solving this problem is to perform a series of linear programming (LP) optimizations. For each optimization, a linear representation of the propulsion system about the specific operating point is provided by the propulsion system matrix. Maximum allowable control input changes are computed to prevent violation of model linearity assumptions. Constraints for each model output are also computed to prevent violation of physical operating limits.

An LP problem is set up and solved, using the Simplex method, to obtain the local optimum under these constraints.

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Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

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Optimization Process Example for Maximum Thrust Mode

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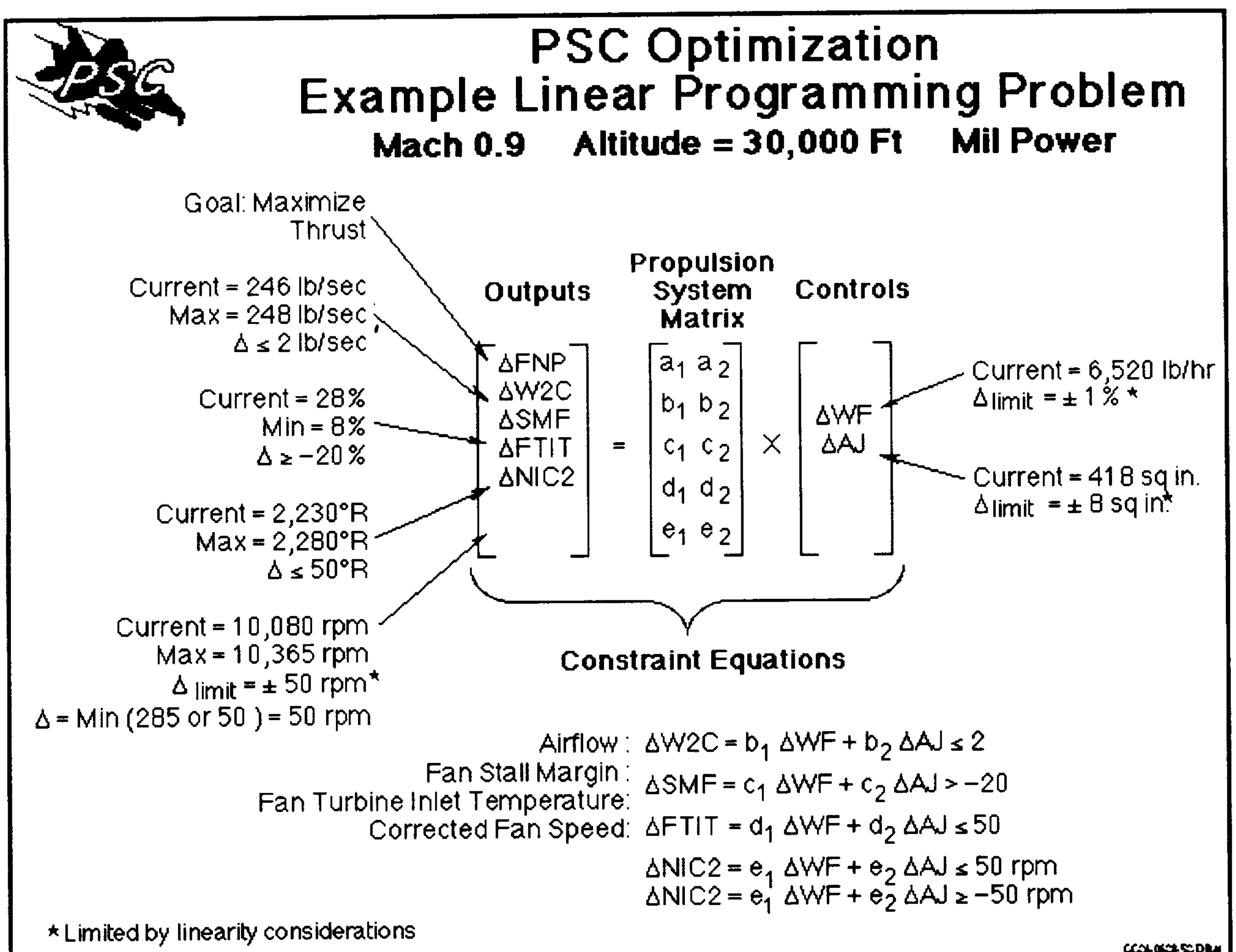

OPTIMIZATION PROCESS EXAMPLE FOR MAXIMUM THRUST MODE

An example of the PSC optimization process is shown for the maximum thrust mode. To simplify the explanation, the PSC optimization is presented for a two dimensional problem (two control variables). In the LP optimization, constraint equations are constructed. Ouput variable limits are based on physical operating limits in the engine and control variable limits are based on model linearity considerations.

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Optimization Region

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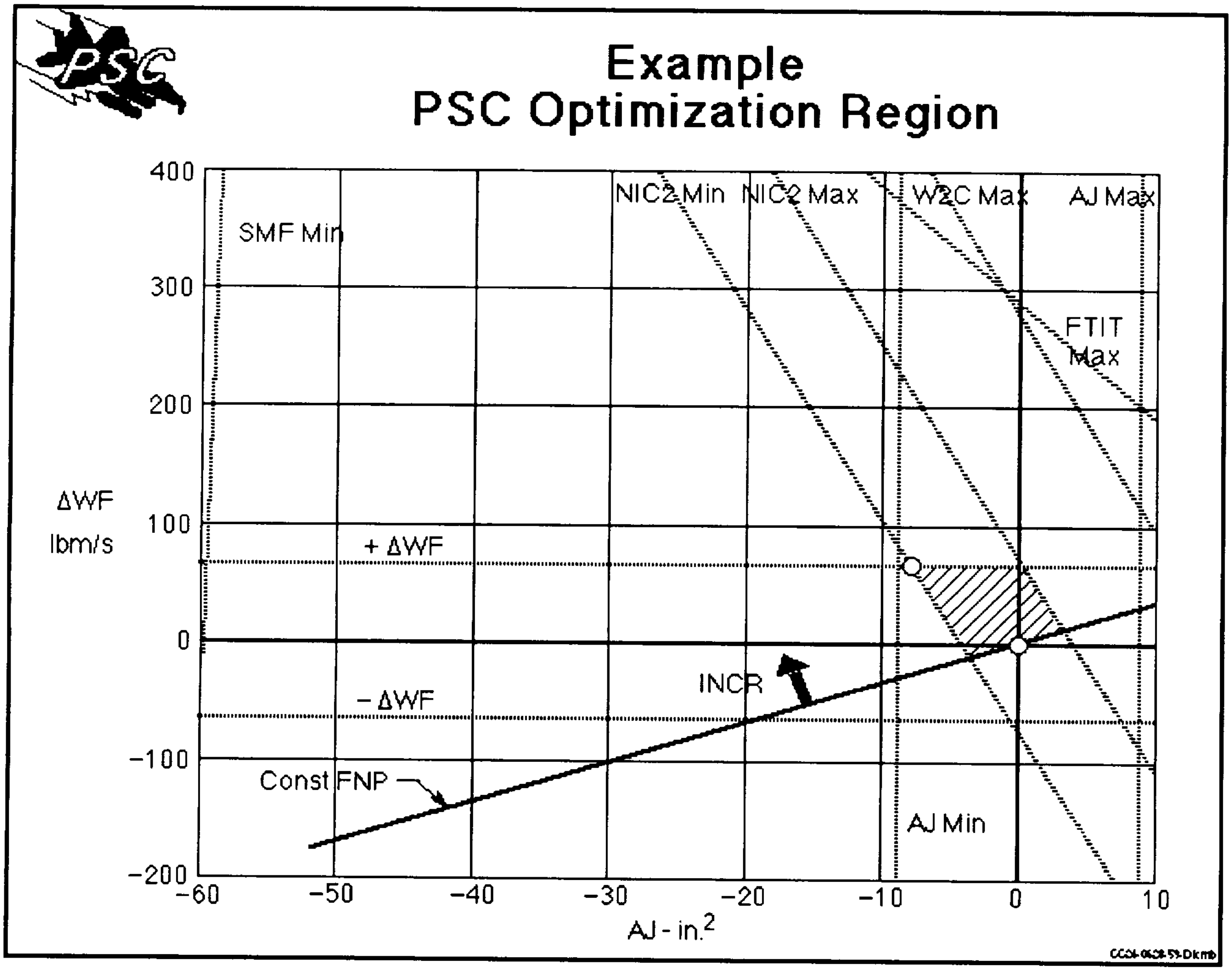

OPTIMIZATION REGION

The PSC optimization region is illustrated for the example problem. The local optimum for this two dimensional problem is at the intersection of two constraints: the maximum fuel flow (WF) and the minimum fan speed (N1C2).

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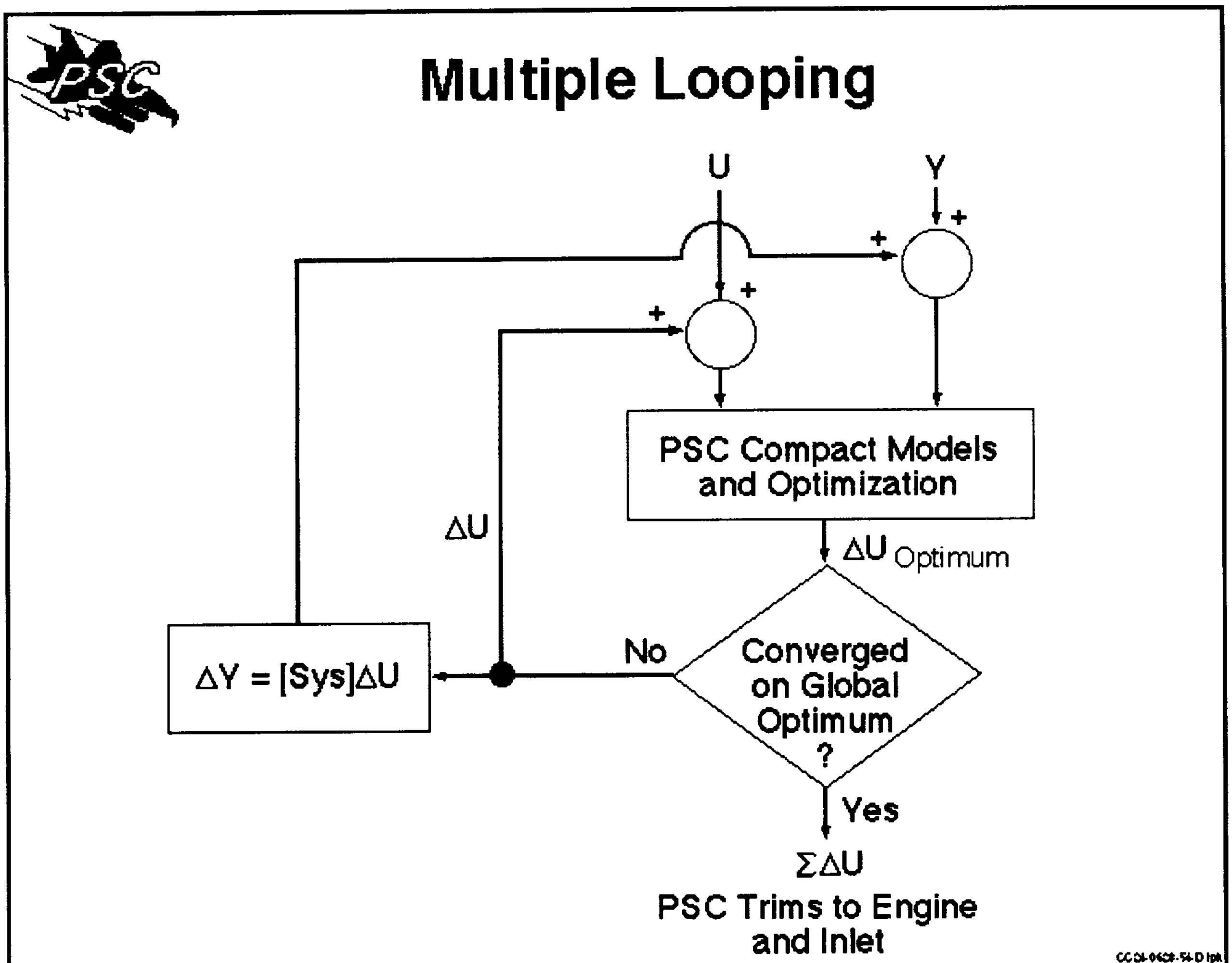
Optimization Looping Procedure



OPTIMIZATION LOOPING PROCEDURE

The control changes resulting from the LP optimization are used to compute a new system operating point, about which the models are again linearized. The above procedure is repeated until a sequence of control variable changes is generated, which converges to the global optimum solution. The number of loops is fixed. For subsonic operation 6 local optimizations are performed and for supersonic operation 3 local optimizations are performed.

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Maximum Thrust Mode Global Optimization Example

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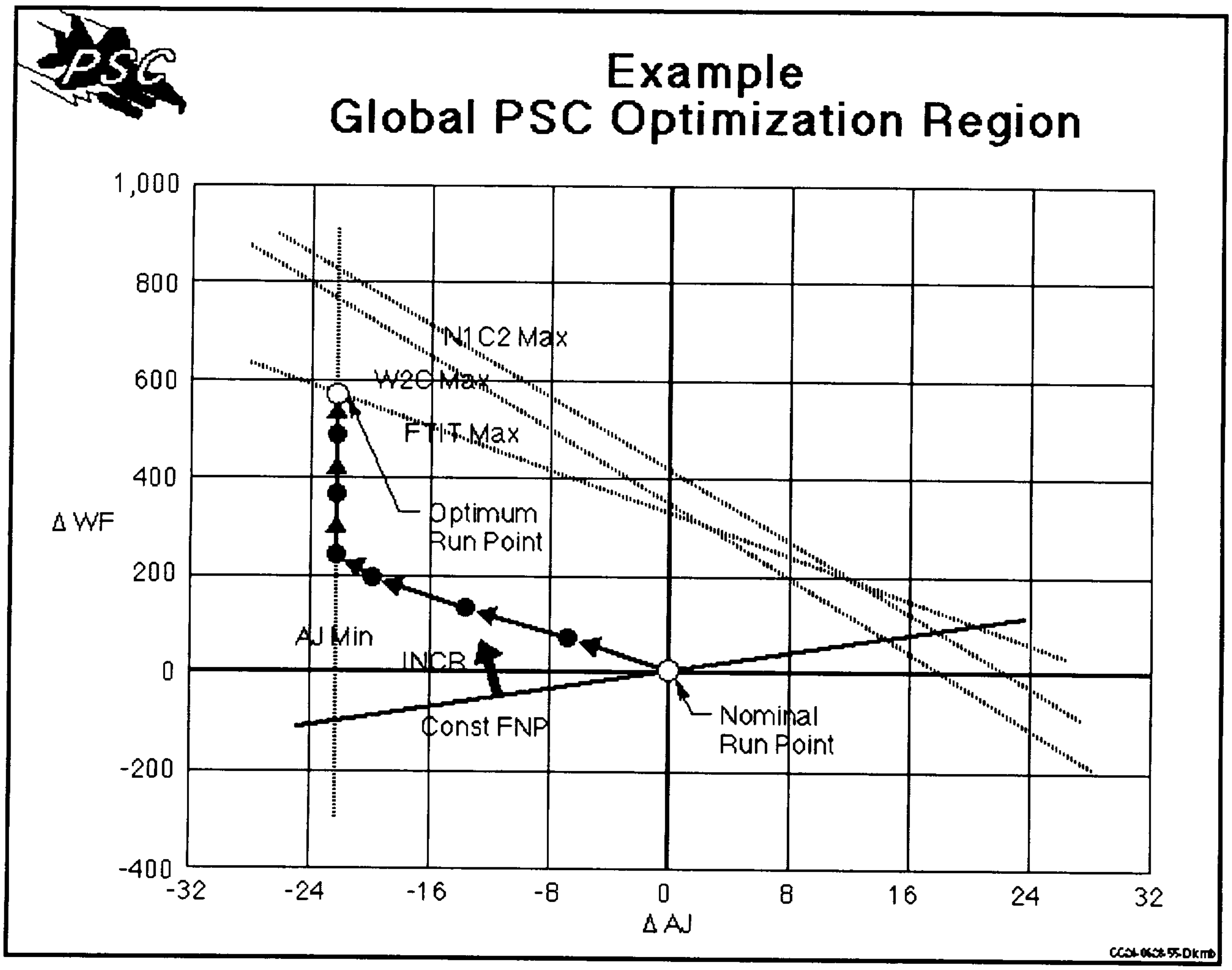

MAXIMUM THRUST MODE GLOBAL OPTIMIZATION

This example illustrates a Maximum Thrust Mode global optimization. As in the local optimization example, the PSC optimization is reduced to a two dimensinal problem (two control variables) to simplify the illustration. The global optimum for this case is at the intersection of two constraints: the minimum nozzle throat area (AJ) and the maximum FTIT.

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Engine Control Interface

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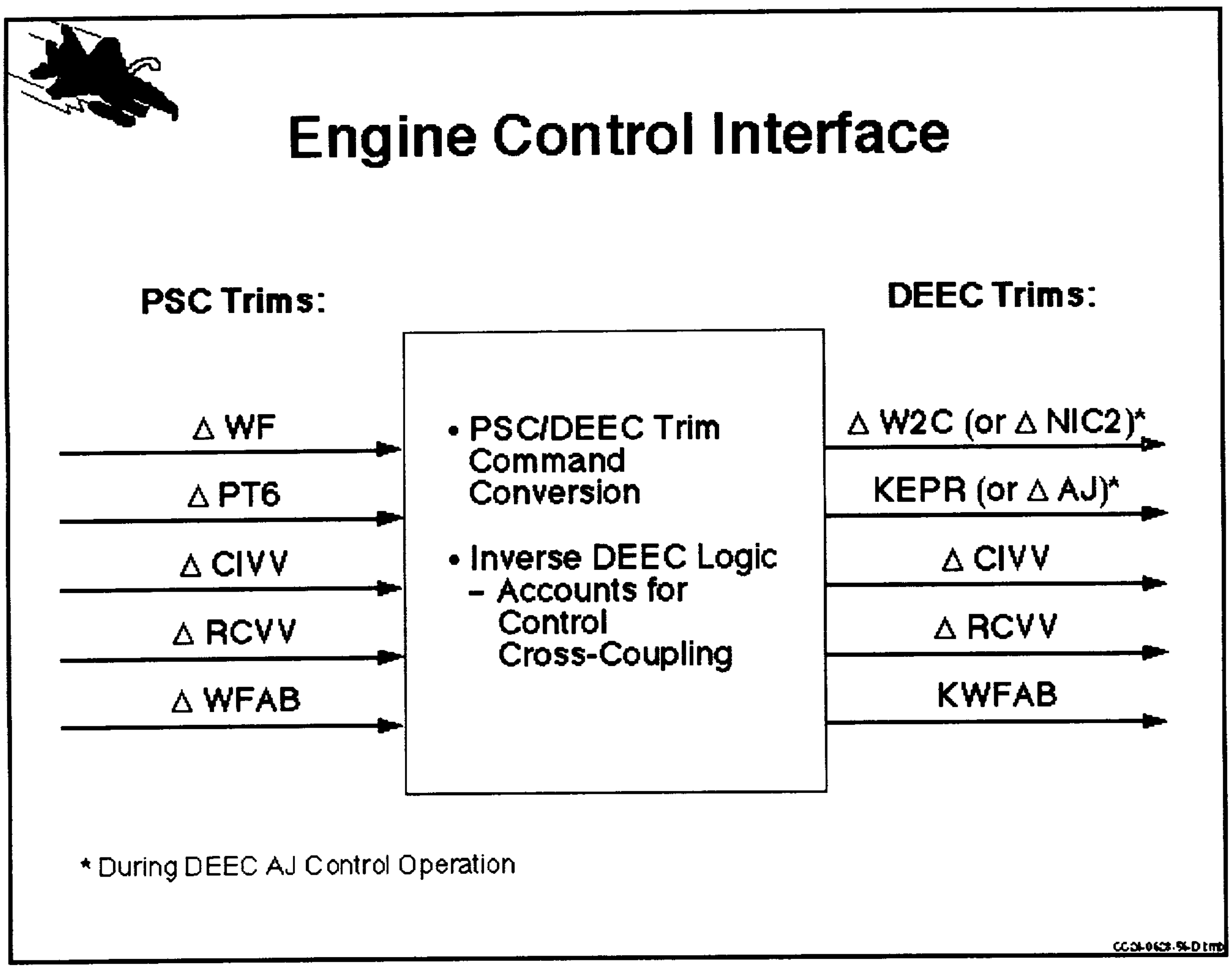

ENGINE CONTROL INTERFACE

The purpose of the engine control interface, or inverse DEEC, is to convert the trims calculated in the PSC optimization to trims that can be applied to the DEEC. For example, the PSC optimization determines a fuel flow (WF) trim which must be converted to either an airflow (W2C) or a fan speed (N1C2) trim so that it can be applied to the DEEC. The engine control interface also accounts for control cross–coupling.

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Author: Steven G. Nobbs
Affiliation: McDonnell Douglas Corporation
Phone: (314)232-2717
Fax: (314)232-4141
Address: MC 1069020, P.O. Box 516, St. Louis, MO 63166
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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PSC Hardware Description

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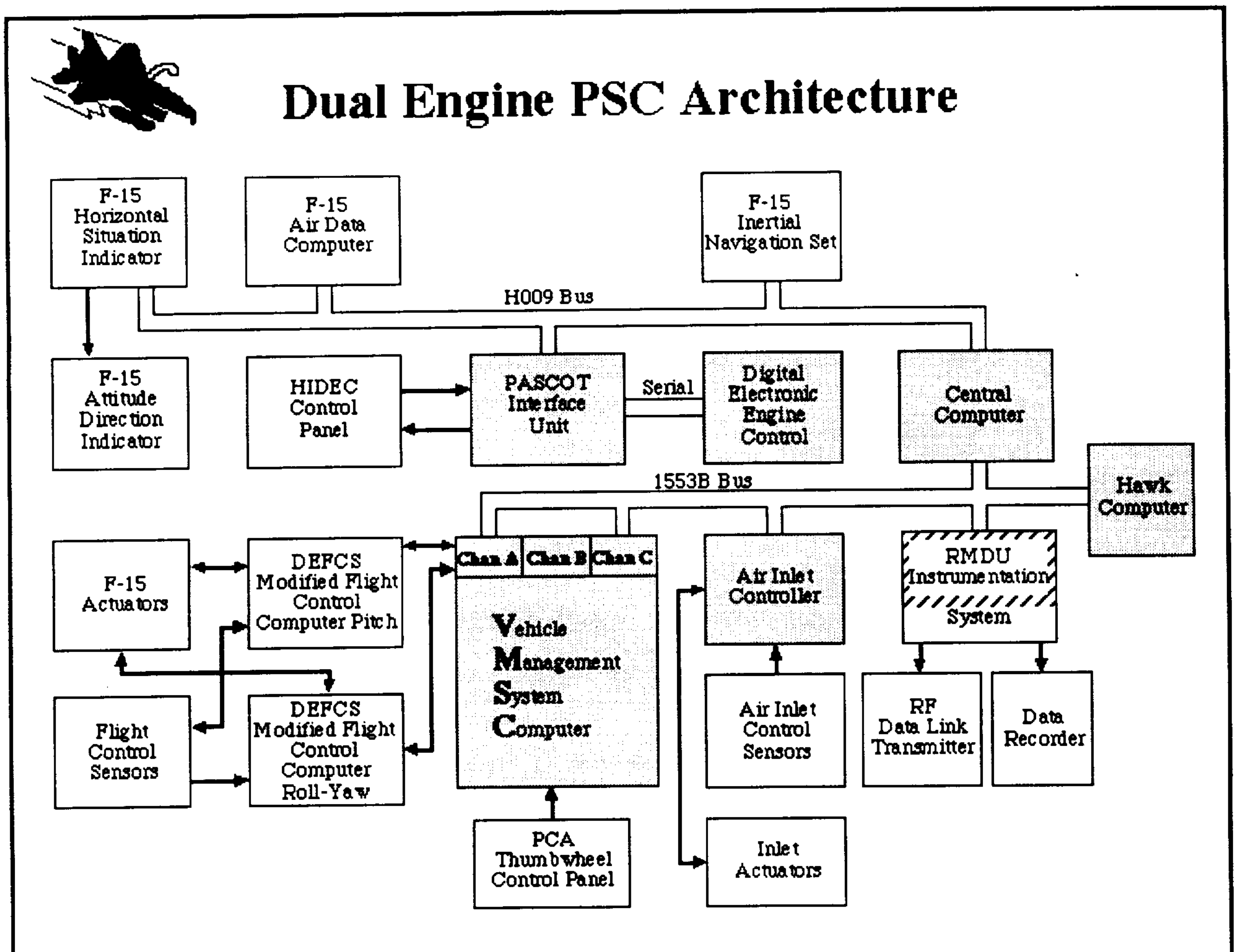

PSC HARDWARE DESCRIPTION

In this section, the PSC hardware will be described. The Hardware Architecture, Vehicle Management System Computer, Pilot Interface, and PSC Mode Selection will be discussed.

The primary computers in the system architecture are the Digital Electronic Engine Controls (DEECs), Electronic Air Inlet Controllers (EAICs), Vehicle Management System Computer (VMSC), Central Computer (CC), and the PASCOT interface unit. The ROLM HAWK computer was used for early testing of the PSC logic and hosted the PCA algorithm. These computers are linked together by data buses which allow information exchange from one to another.

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Vehicle Management System Computer (VMSC)

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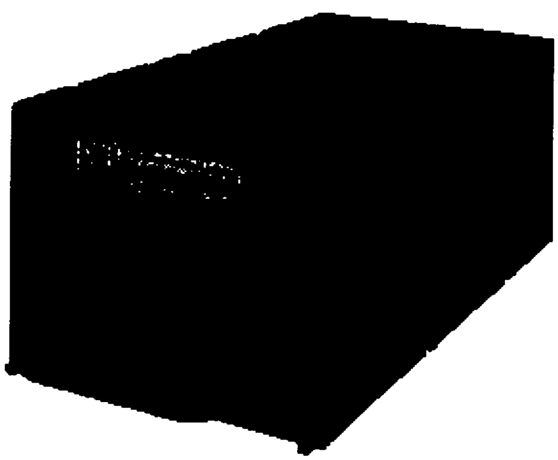
Vehicle Management System Computer



Advanced Computer Architecture

- Motorola 88000 RISC Architecture
- Three Redundant Channels
- Three Processors/Channels
- High Speed FO Bus Provisions for VMS
- 1553 I/O for Avionic and VMS

Flight Quality Design

- F-15 Flight Worthiness
- Replaces DEFCC
- Expands VMS Flight Demo Capability
- Flight Tested in NASA F-15

VMSC Provides

- State-of-the-Art Capabilities
- High Throughput (11-15 MIPS/ Processor)
- Large Memory to 4.5 MBYTE/ Processor Plus Global Memory
- Integrated Ada and Fortran Environment

VEHICLE MANAGEMENT SYSTEM COMPUTER (VMSC)

The Vehicle Management System Computer (VMSC) has state–of–the–art capabilities which make dual engine optimizaton possible. The VMSC has three redundant channels with up to three processors per channel. It features high speed inter–channel communication and Motorola 88000 RISC architecture. Each processor has large local memory and is capable of operating at 11 to 15 million instructions per second.

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VMSC Channels

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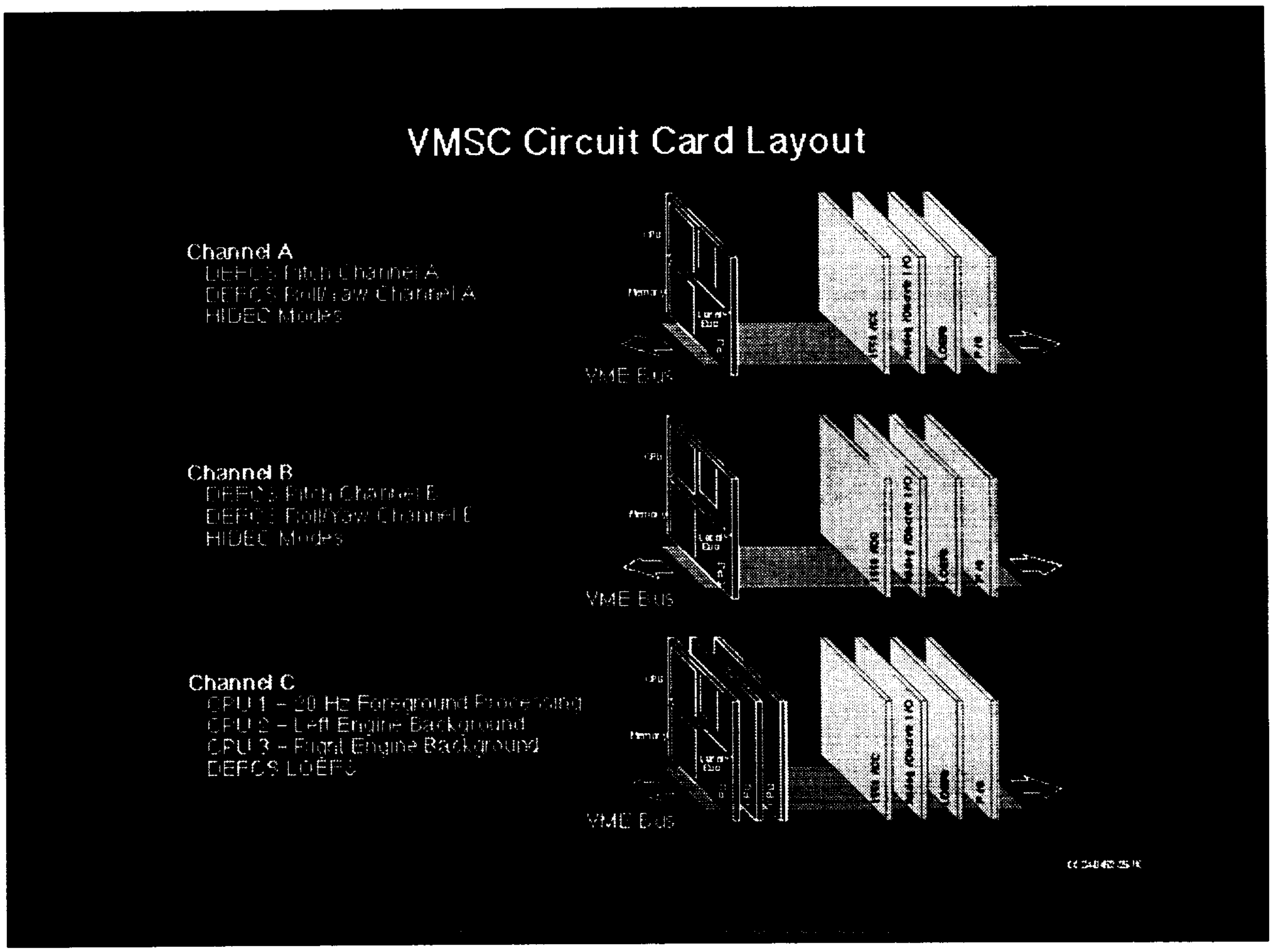

VMSC CHANNELS

Channels A and B of the VMSC contain the basic F-15 flight control laws. Each channel contains one 1553/Inter-channel communication (ICC) card, two analog/discrete I/O cards, one power supply (P/S) card, and one CPU. Each CPU contains Pitch and Roll/Yaw flight control laws thus providing dual redundancy.

Channel C is dedicated to the PSC control laws. It contains one 1553/Inter-channel communication (ICC) card, one analog/discrete I/O card, one P/S card, one LOFES card and three CPUs. The first CPU contains the foreground logic which executes at 20 hertz. The second CPU contains the logic for the left engine optimization and the third CPU contains the logic for the right engine optimization. The three CPUs operate concurrently.

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Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Pilot Interface

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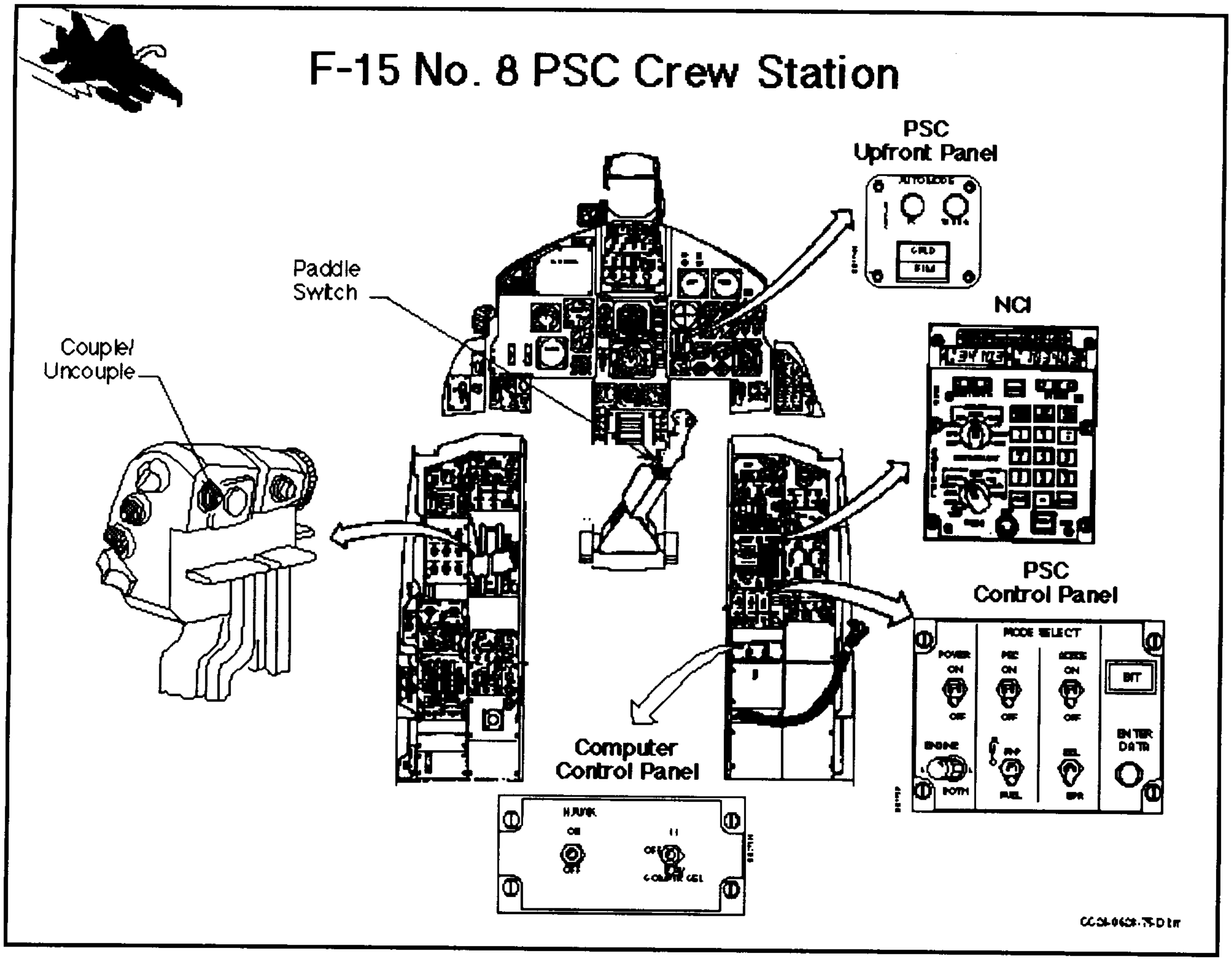

PILOT INTERFACE

The crew station in F–15A ship 8 has been configured to allow the pilot to interface with the PSC control laws. The pilot interfaces are the couple button, the paddle switch, the PSC control panels, the HUD, and the NCI.

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Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

PSC Couple Button

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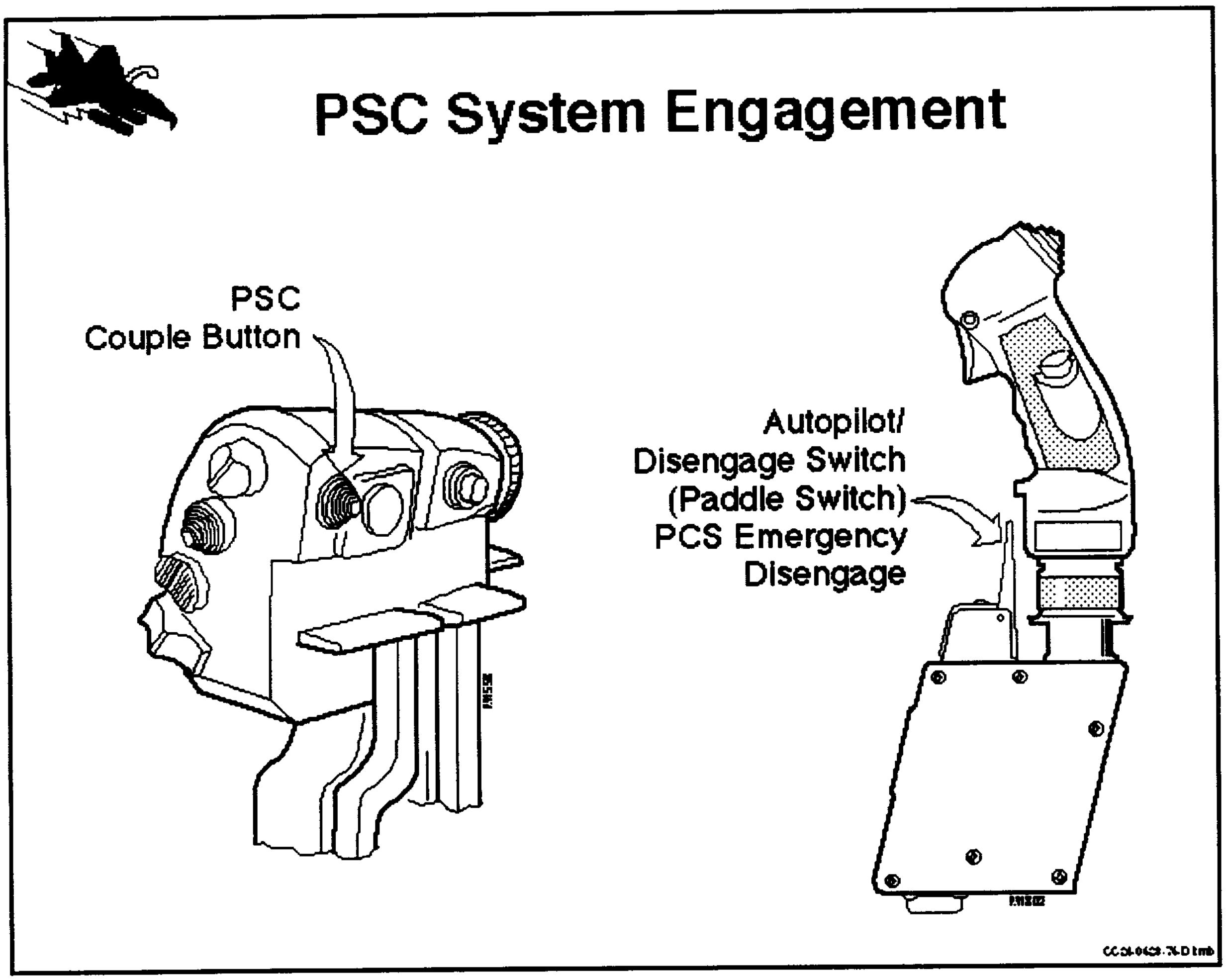

PSC COUPLE BUTTON

The PSC couple button, located on the throttle, is the only means of coupling PSC. The couple button can also be used to uncouple PSC by depressing the button when PSC is coupled. The paddle switch, located on the stick allows the pilot to rapidly uncouple PSC in case of an emergency.

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PSC Control Panels

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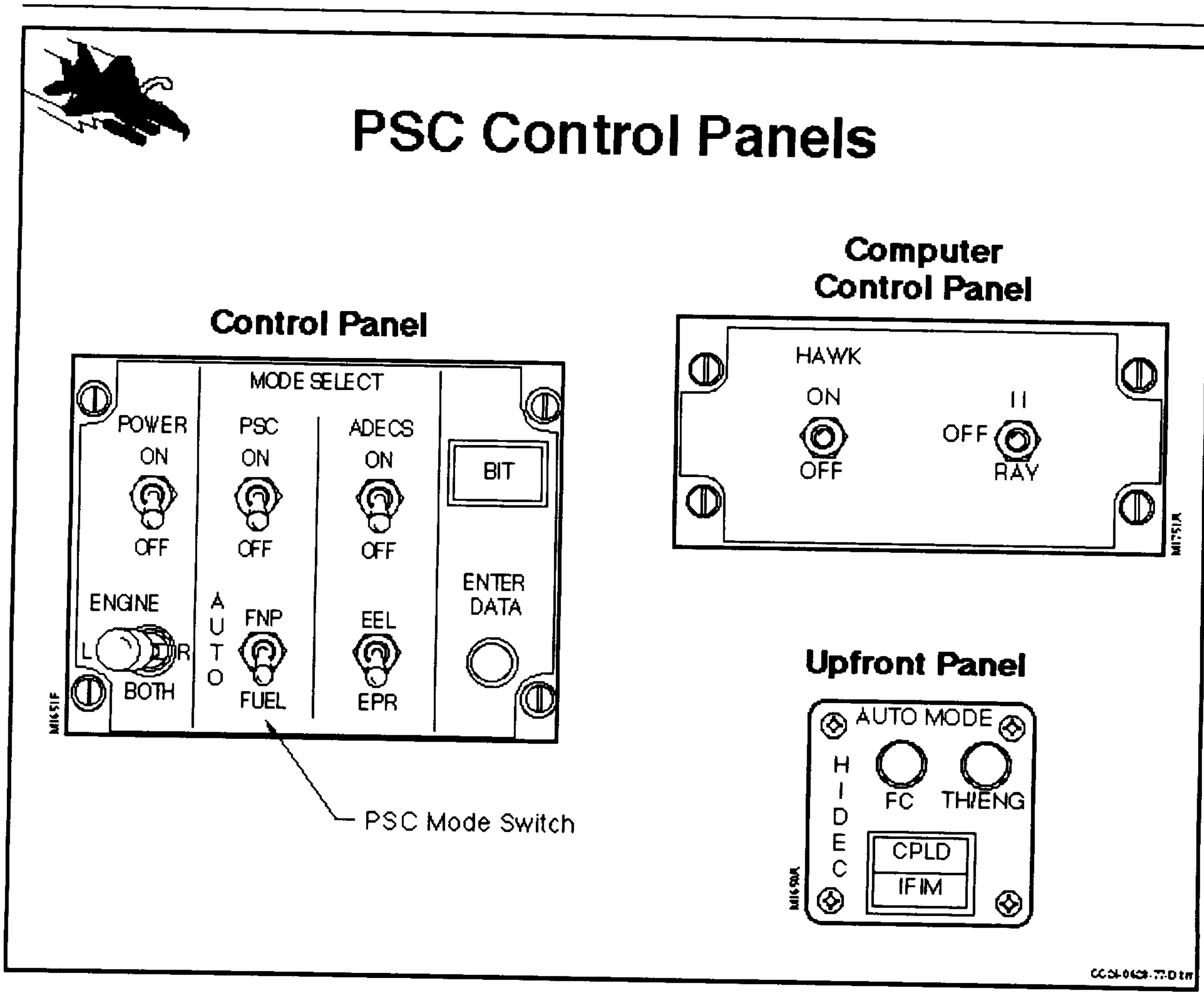

PSC CONTROL PANELS

The PSC control panel and the computer control panel allow the pilot to select various PSC or HIDEC modes, select the engine to be optimized, initiate BIT, enter NCI data, power the Hawk computer, and reset VMSC channel C. The upfront panel indicates that a mode has been selected which will send trims to the engine by lighting the TH/ENG light, that PSC is coupled by lighting the CPLD light, and that a system in–flight integrity management error has occurred by lighting the IFIM light.

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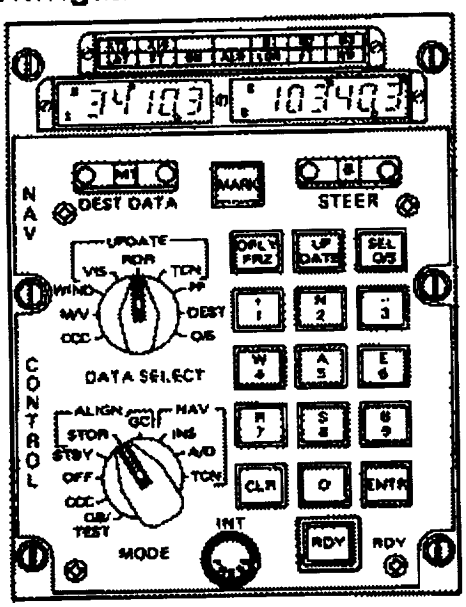
Navigation Control Indicator (NCI)

NCI Selectable Options

- NCI Can Be Used By Pilot to Modify the Control Laws In-Flight

Navigation Control Indicator



Input Procedure

1. Mode Switch = INS
2. Data Select to Destination
3. Destination Data to "8" or "9" or "10" or "11"
4. Depress Ready (RDY) Button (Lights)
5. Enter Data:
   Latitude: N X X X X X X ENTER
   Longitude: W X X X X X X X ENTER
   Altitude: A+ X X X X X X ENTER
6. Depress Enter Data Button on PSC Control Panel

NAVIGATION CONTROL INDICATOR (NCI)

The NCI can be used by the pilot to modify the PSC control laws in–flight. It is used to select sensor bias corrections, system gains, trim biases, optimization limits, and logic switches. The NCI is also used to select ground maintenance functions and initiate preflight BITs during ground tests.

Author: Steven G. Nobbs

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PSC Algorithm Design Flexibility

Algorithm Flexibility

NCI Entries Allow Inflight Selections

Mode Selections

- Engine Only Optimization
- Explicit Thrust
- Optimization Without CIVV
- Optimization Without RCVV
- Velocity Hold
- Maximum Thrust at Constant FTIT
- Supersonic Rapid Decel Mode
- New/Old Stabilator Trim Drag

System Constants Selections

- Bias on Engine Commands
- One Shot Kalman Filter
- Nominal Efficiency Curves
- Calculated Alpha and Beta in Calculator/Predictor
- Inlet Percent Critical
- Inlet Shock Displacement
- FTIT Limit
- Alpha/Beta Predictor Lead Time
- Excess Stall Margin
- Bleed Air Multiplier
- Stored Tables of Component Deterioration
- Filter Time Constant on Commands
- HAMSTR Inlet Recovery

Maximum Flight Test Flexibility

PSC ALGORITHM DESIGN FLEXIBILITY

The PSC algorithm has been designed to have great flexibility to maximize flight test effectiveness. The NCI and the PSC control panel are used to select various optimization modes and system constants. This allows the control laws to be modified during or between flights without generating a new OFP.

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PSC Software Descriptions

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PSC SOFTWARE DESCRIPTION

The PSC software is distributed among the Vehicle Management System Computer, Central Computer, DEECs and EAICs. This section describes the major PSC modules, VMSC logic, VMSC Ch. C memory requirements, VMSC Ch. C timing, NCI variables and where they are located.

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Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Major PSC Modules

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MAJOR PSC MODULES

The majority of the PSC modules reside in channel C of the VMSC. These modules are split between the foreground processor and two background processors. The major foreground modules are the supervisory logic, the Kalman Filter, and the stall protection logic. The major background modules are the compact engine model, compact inlet model, optimization logic, and inverse DEEC. VMSC channels A and B, the Central Computer (CC), the DEECs and the EAICs also contain important PSC modules. VMSC channels A and B contain the alpha and beta calculator/predictor logic. The CC contains the BIT/IFIM logic and the DEEC/VMSC and EAIC/VMSC data transfer logic. The DEECs and EAICs contain PSC trim command interface logic.

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Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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VMSC Logic Partitioning

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VMSC Logic Partioning

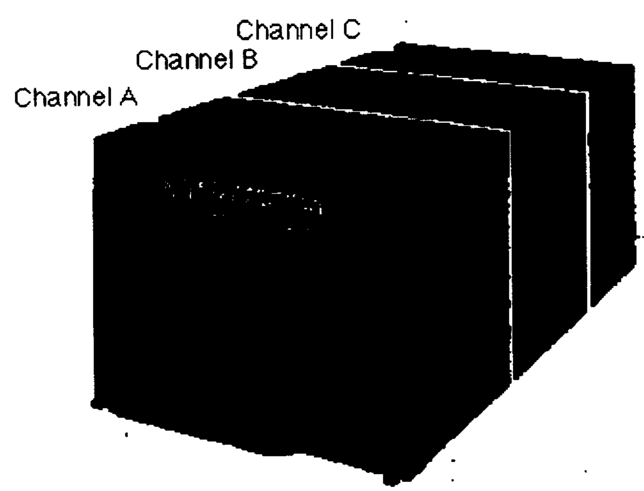
Channels A, B and C

Channels A and B

- One CPU Card Per Channel
- Each Channel Executes the Following Logic:
  - Digital Flight Control Laws
  - HIDEC Logic
    - ADECS
    - Inlet Integration
    - Extended Engine Life
  - Alpha/Beta Calculator Predictor
  - MUX I/O (Channel A Only)
  - Inter-Channel Communication Logic

Channel C

- 3 CPU Cards
  - CPU 1 - FG OFP
  - CPU 2 - BG OFP (Left)
  - CPU 3 - BG DFP (Right)



VMSC LOGIC PARTITIONING

The VMSC has three redundant channels with up to three CPUs per channel. Channels A and B each contain one CPU. Each CPU contains digital flight control laws, HIDEC logic, Alpha/Beta calculator predictor, MUX I/O, and inter–channel communication logic. The logic in channel A is identical to that in channel B. Channel C contains three CPUs. CPU No. 1 contains the PSC foreground logic which operates at 20 hertz. CPU No. 2 contains the left PSC background logic and CPU No. 3 contains the right PSC background logic. The three CPUs operate concurrently.

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PSC Logic in VMSC Channel C

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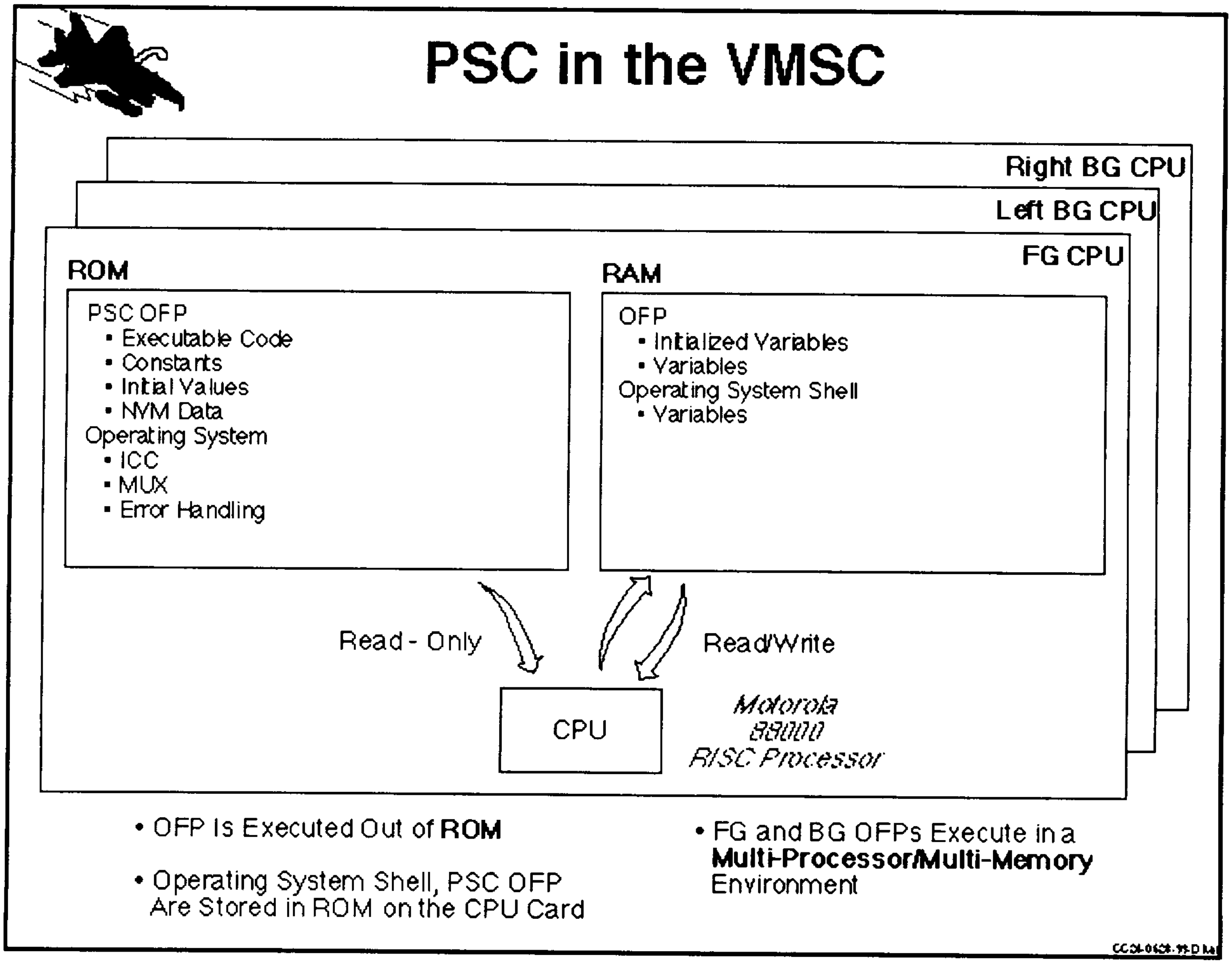

PSC LOGIC IN VMSC CHANNEL C

The PSC logic in VMSC channel C executes in a multi–processor/multi–memory environment, unlike the Hawk which executed in a single processor. Each processor contains Read–Only–Memory (ROM) and Random–Access–Memory (RAM). The executable code, constants, initial values and the operating system are stored in ROM. The limited amount of RAM is reserved for variable memory. The CPU reads from both ROM and RAM but it only writes to RAM. The implementation is the same for all three CPUs.

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VMSC Channel C Memory Requirements

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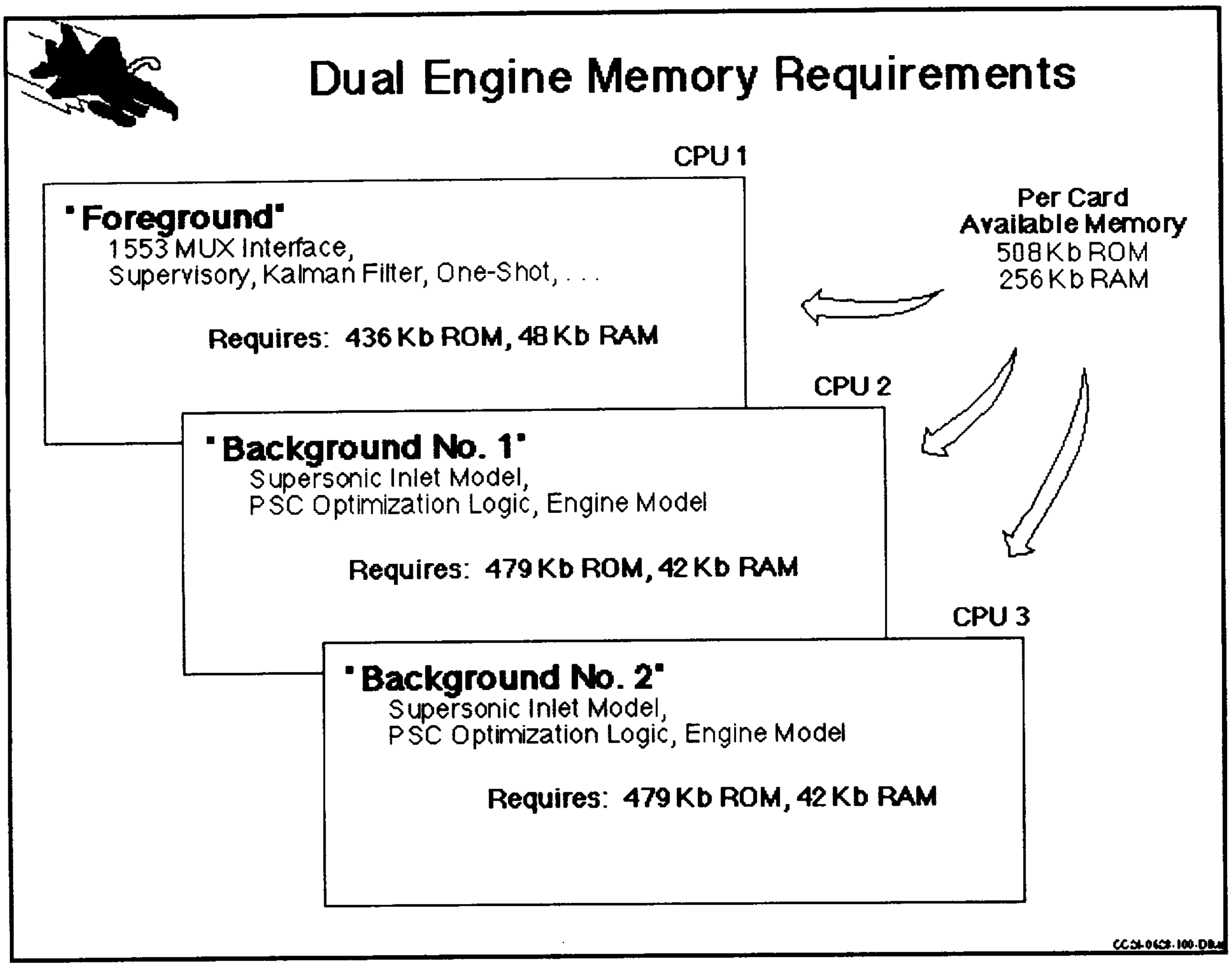

VMSC CHANNEL C MEMORY REQUIREMENTS

The PSC control laws in channel C of the VMSC reside in three separate CPUs. Each CPU has 508 Kb of Read–Only–Memory (ROM) and 256K of Random–Access–Memory (RAM) available. Due to the limited RAM, the executable logic is run from ROM on each CPU. The foreground Operational Flight Program (OFP) uses 436 Kb of ROM and each background OFP uses 479 Kb of ROM. Only a small portion of RAM is utilized. The foreground uses 48 Kb of RAM and each background uses 42 Kb of RAM.

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VMSC Channel C Timing; Foreground Operational Flight Program (OFP)

Foreground Execution Rate in the VMSC

- **Foreground OFP Executes at a Fixed Rate**
  - 20 Hz, 50 Millisecond (mS) Frame
- **Critical Module Timing Data:**
  - Kalman Filter: 3.4 mS
  - Stall Protection: 1.4 mS
- **Foregound Frame Utilization**
  - Single Engine: 14 mS Out of 50 mS Frame
  - Dual Engine: 21 mS Out of 50 mS Frame

VMSC CHANNEL C TIMING

The PSC foreground Operations Flight Program (OFP) operates at a fixed rate of 20 Hz. Timing analyses have been conducted to ensure that the PSC logic will complete in the 20 Hz frame. The background logic runs at a variable rate which depends on flight conditions. Background timing is important because it corresponds to the time between PSC trim applications.

The PSC foreground OFP contains the supervisory logic which executes at 20 Hz. If a failure is detected in the supervisory logic, the system must be uncoupled quickly. Timing data has been taken which shows that during single engine operation 14 ms out of the 50 ms frame is used. During dual engine operation, 21 ms out of the 50 ms frame is used. Two key foreground modules, the Kalman Filter and stall protection use 3.4 ms and 1.4 ms, respectively.

Background OFP

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Background Execution Rate in the VMSC

- **Background Runs at Variable Rate**
- **Critical Module Timing Data (Per Call Basis)**
  - Compact Engine Model:
    32 mS (Milliseconds)
  - Compact Inlet Model:
    Subsonically: 16 mS
    Supersonically: 160 mS
  - Linear Programming Logic:
    10 - 20 mS (Constraint Dependent)
- **Background Execution Rate is Dependant on Flight Condition**
  - Subsonically: 0.2 - 0.3 Seconds (6 Optimization Loops)
  - Supersonically: 0.45 - 0.65 Seconds (3 Optimization Loops)

BACKGROUND OPERATIONAL FLIGHT PROGRAM (OFP)

The PSC background OFP runs at a variable rate. The execution rate is dependent on flight condition. At subsonic conditions, the background completes in 0.2–0.3 seconds, while at supersonic conditions, the background completes 0.45–0.65 seconds. The timing data show that the compact engine model and linear programming logic take 32 ms and 10–20 ms, respectively. The compact inlet model timing depends on flight condition. Subsonically it takes 16 ms while supersonically it takes 160 ms. The supersonic portion of the compact inlet model is the main reason for the large execution times required at supersonic conditions.

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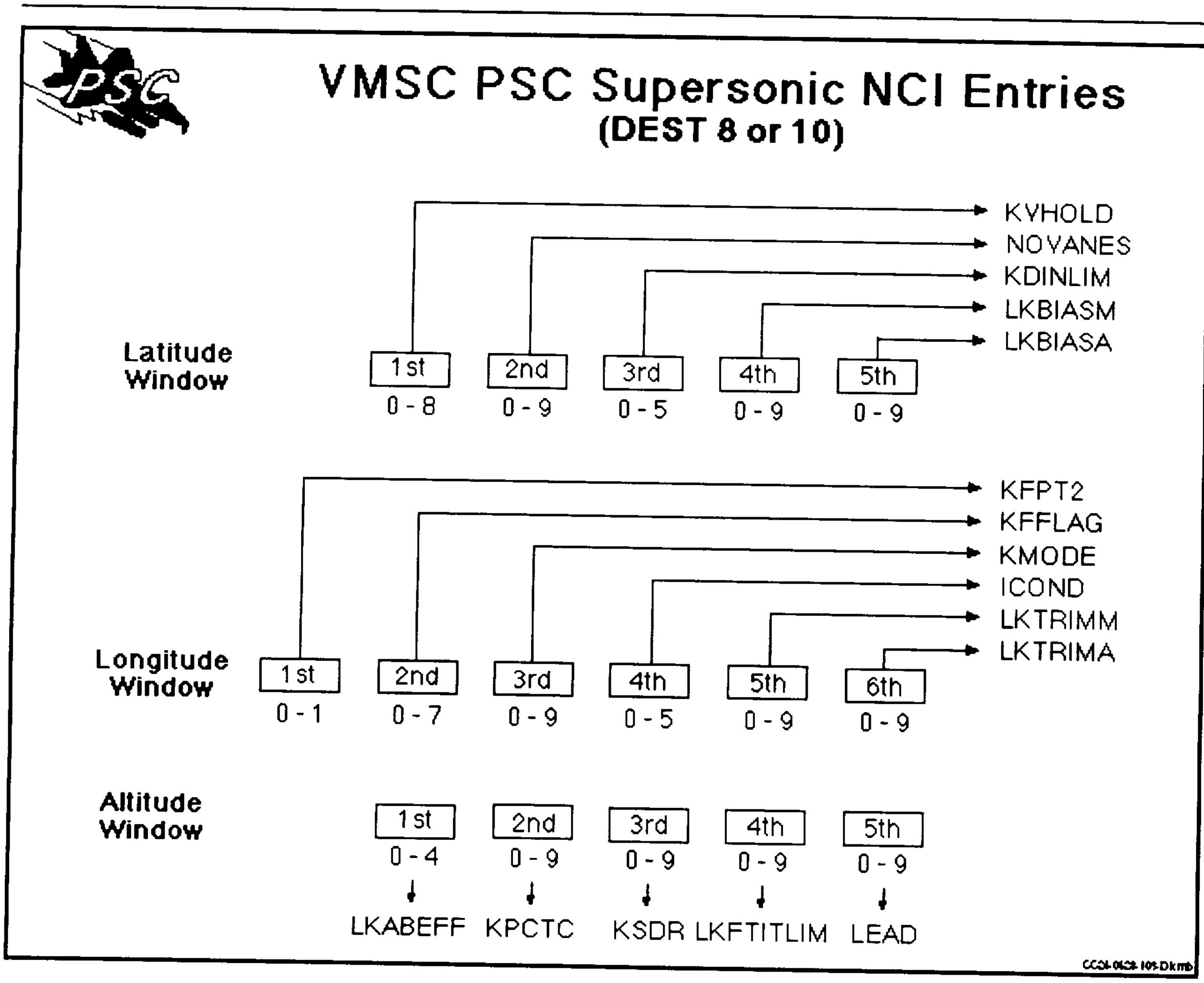

NAVIGATION CONTROL INDICTOR (NCI) VARIABLES

The aircraft Navigation Control Indicator (NCI) is used by the pilot to modify the PSC control laws in–flight. The longitude, latitude, and altitude entries are decoded by the PSC control laws when the DATA SELECT switch is in the DEST position. The NCI is used to select switches or table pointers in the PSC control laws. This greatly enhances the experimental capabilities of PSC. There are five entries available in the latitude and altitude windows and six in the longitude window. Beyond this, the pilot can choose 2 separate definitions for each entry by setting the DEST DATA switch to an odd number for one definition or an even number for the other definition. This results in 32 available entries to modify the control laws in–flight. This chart shows the 16 entries available when an even DEST DATA position is selected.

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Couple/Uncouple Logic

- Designed to Prevent Uncommanded, Unsafe, or Invalid Trim Application
- Coupling Is Initiated Only by the Pilot
- All Coupling Criteria Must Be Satisfied Before the Trims Are Applied to the DEEC/EAIC
- The Aircraft Resumes Normal F-15 Operation If Any Coupling Criteria Becomes Unsatisfied
- Pilot May Uncouple at Any Time
- Several Uncouple Methods Available to Pilot

IMPLEMENTATION OF SAFETY DESIGN FEATURES

Several system safety design features have been implemented for PSC. These include the couple/uncouple logic, extensive In–Flight Integrity Management (IFIM), trim command limiting, engine stall protection, VMSC safety features, NCI data entry restrictions, and a limited flight test envelope.

The PSC couple/uncouple logic is designed to prevent uncommanded, unsafe, or invalid trim application. Coupling of the system can be initiated only by the pilot. An extensive set of coupling criteria must be satisfied before the system couples and if the criteria becomes unsatisfied while coupled, the system automatically uncouples. In this case, the aircraft reverts to normal F–15 operation. The pilot has the authority to uncouple at any time.

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Manual and Automatic Methods for Uncoupling System

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PSC UNCOUPLE REASONS

- PADDLE SWITCH DISENGAGE
- PILOT INITIATED UNCOUPLE
- POWER SWITCH OFF
- MODE NOT SELECTED
- INCOMPATIBLE MODES
- LANDING GEAR HANDLE DOWN (WITHOUT OVERRIDE)
- IFIM FAILURE

MANUAL AND AUTOMATIC METHODS FOR UNCOUPLING SYSTEM

There are several manual and automatic methods for uncoupling the system. The manual methods available to the pilot are to depress the paddle switch disengage, depress the couple/uncouple button, turn the power switch off, turn the selected mode off, select an incompatible mode, and set the landing gear handle down. Automatic uncoupling ocurs when there is an IFIM failure.

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Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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PSC In-Flight Integrity Management (IFIM)

PSC UNCOUPLE/IFIM REASONS

The uncouple/ IFIM reasons listed cause the PSC system to uncouple and illuminate the IFIM light on the upfront panel in the cockpit.

- CC Self Test Fail
- VMSC Self Test Fail
- DEEC Self Test Fail
- EAIC Self Test Fail
- 1553 MUX Check Fail
- H009 MUX Check Fail
- Loss of CC Power
- Loss of PASCOT Power
- Loss of VMSC Power
- INS Validity Failure
- INS Attitude Validity Failure
- Mach Number Validity Failure
- Pressure Ratio Validity Failure
- ADC True Airspeed Validity Failure
- CAS Disengagement (Any Axis)
- VMSC NVM Checksum Failure (Any Channel)
- VMSC OFP Checksum Failure (Any Channel)
- VMSC Channel C Background CPU Failure
- VMSC Input Data Out of Range
- VMSC Arithmetic Error Fault
- PSC Optimization Unbounded
- VMSC Mechanical/ Autothrottle PLA Mismatch
- Stall on Selected Engine(s)
- Reversion to BUC on Selected Engine(s)
- Augmentor Failure on Selected Engine(s)
- UART Did Not Receive Valid Data in Time
- EPR Trim Out of Range
- Airflow Trim Out of Range
- CIVV Trim Out of Range
- RCVV Trim Out of Range
- A/B Fuel/Air Trim Out of Range
- N1C2 Trim Out of Range
- AJ Trim Out of Range
- Autothrottle Trim Out of Range
- CC/ VMSC Wrap Failure, Declared by CC
- CC/ VMSC Wrap Failure, Declared by VMSC
- DEEC/ VMSC Wrap Failure, Declared by Selected DEEC(s)
- DEEC/ VMSC Wrap Failure, Declared by VMSC
- EAIC/VMSC Wrap Failure, Declared by VMSC
- CC/ DEEC Wrap Failure, Declared by CC
- CC/ DEEC Wrap Failure, Declared by DEEC(s)

PSC IN-FLIGHT INTEGRITY MANAGEMENT (IFIM)

The PSC In-Flight Integrity Management (IFIM) logic is designed to automatically uncouple the PSC system and notify the pilot via the IFIM light in the event of certain hardware or software failures. An IFIM failure is declared when a computer fails a self check, the multiplex bus fails a check, a computer loses power, validity bits are not transmitted or received from the INS or ADC, CAS disengages, Checksum fails, PSC logic gives erroneous results, the DEECs receive invalid trim commands, or wrap words fail to increment.

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

Trim Command Limiting

Trim Command Limiting

- DEEC Limits Trim Commands to Protect Engine Stability and Dynamic Response
  - Range Checking
  - Rate Limiting
  - Commands Overridden to Maintain Safe Operation
  - Commands Cancelled if a Failure Is Detected
- EAIC Commands Are Limited to Maintain Stable Flow to the Engine
  - MUX Scaling Limits the Magnitude of Trim Commands (±5 deg)
  - Commands Cancelled if a Failure Is Detected

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Engine Stall Protection

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ENGINE STALL PROTECTION

The PSC software contains stall protection logic which limits the amount of EPR uptrim during aircraft maneuvers to maintain an adequate fan stall margin. The stall protection logic runs in the foreground CPU at 20 Hz.

¥ PSC sends commands to the DEEC which could potentially stall the engine

¥ Engine Stall Protection Logic included in the DEEc to decrease this risk

¥ The DEEC Limits only maintain adequate stall margin for straight and level flight

¥ The PSC Stall Protection Logic operates at 20 Hz and limits the amount of EPR uptrim to maintain adequate stall margin during all aircraft maneuvers

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Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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VMSC Safety Features

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VMSC SAFETY FEATURES

Re–hosting the PSC control laws in the VMSC required the addition of several safety features to the system. Wrap checks with the CC and both DEECs were added. Since the PSC operates in three CPUs, wrap checks between the foreground and background CPUs were added. In addition, logic was added to perform checksums, timing checks, and power–up tests.

¥ CC to VMSC Channel C Foreground Wrap Failure Check

¥ DEEC to VMSC Channel C Foreground Wrap Failure Checks (Left and Right Engines)

¥ VMSC Channel C Background CPU Failure Checks

¥ OFP Checksum Failure Checks

¥ NVM CHecksum Failure Checks

¥ Watch Dog Timers

¥ Power Up Tests

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Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

NCI Data Entry Restrictions

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Data Entry Restrictions

- NCI Panel Can Be Used to Input Code Words to Reconfigure PSC Control Laws
- The Code Word Is Used by the VMSC Only When
  - "Enter Data" Button on the PSC Control Panel Is Depressed and
  - The PSC System Is Uncoupled

Transients Avoided by Preventing Data Entries While Coupled

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Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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PSC Flight Test Envelope Limitations

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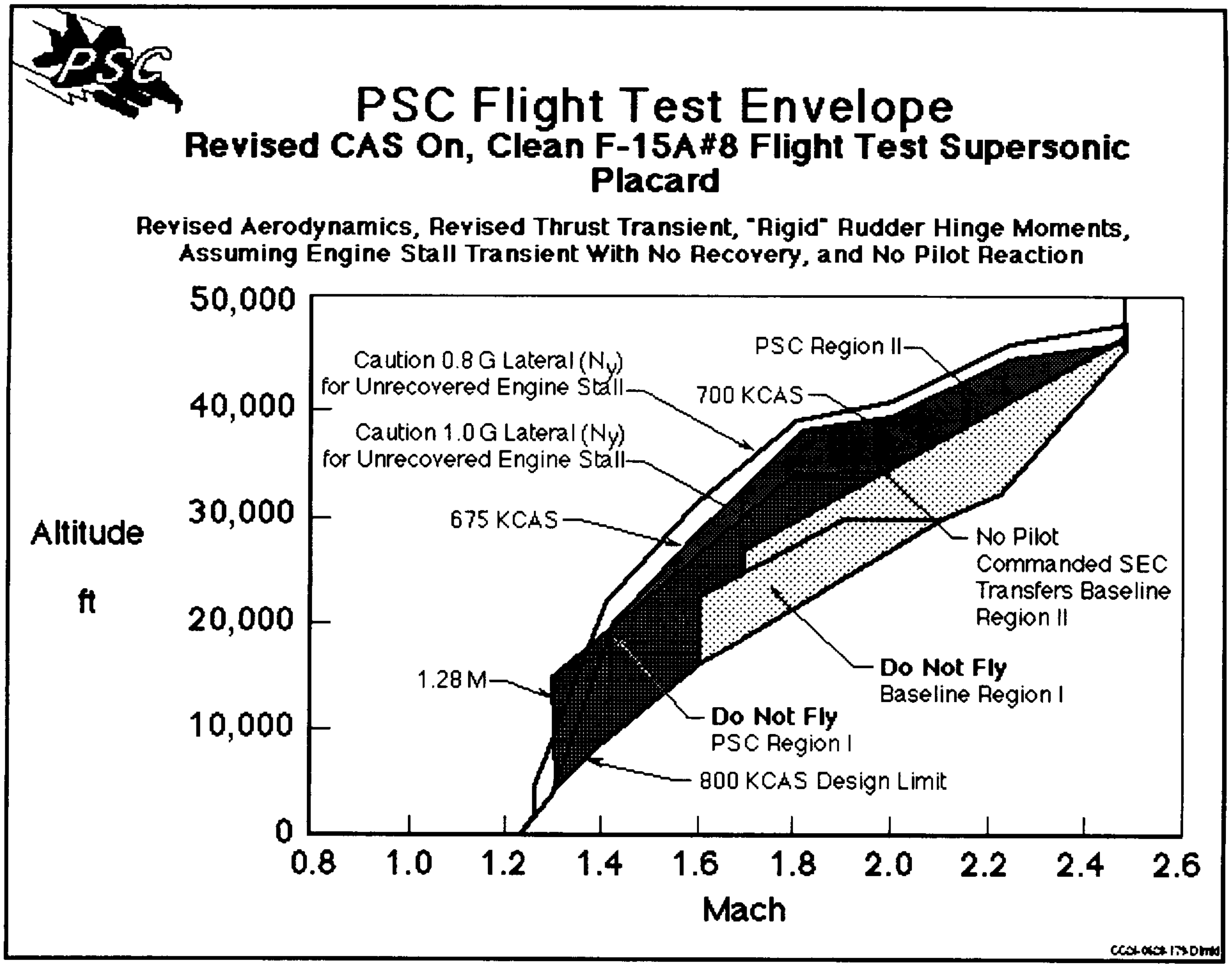

PSC FLIGHT TEST ENVELOPE LIMITATIONS

The PSC flight test envelope has been limited based on a simulation study performed on a clean F-15/A with CAS on. The study assumed an engine stall on one engine with no recovery and no pilot action to counter the large yaw moment. Region 1 is a "do not fly" region. Region 2 is a "no commanded SEC tranfer" region. Also shown are 0.8 g and 1.0 g lateral acceleration lines which are pilot discomfort boundaries.

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Author: Steven G. Nobbs

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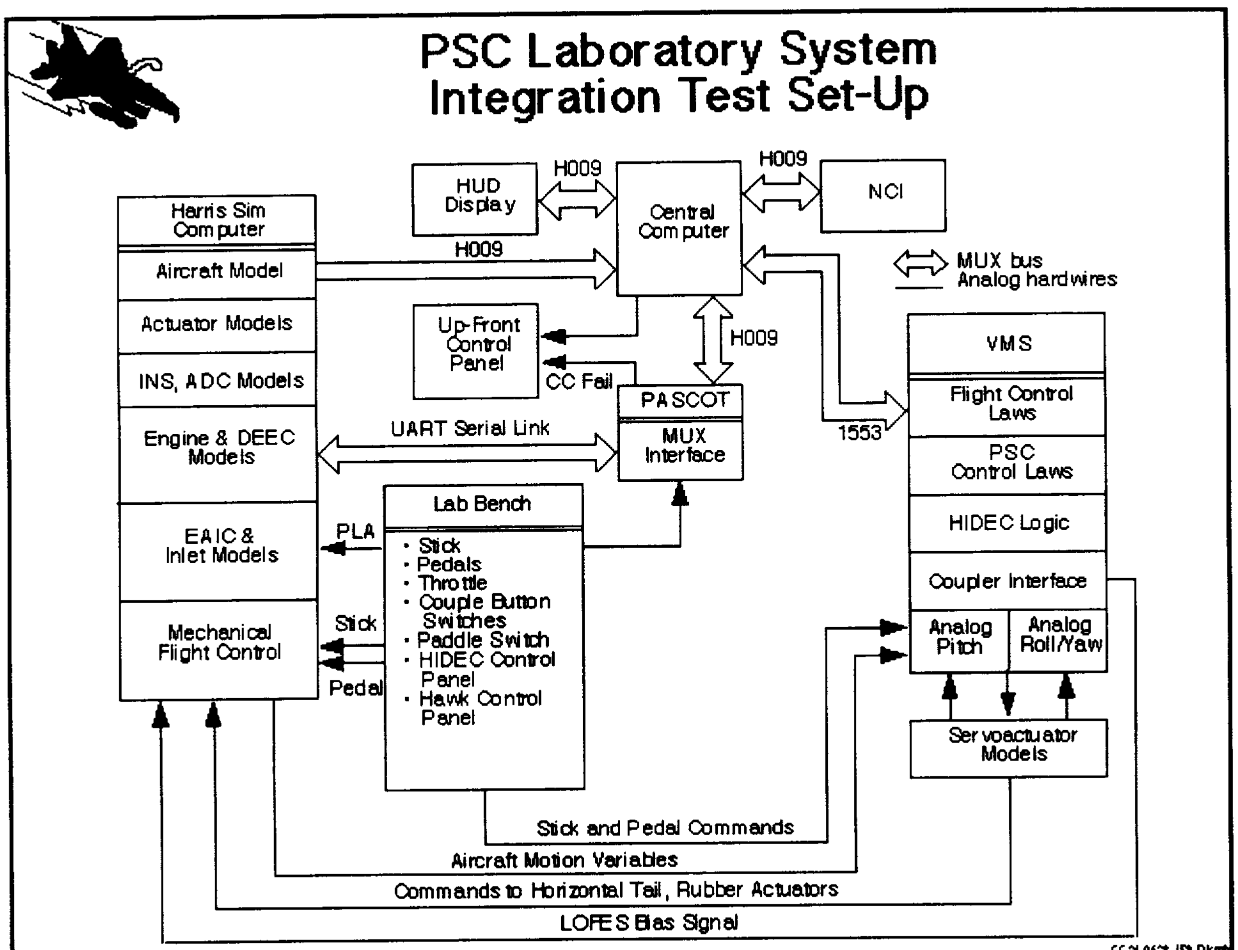
"PSC Implementation and Integration", page 25

Software Verification and Validation Process and System Integration Test



SOFTWARE VERIFICATION & VALIDATION PROCESS AND SYSTEM INTEGRATION TEST

The Software Verification and Validation Process consists of laboratory system integration tests, hardware–in–the–loop simulation and aircraft ground tests.

The System Integration Test is performed in the McDonnell Douglas Software Test Facility and Flight Control Laboratory. The purposes of the test are to validate the communication interfaces between the various flight computers, verify the system safety features, and verify proper operation of the PSC control laws.

Actual flight hardware and software are used for the CC, PASCOT, and VMSC in the System Integration Test. Software models of the engines, inlets, and nozzles reside in the Harris host computer. The DEECs and EAICs have been modeled since these units will not be available.

The Harris also contains the simulation software for cockpit displays (e.g., HUD) and an F-15 aircraft with six degree of freedom dynamics.

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Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Hardware–In–The–Loop (HILS) Simulation

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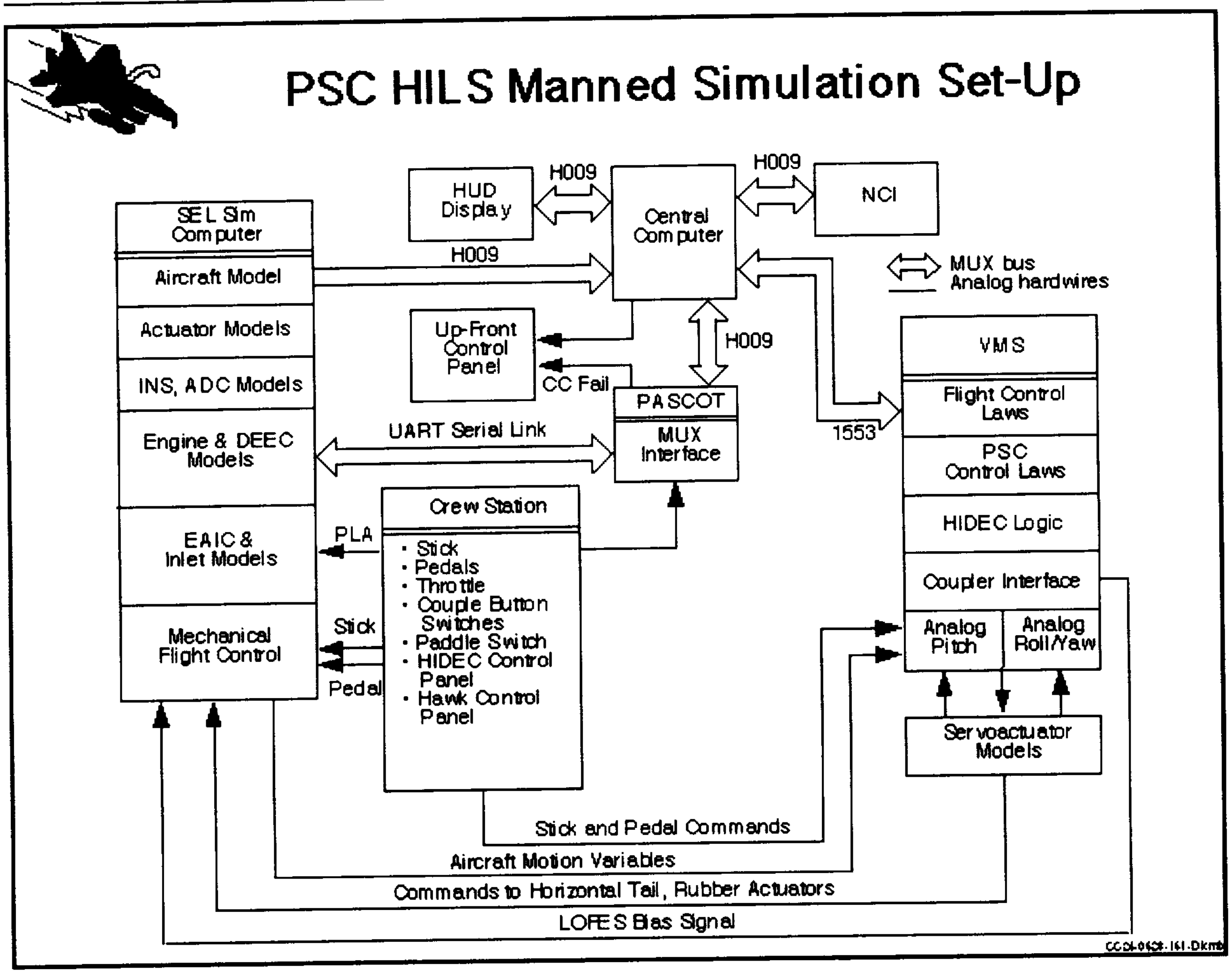

HARDWARE–IN–THE–LOOP SIMULATION (HILS)

The Hardware–in–the–Loop Simulation is conducted at the McDonnell Douglas manned simulation facility. The purposes of the test are to verify proper operation of the PSC control laws under realistic variations in altitude, Mach number and power setting throughout the flight envelope, verify that the flight control system has not been adversly affected by the additional PSC logic, verify PSC system safety features, and familiarize the pilot with the PSC control functions.

Actual flight hardware and software are used for the CC, PASCOT, and VMSC in the Hardware–in–the–Loop Simulation. The crew station is a replication of the F–15 cockpit with all the normal switches, gauges and controls. A high fidelity six degree of freedom F–15 aircraft simulation and models of the Air Data Computer, Inertial Navigation System, mechanical Flight Control System, and flight control actuators are installed in the SEL host computer. The engine/DEEC and inlet/EAIC models also reside in the SEL computer.

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Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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NASA Dryden Flight Research Center

"Minimum Fuel Mode Evaluation"

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Author: John S. Orme
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3683
Fax: (805)258-3744
Address: P.O. Box 273, MS D-2033, Edwards, CA 93523
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
Affiliation: McDonnell Douglas Corporation
Phone: (314)232-2717
Fax: (314)232-4141
Address: MC 1069020, P.O. Box 516, St. Louis, MO 63166
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Minimum Fuel Mode Predictions

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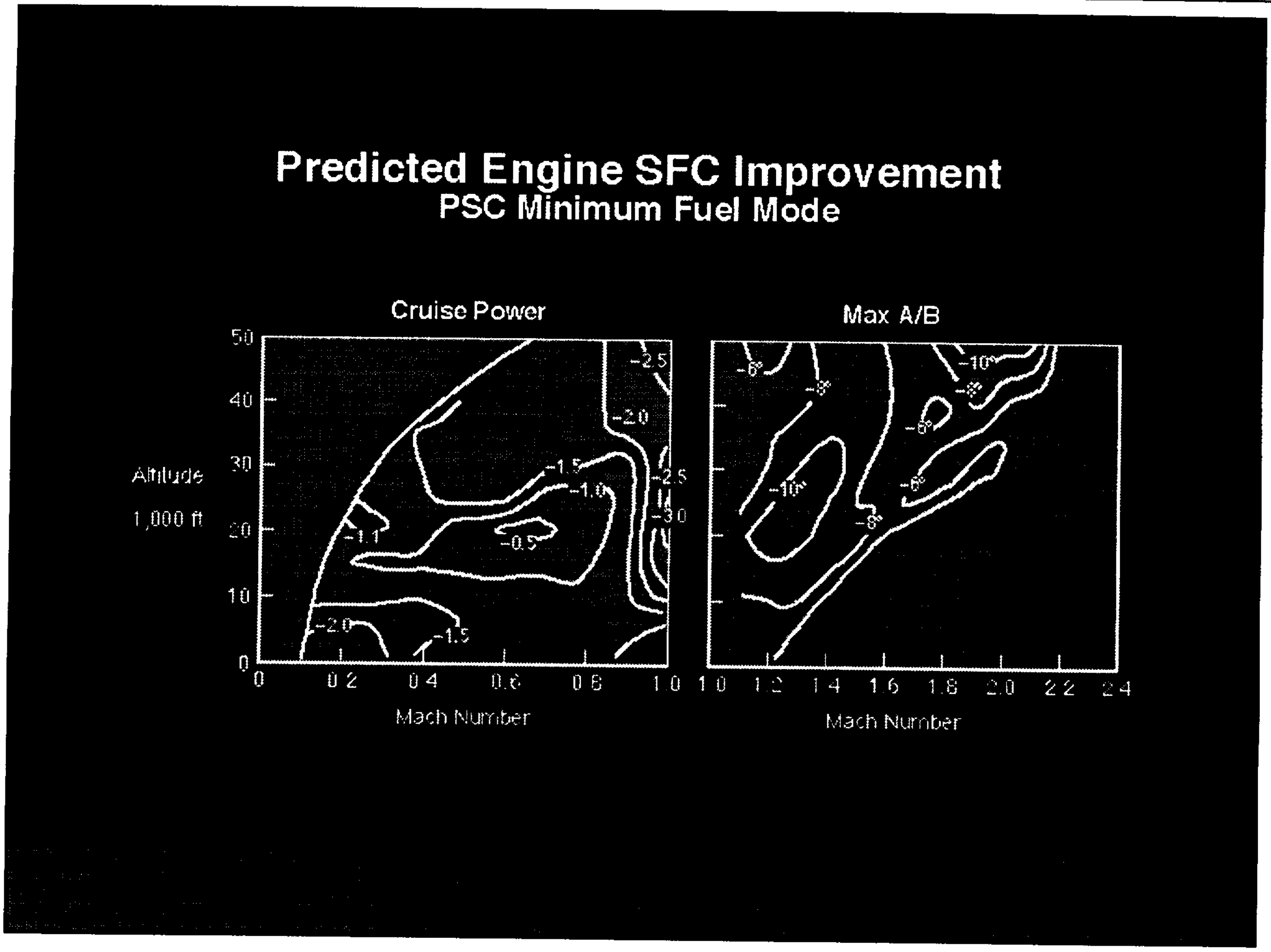

In the Minimum Fuel Mode, fuel flow is reduced while baseline engine thrust is maintained. Thrust Specific Fuel Consumption (TSFC) reductions for the Minimum Fuel Mode are predicted to range from 0.5% to 3% at cruise power settings subsonically and 6% to 10% at maximum power supersonically. These results were generated using the Dynamic Propulsion System Simulation. At part power settings, core fuel flow is reduced while baseline engine thrust is maintained. Much greater TSFC reductions are obtained at maximum power because fuel flow in the inefficient augmentor is reduced and thrust in the engine core is increased.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Minimum Fuel Mode Subsonic Analysis

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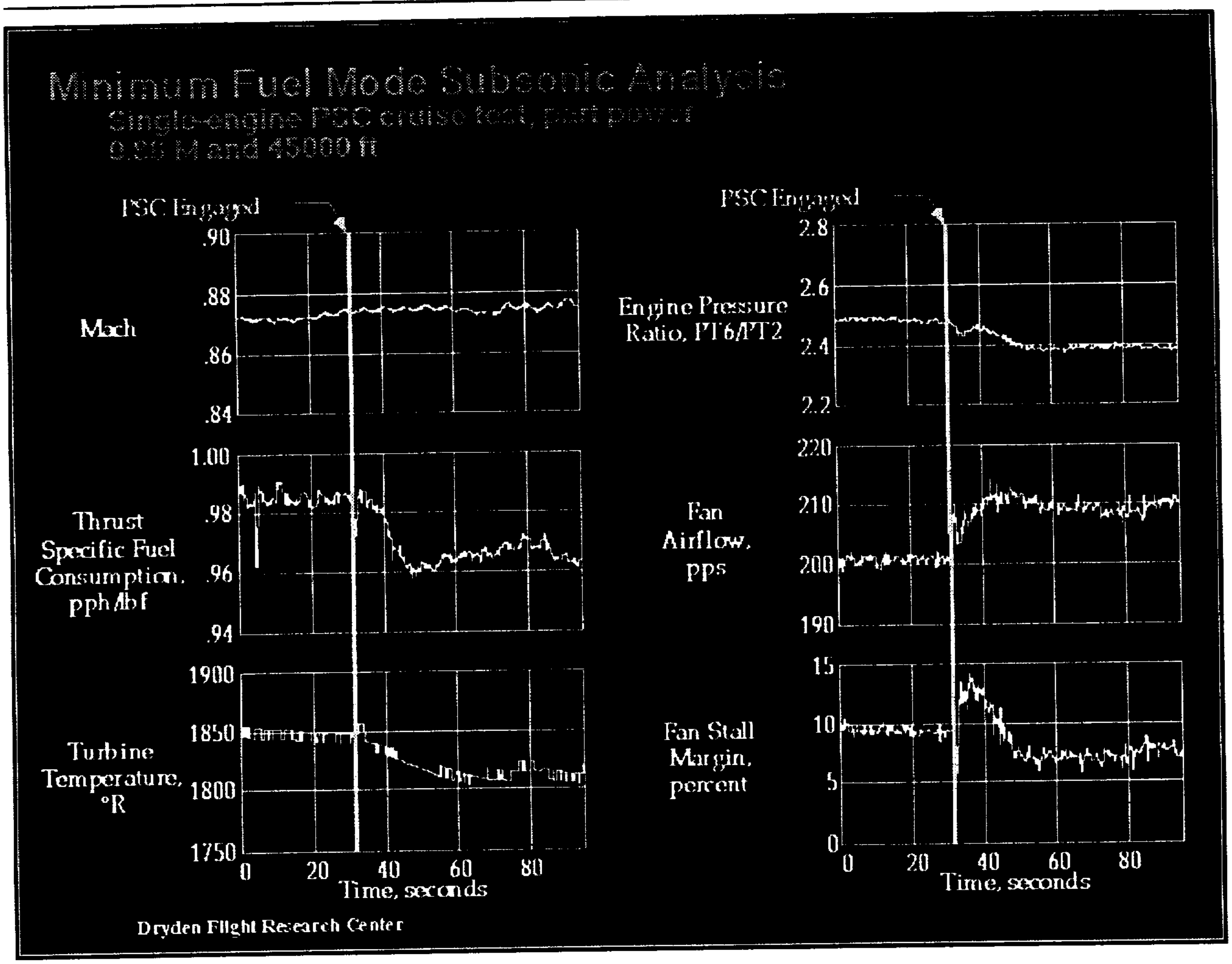

The Minimum Fuel mode is designed to minimize fuel flow while maintaining constant FNP (effectively reducing TSFC) during cruise flight conditions. The test maneuvers were at stabilized flight conditions. The aircraft test engine was allowed to stabilize at the cruise conditions before data collection initiated; data were then recorded with PSC not-engaged, then data were recorded with the PSC system engaged. The maneuvers were flown back-to-back to allow for direct comparisons by minimizing the effects of variations in the test day conditions. The Minimum Fuel mode was evaluated at subsonic and supersonic Mach numbers and focused on three altitudes: 15,000, 30,000, and 45,000 feet. Flight data were collected for part, military, partial and maximum afterburning power conditions.

Analysis for a typical Minimum Fuel mode demonstration during the single-engine subsonic test phase is shown. The cruise flight condition was Mach, 0.88, and 45,000 feet. When necessary, the pilot maintained flight condition by commanding the non-test engine throttle and stick. This was done for all single engine testing.

Time histories are presented for performance parameters (M, FTIT, and TSFC), and engine operating parameters (EPR, DEEC calculated fan airflow, and fan stall margin). The PSC system was not engaged from 0 to approximately 30 sec. The steady state value of TSFC with the PSC system disengaged was approximately 0.99. The PSC system was engaged from 30 seconds through the end of the run. The PSC algorithm held FNP to within +/−2% of the initial value after the PSC system was engaged. The steady state TSFC with the PSC system engaged was approximately 0.97, a nearly 2% improvement on fuel consumption. The fuel reduction was achieved by decreasing EPR and increasing fan airflow as well as repositioning the compressor and fan variable guide vanes. The fan stall margin was driven lower by the change in engine operating condition. This flight condition is near the optimal minimum TSFC condition for the baseline aircraft.

It is of interest to note the reduction in turbine temperature of nearly 40 deg.R. Since FTIT was not included as part of the performance index of the PSC optimization, the temperature decrease was coincidental. As will be shown later, the Minimum Fuel mode does not always produce a FTIT reduction.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Minimum Fuel Mode Supersonic Analysis

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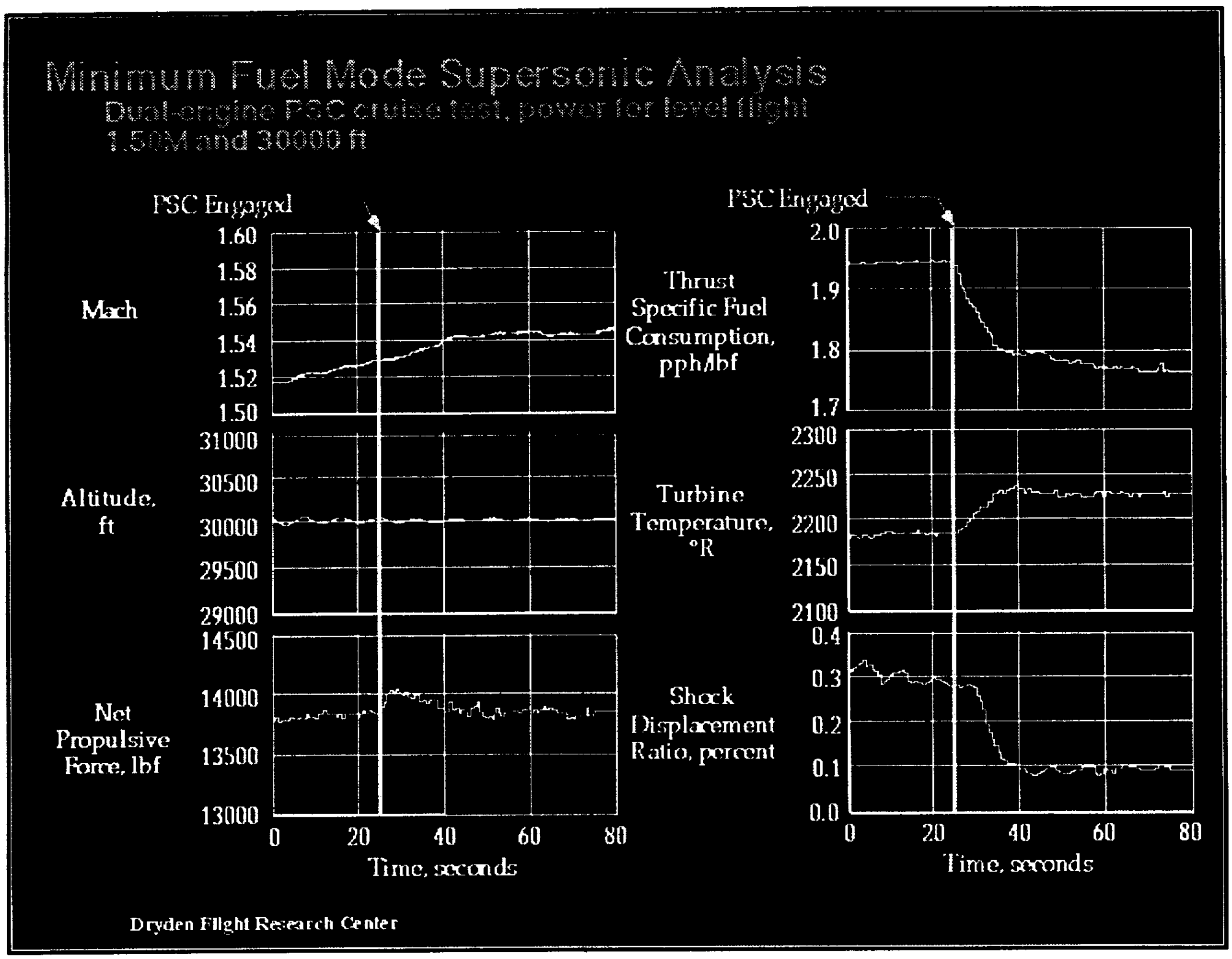

The figure shown presents time histories for a typical test of the Minimum Fuel mode demonstration during the dual–engine supersonic test phase. The cruise flight condition was Mach 1.50 at an altitude of 30,000 feet. At supersonic conditions, PSC controls the inlet ramps and afterburner fuel flow in addition to all the other engine controls. Because this was a two engine test, the pilot made no throttle inputs and Mach number was controlled indirectly by the PSC system maintaining a constant Net Propulsive Force (FNP). Any model errors in FNP will show up in a change in Mach number. During the test Mach number was unaffected by engaging PSC, lending confidence in the modeled FNP being maintained well within 2% of initial FNP.

Time histories are presented for flight condition (M and altitude), performance parameters (FNP, FTIT, and TSFC), engine operating parameters (EPR, airflow, total fuel flow, and variable vane angle) and inlet parameters (inlet ramp angles and shock displacement ratio). The PSC system was not engaged from 0 to approximately 25 sec. The steady state value of TSFC with the PSC system disengaged was approximately 1.95. The PSC system was engaged from 25 seconds through the end of the run. The steady state TSFC with the PSC system engaged was approximately 1.77, over a 9% improvement on fuel consumption.

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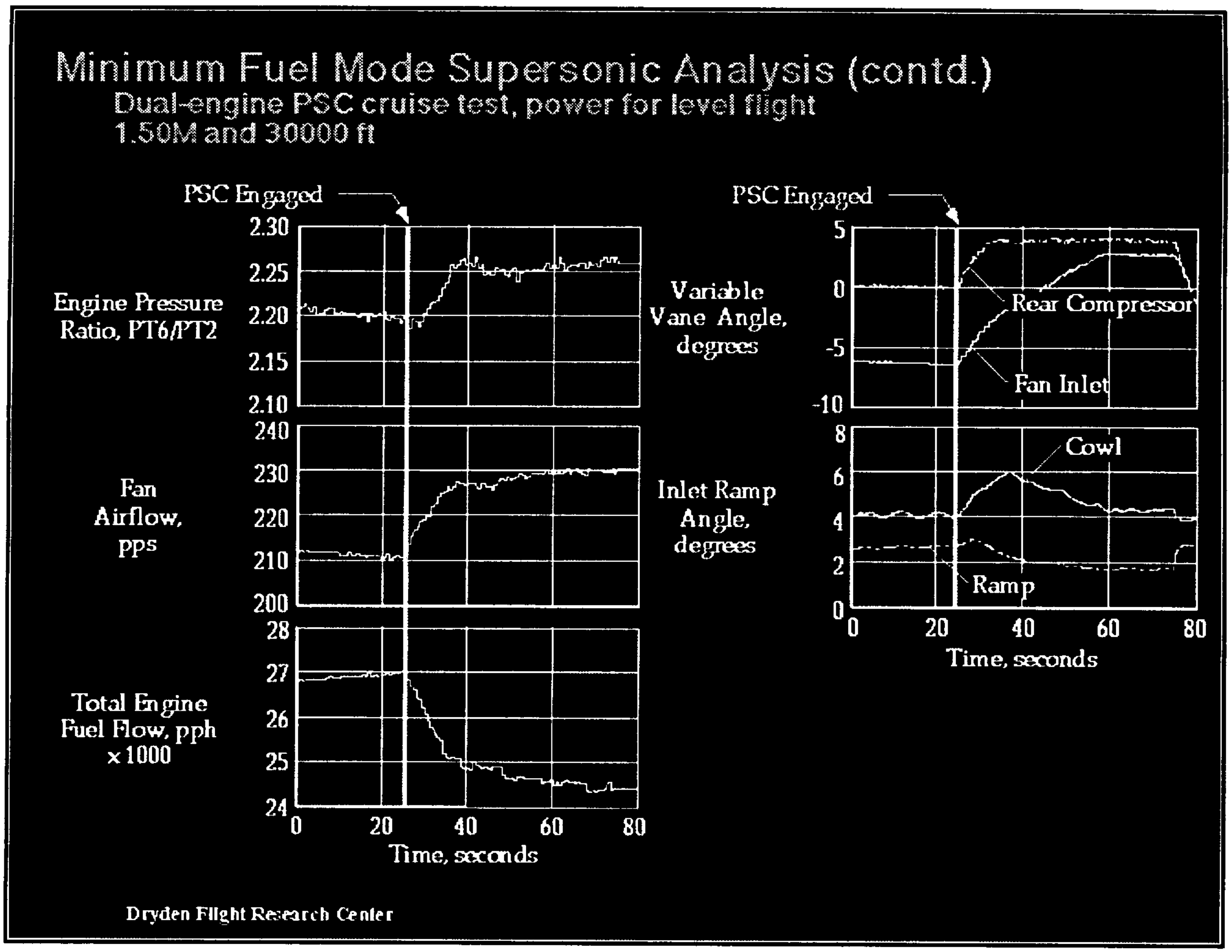
Minimum Fuel Mode Supersonic Analysis (contd.)



A fuel reduction of about 2500 pph was achieved by increasing EPR and fan airflow, while reducing afterburner fuel flow. In effect, thrust produced by the less efficient afterburner was traded for thrust produced from the engine core. The result is evident from the increase in turbine temperature, reflecting more thrust and fuel flow in the core. The shock displacement ratio, a measure of the distance the oblique shock wave stands from the inlet cowl, was driven to its lower limit of approximately 10% by the change in airflow and inlet cowl position.

Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs

Summary of Results for the Minimum Fuel Mode

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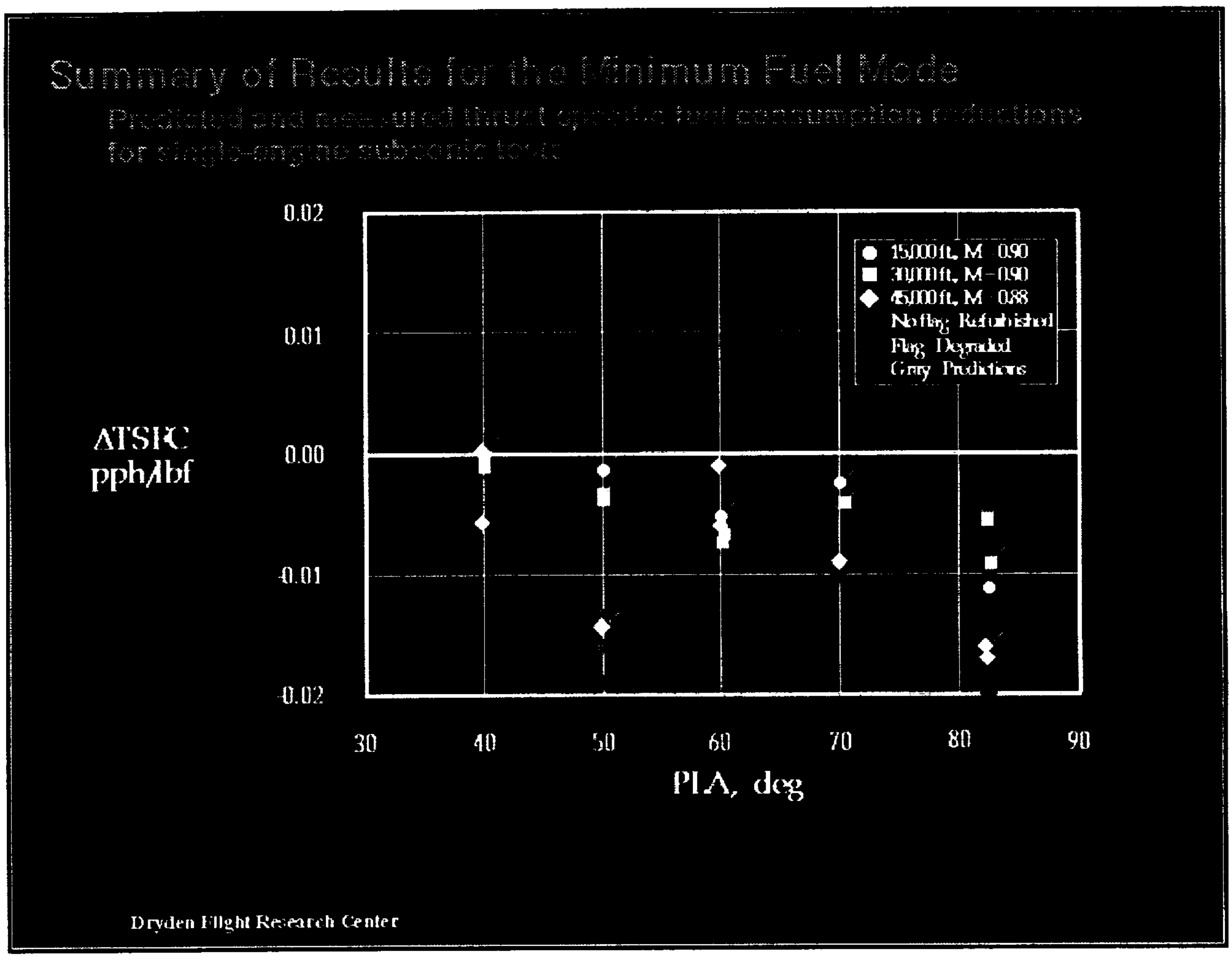

A comparison of measured and predicted TSFC savings which resulted from the PSC system during the single–engine and deteriorated engine test phase is presented above as a function of test engine power setting and flight condition. Data were collected at Mach 0.9 at an altitude of 15,000 and 30,000 feet, and at Mach 0.88 at an altitude 45,000 feet for both the refurbished and degraded engines. The TSFC savings are in general relatively small. The calculation of TSFC is especially sensitive to the parameters that define it (TSFC = total fuel flow/net propulsive force) and the relatively short run of data collected. In spite of the scatter, the TSFC savings are clearly established with savings ranging from a few tenths of a percent at the lowest power settings to one and one–half percent savings at the MIL power setting. The flight data are in good agreement with the predictions at the high PLAs but are noticeably lower than predictions at 50deg. PLA. In general, the best improvements appear to be at 45,000 feet altitude. Based on the general similarity of the data, it is clear that the PSC algorithm has the ability to adapt to the specific health state of the engine.

Although not large, the TSFC reductions could significantly reduce takeoff gross weight or increase range when considering long–range cruise segments, as might be encountered for a second–generation supersonic transport.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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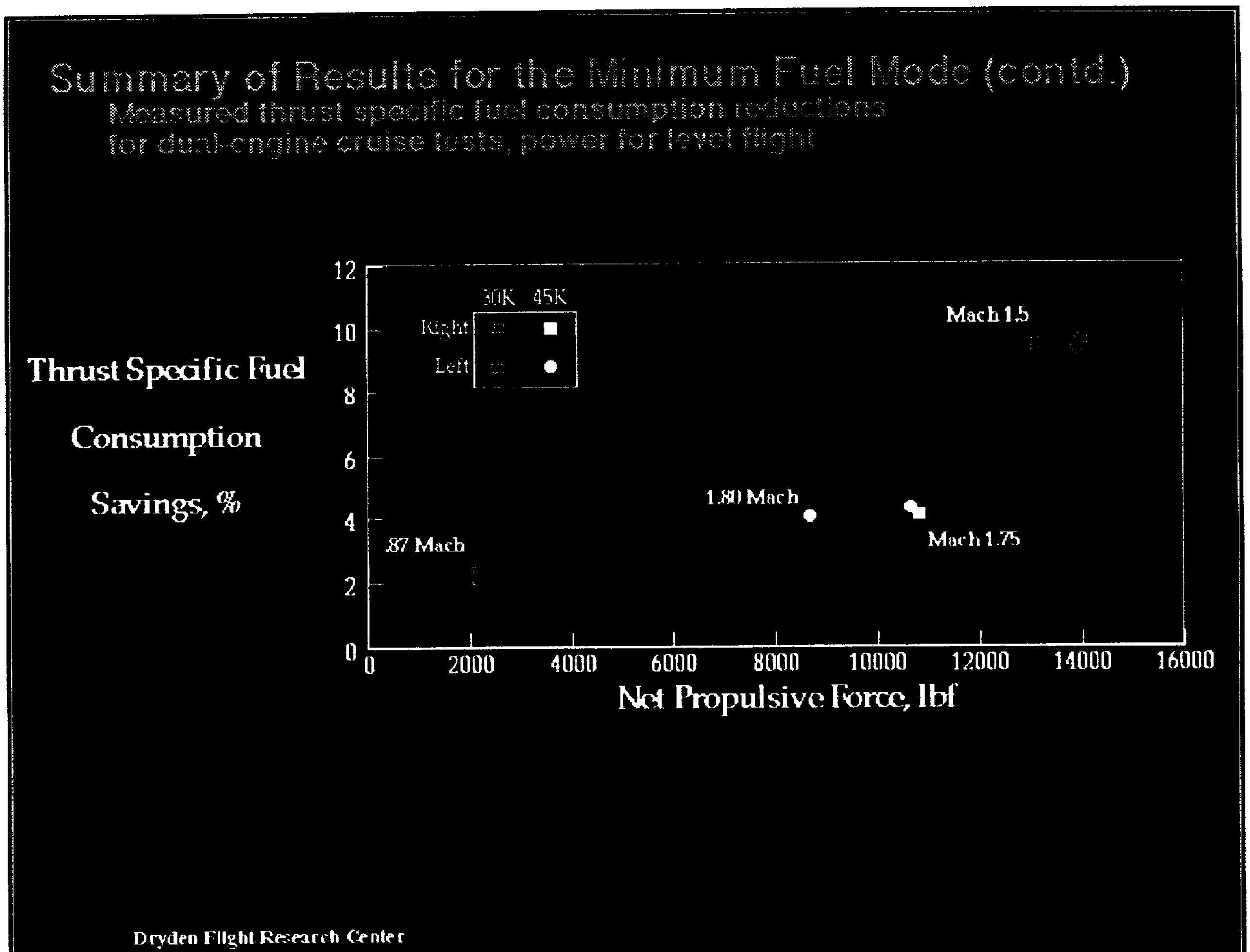

Measured TSFC savings which resulted from the PSC system during the dual–engine test phase are presented above as a function of test engine net propulsive force (FNP) and flight condition. Data were collected at altitudes of 30,000 and 45,000 feet. The TSFC savings at supersonic Mach numbers are in general much larger than at subsonic Mach numbers because of PSC trims to the afterburner (A/B). Supersonically, TSFC savings range from approximately 4% to nearly 10 %. The magnitude of these savings is phenomenal. Reductions in TSFC of this order usually come about only through significant and costly hardware reconfigurations. PSC has achieved very substantial results with computer software alone.

The results indicate more TSFC savings at higher FNP levels. At higher FNP levels the afterburner is consuming more fuel, allowing for larger afterburner fuel flow down trims. It is clear from the data that the PSC algorithm produces similar results independent of the specific engine it is applied to.

The TSFC reductions could significantly reduce takeoff gross weight or increase range when considering long–range cruise segments, as might be encountered for a second–generation supersonic transport.

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"Minimum Fan Turbine Inlet Temperature Mode Evaluation"

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Author: John S. Orme
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3683
Fax: (805)258-3744
Address: P.O. Box 273, MS D-2033, Edwards, CA 93523
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
Affiliation: McDonnell Douglas Corporation
Phone: (314)232-2717
Fax: (314)232-4141
Address: MC 1069020, P.O. Box 516, St. Louis, MO 63166
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Minimum Fan Turbine Inlet Temperature Mode Predictions

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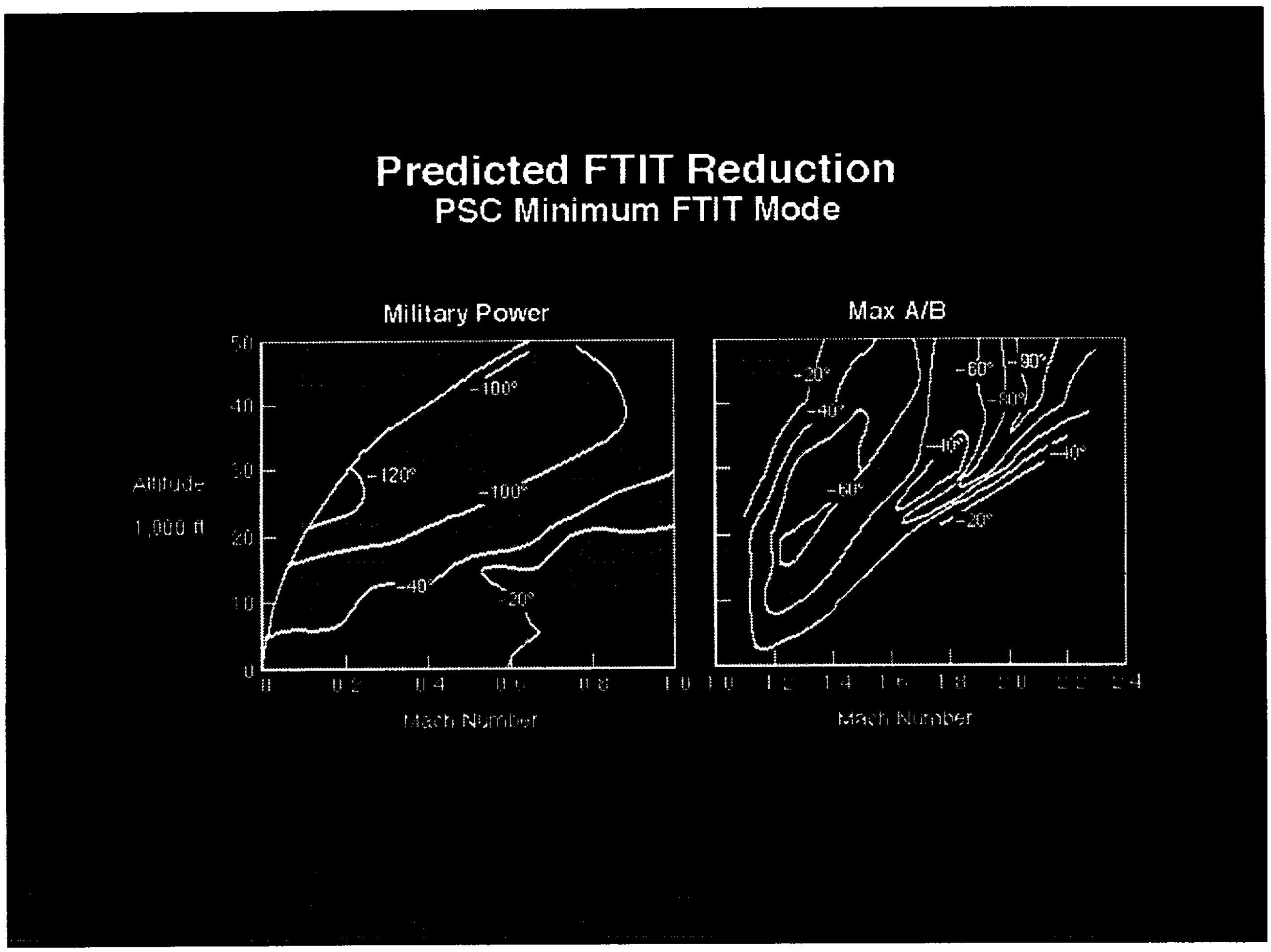

In the Minimum Fan Turbine Inlet Temperature (FTIT) Mode, FTIT is reduced while baseline engine thrust is maintained. FTIT reductions of up to 120 degrees Fahrenheit at military and up to 90 degrees at maximum power are predicted for the Minimum FTIT Mode. These reductions in FTIT translate into substantial increases in engine life.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Estimated Extended Engine Life

PSC Extended Engine Life Mode

Typical Life Improvements

Airfoil	Oxidation Erosion	Stress Rupture
1st Vane	16%	n/a
1st Blade	16%	46%
2nd Vane	27%	n/a
2nd Blade	18%	51%

16% Increase in Life

P&W estimated the increase in engine life due to the reduction in FTIT. They did this for a composite F-15 mission in which the engine was operated over 4,000 TAC cycles. The result was a 16% increase in engine hot part life. This improvement was achieved by reduced oxidation/erosion to the high pressure turbine vanes and blades.

Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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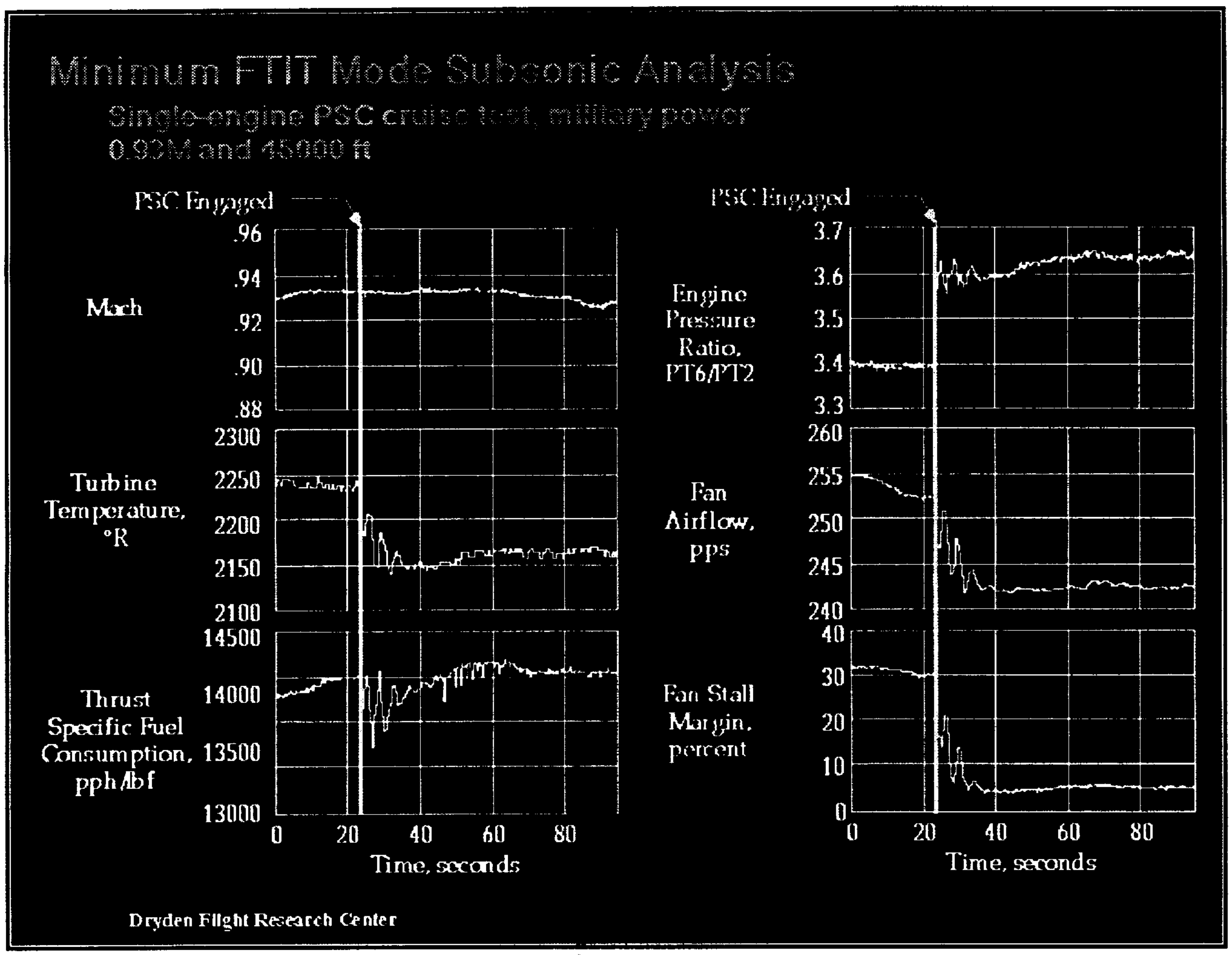
Minimum Fan Turbine Inlet Temperature Mode Subsonic Analysis



The Minimum FTIT mode is designed to minimize fan turbine inlet temperature while maintaining constant FNP (effectively extending engine life) during cruise flight conditions. The maneuvers flown consisted of flying at stabilized flight conditions. The aircraft test engine was allowed to stabilize at the cruise conditions before data collection initiated; data were then recorded with PSC not–engaged, then data were recorded with the PSC system engaged. The maneuvers were flown back–to–back to allow for direct comparisons by minimizing the effects of variations in the test day conditions. The Minimum FTIT mode was evaluated at subsonic and supersonic Mach numbers and focused on three altitudes: 15,000, 30,000, and 45,000 feet. Flight data were collected for part, military, partial and maximum afterburning power conditions.

Analysis for a typical Minimum FTIT mode demonstration during a single–engine subsonic test is presented. The cruise flight condition was Mach 0.93 and altitude of 45,000 feet. When necessary, the pilot maintained flight condition by commanding the non–test engine throttle and stick. This was done for all single engine testing.

Time histories are presented for performance parameters (M, FTIT, and TSFC) and engine operating parameters (engine pressure ratio(EPR), model estimated fan airflow, and fan stall margin). The PSC system was not engaged from 0 to approximately 25 sec. The steady state value of FTIT with the PSC system disengaged was approximately 2237deg.R. The PSC system was engaged from 25 seconds through the end of the run. The PSC algorithm held FNP to within +/−2% of the initial value after the PSC system was engaged. The steady state FTIT with the PSC system engaged was approximately 2166deg.R, over a 70deg.R temperature reduction. The FTIT reduction was achieved by increasing EPR and decreasing fan airflow as well as repositioning the compressor and fan variable guide vanes. The fan stall margin was driven to the lower limit of 4% by the change in engine operating condition.

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Author: John S. Orme
e−mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e−mail: m236054%etd.decnet@mdcgwy.mdc.com

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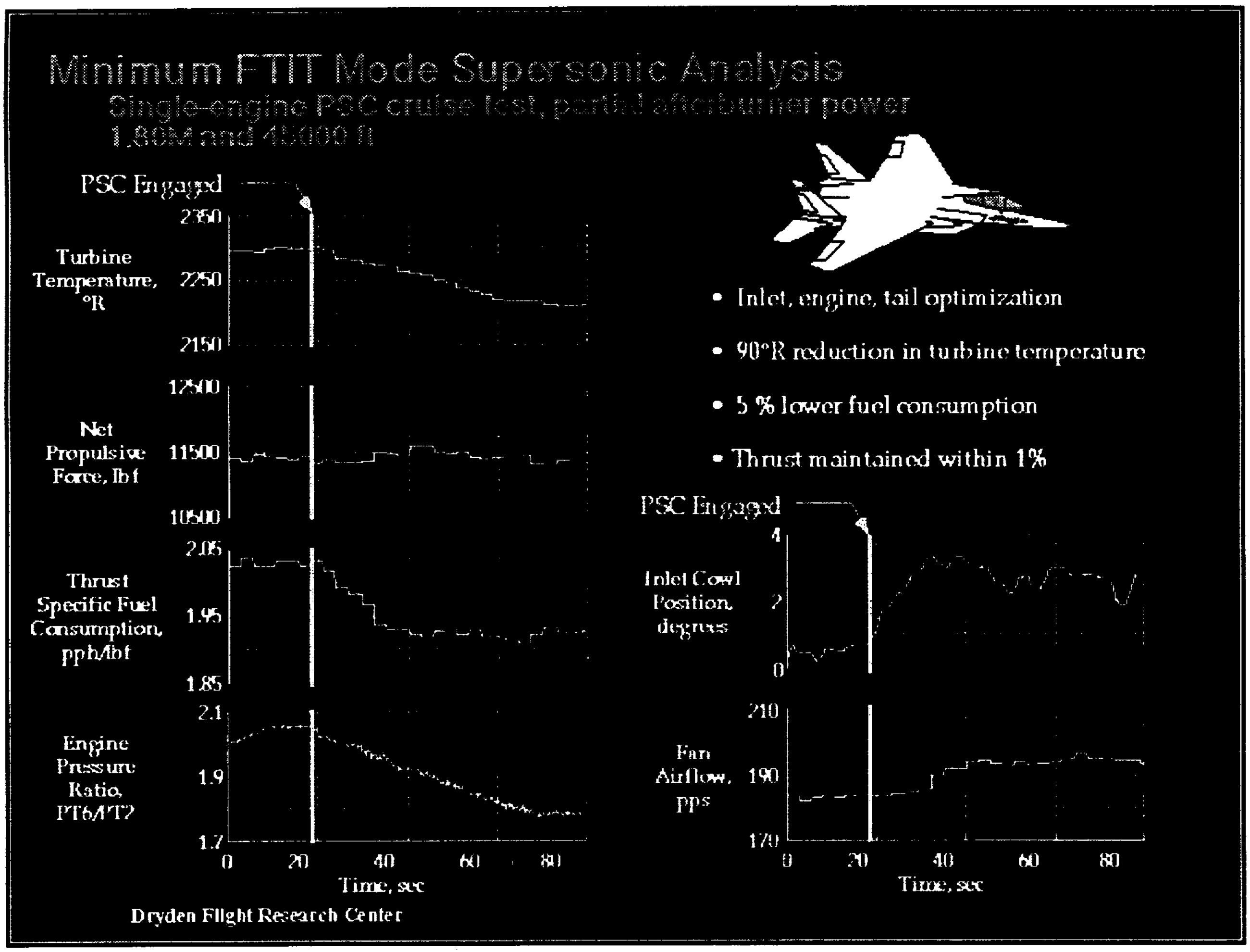

The above figure presents time histories and an illustration of net propulsive force contributions for a typical test of the Minimum FTIT mode for supersonic conditions. The cruise flight condition was Mach 1.80 at an altitude of 45000 ft with a partial afterburner power setting.

The most effective way of reducing turbine temperature is by reducing core fuel flow. If afterburner fuel flow was included as a control for the Minimum FTIT mode, as it is for the Minimum Fuel mode, then core flow would be cut back and afterburner flow increased. The optimum minimized FTIT in this case would result from producing as much thrust as possible from the very fuel–inefficient afterburner. The excessive amount of fuel burned in this "optimum" engine configuration would far outweigh any extended engine life benefits from reducing turbine temperature. Thus, afterburner fuel flow is not included as a control for the Minimum FTIT mode. Another method for reducing core fuel flow is to lessen the thrust required for flight. By reconfiguring the integrated aircraft and propulsion system, decreases in gross drag will reduce the required net thrust while still maintaining FNP.

Time histories are given for the engine operating parameters (EPR and airflow), inlet cowl angle, and performance parameters (TSFC, FNP, and FTIT). After approximately 20 seconds of steady–state trim cruise condition, PSC was engaged. After converging, steady–state results are reflected from approximately 70 seconds until the end of the maneuver. With the use of PSC, FTIT was reduced by 90deg.R, and FNP was maintained to within 1 percent of baseline engine operation. In addition, TSFC was reduced by approximately 5 percent. EPR decreased from 2.05 to 1.80 and airflow was up trimmed by 11 pps to produce the FTIT and TSFC savings.

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Author: John S. Orme
e–mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

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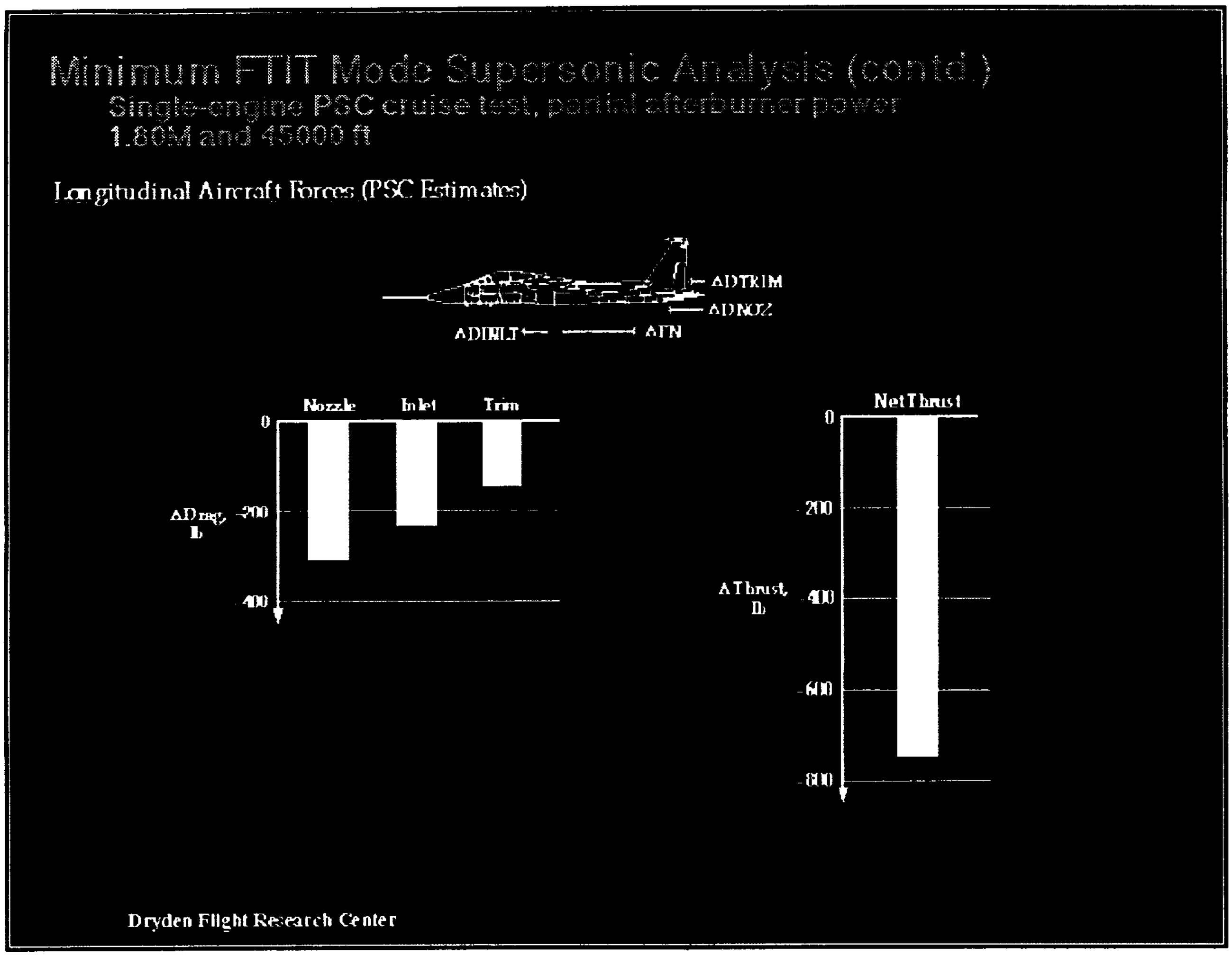

According to the PSC models, a combination of drag reductions reduced the required amount of net thrust as seen in the above longitudinal aircraft forces diagram. All three drag components of FNP were decreased and together produced over 670 lbs of drag savings. Together, DINLT and DTRIM, the two drag terms most effected by inlet optimization, indicate that the inlet and stabilator provided an approximately 370 lbs drag reduction.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs

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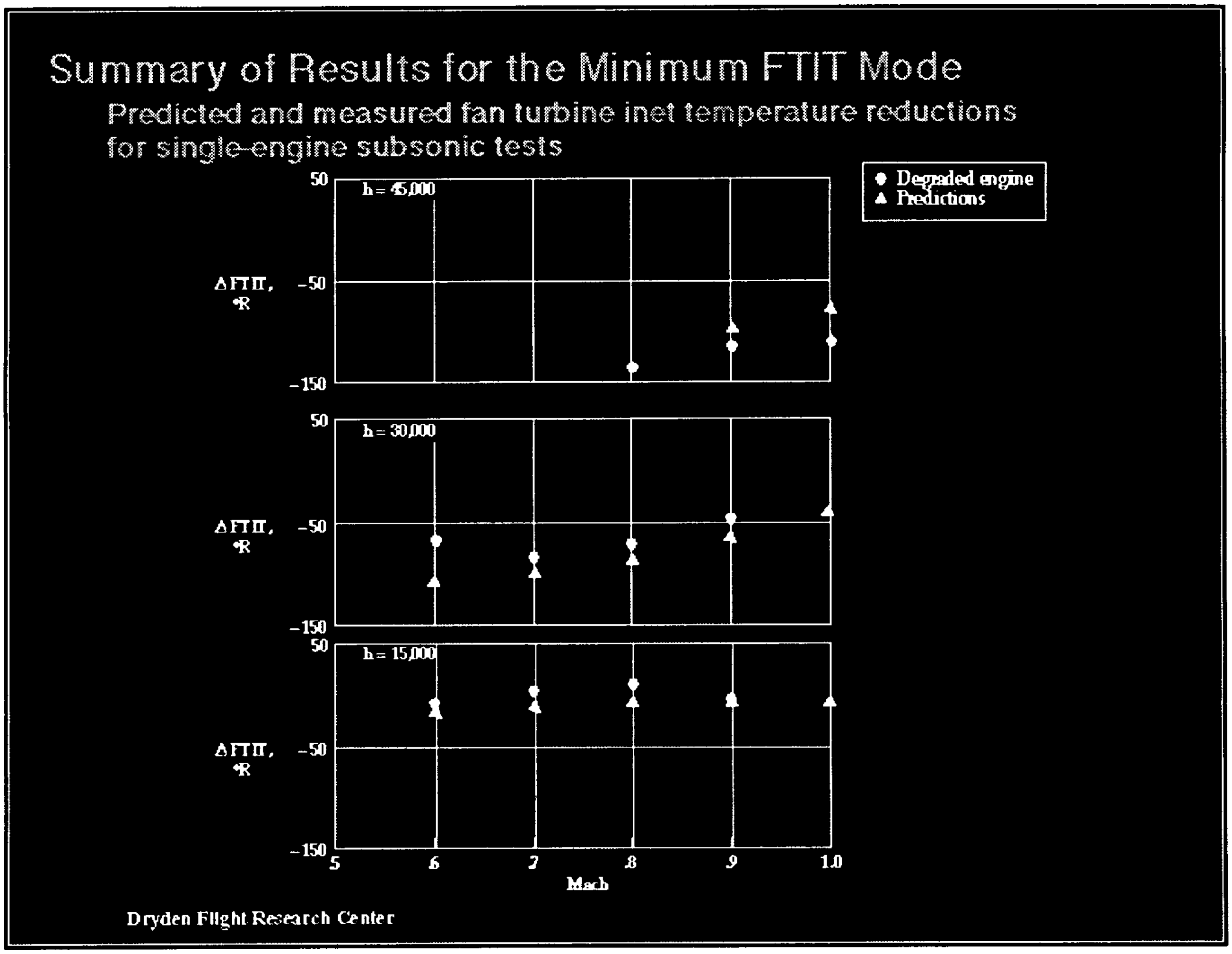

A comparison of measured and predicted FTIT reductions as a result of the PSC system is shown for the engine at a MIL power setting. Data were collected at 15,000, 30,000, and 45,000 feet altitudes. The FTIT reductions are large at 45,000 feet ranging from in excess of 100deg.R at the lower Mach numbers and diminishing slightly as transonic Mach numbers are approached. The measured and predicted FTIT reductions agree well for all flight conditions.

To put these temperature reductions in perspective, every 70deg.R reduction will double turbine life caused by temperature effects. These benefits are very important especially at high power settings where the engine operates near its temperature limit. At 30,000 feet, the FTIT reductions range from 45deg.R to 80deg.R at the higher subsonic Mach numbers. Although less than those at 45,000 feet, these reductions are still significant in terms extending engine life. The FTIT reductions at 15,000 feet are at best small, and in some cases small increases in temperatures were observed. These small temperature reductions at lower altitudes are consistent with predictions. The variations in the data at 15,000 feet also reflect the resolution and accuracy of the closed–loop PSC algorithm throughout the flight envelope.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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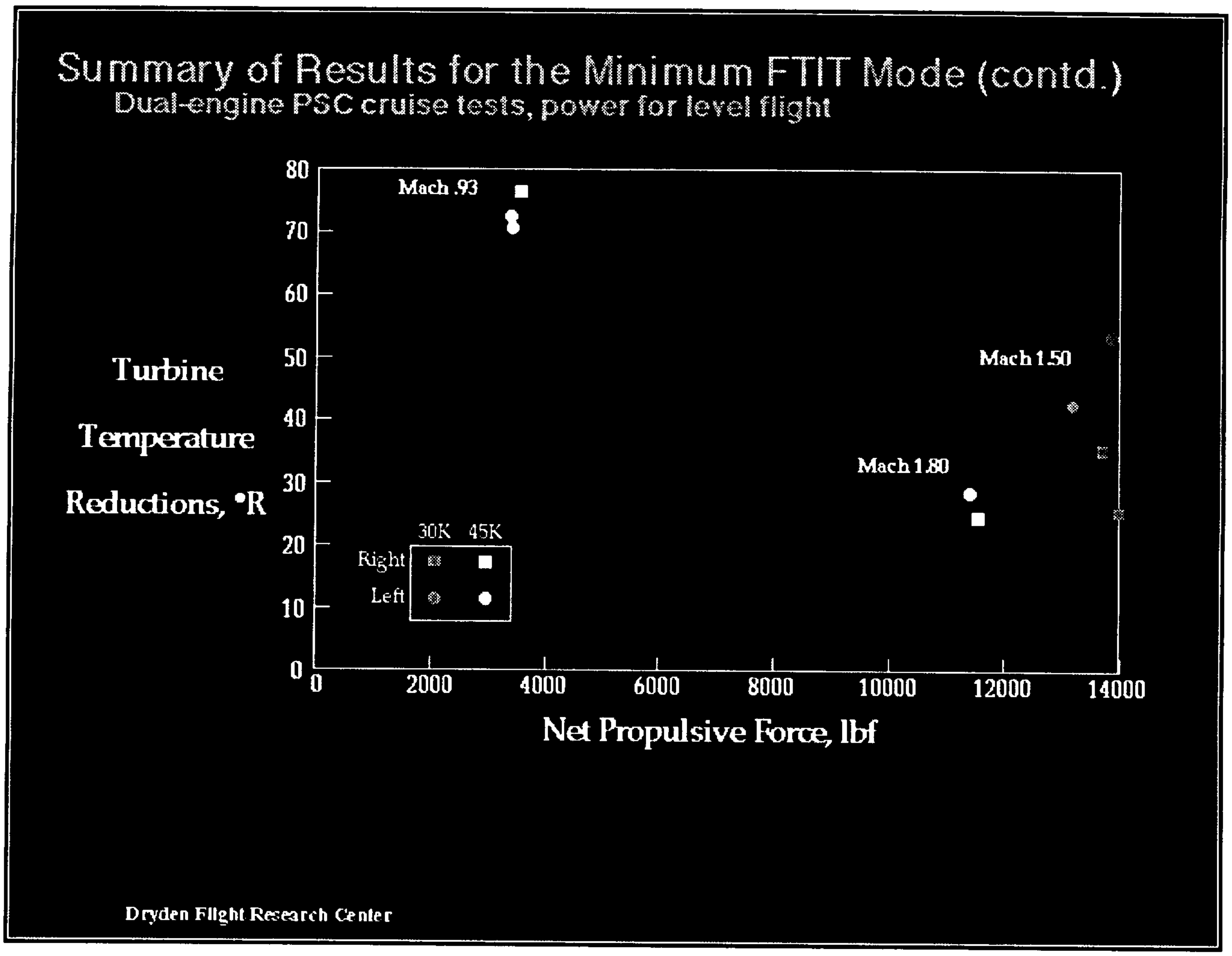

Measured reductions in turbine temperature which resulted from the application of the PSC Minimum FTIT mode during the dual–engine test phase is presented above as a function of net propulsive force and flight condition. Data were collected at altitudes of 30,000 and 45,000 feet at military and partial afterburning power settings. The FTIT reductions for the supersonic tests are less than at subsonic Mach numbers because of the increased modeling and control complexity. In addition, the propulsion system was designed to be optimized at the mid supersonic Mach number range.

Subsonically at military power, FTIT reductions were above 70deg.R for either the left or right engines, and repeatable for the right engine. At partial afterburner and supersonic conditions, the level of FTIT reductions were at least 25deg.R and as much as 55deg.R. Considering that the turbine operates at or very near its temperature limit at these high power settings, these seemingly small temperature reductions may significantly lengthen the life of the turbine.

In general, the Minimum FTIT mode has performed well, demonstrating significant temperature reductions at military and partial afterburner power. Decreases of over 100deg.R at cruise flight conditions were identified. Temperature reductions of this magnitude could significantly extend turbine life and reduce replacement costs.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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"Maximum Thrust Mode Evaluation"

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Author: John S. Orme
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3683
Fax: (805)258-3744
Address: P.O. Box 273, MS D-2033, Edwards, CA 93523
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
Affiliation: McDonnell Douglas Corporation
Phone: (314)232-2717
Fax: (314)232-4141
Address: MC 1069020, P.O. Box 516, St. Louis, MO 63166
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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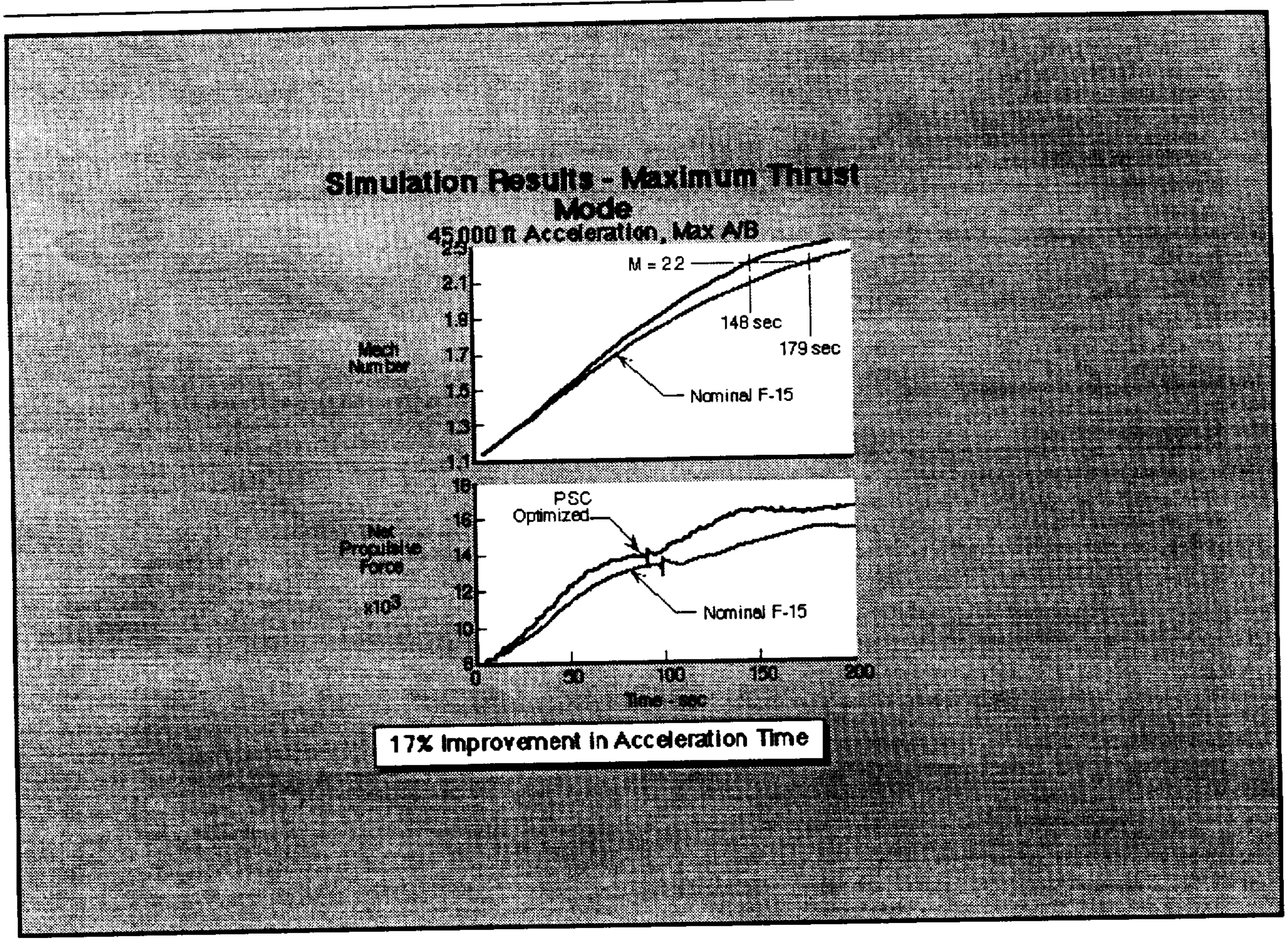
Prediction of a Maximum Thrust Mode Acceleration



In the Maximum Thrust Mode, net propulsive force is increased resulting in greater aircraft excess thrust, allowing faster accelerations or greater climb rates. A maximum power acceleration was simulated with the Six Degree of Freedom Simulation. An aircraft with PSC Maximum Thrust Mode engaged accelerates from 1.1 to 2.2 Mach number in 148 seconds where as a baseline aircraft takes 179 seconds. This is a 17% improvement in acceleration time.

Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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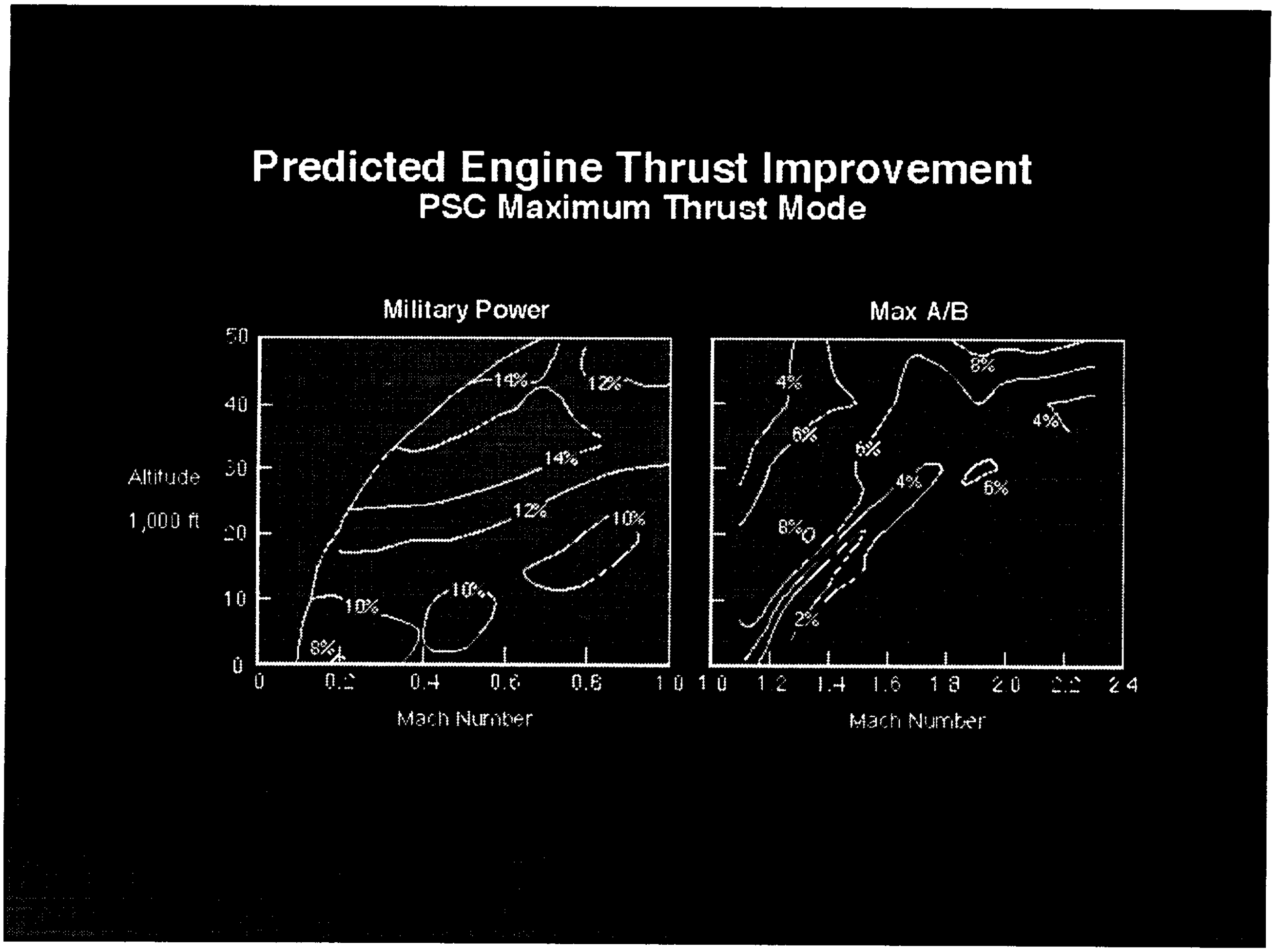
Maximum Thrust Mode Predictions



Thrust improvements of up to 14% at military power and up to 8% at maximum power are predicted for the Maximum Thrust Mode.

Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Maximum Thrust Mode Analysis

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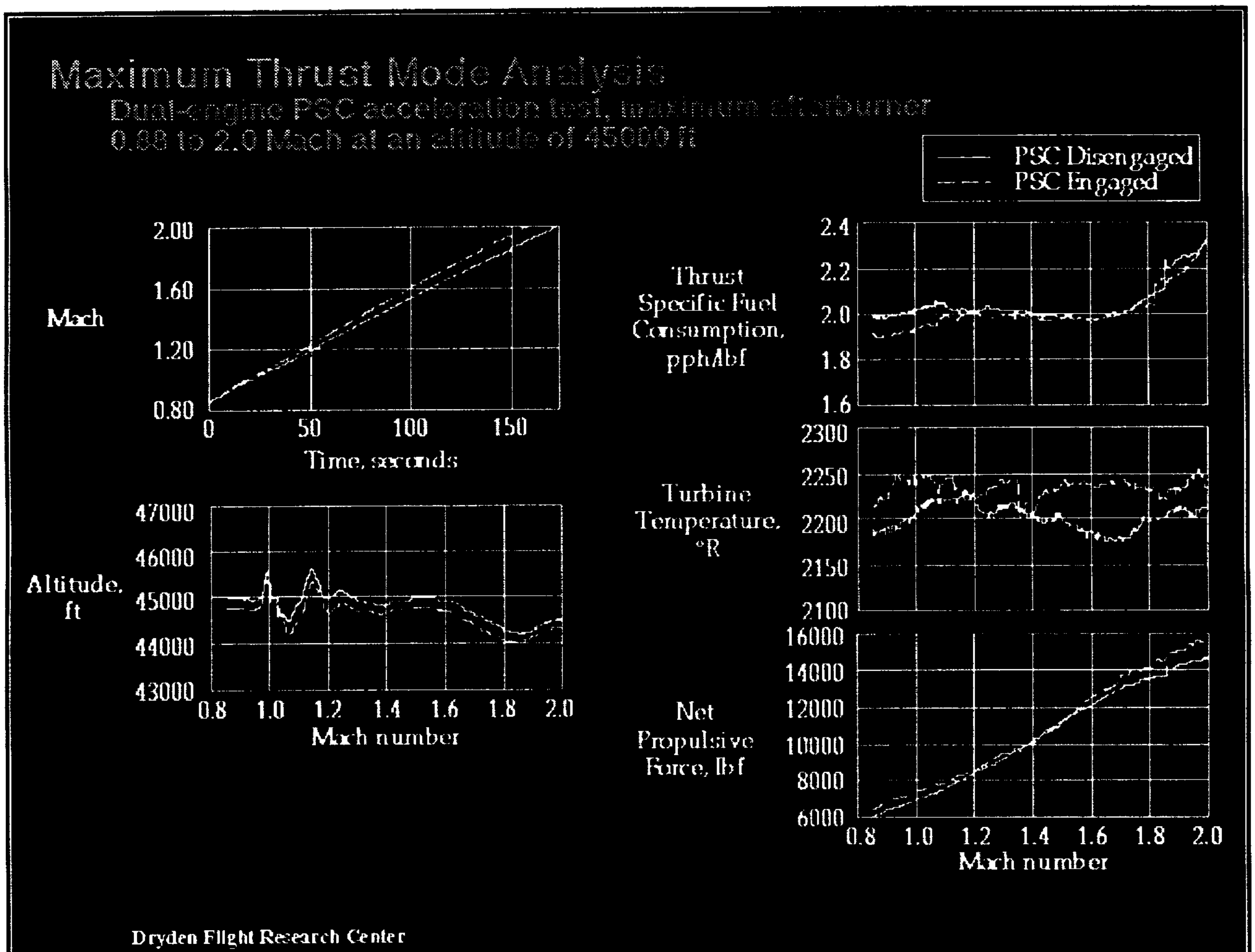

The Maximum Thrust mode is designed to maximize Net Propulsive Force, FNP, during accelerations. The test maneuvers were conducted by stabilizing both engines at a given power setting prior to beginning an acceleration. Usually, back to back accelerations were performed through the same air mass with an without the PSC system engaged. This helped to reduce the effect of atmospheric differences on performance when making comparisons between the two runs. In addition, results from comparisons of time to accelerate between separate accelerations were standardized for differences in weight. the Maximum Thrust mode was evaluated at subsonic and supersonic Mach numbers and focused on three altitudes: 15,000, 30,000, and 45,000 feet. Flight data were collected for military rated and maximum afterburning power settings.

Analysis is shown from a single test point demonstration of the PSC Maximum Thrust Mode during the dual–engine test phase. Comparison data of two accelerations performed at 45000 feet from Mach 0.9 to Mach 2.0 with and without use of the PSC Maximum Thrust Mode are plotted. The runs were completed back to back and through the same air mass to minimize the effects of outside influences on the experiment, such as ambient temperature fluctuations. To further produce a valid comparison, the acceleration times were corrected for weight and temperature differences. Because this was a two engine test, the pilot made no throttle inputs and Mach number was controlled indirectly by the PSC system maximizing Net Propulsive Force (FNP).

Time histories are presented for flight condition (M and altitude), and the left-side propulsion system performance parameters (FNP, FTIT, and TSFC), engine operating parameters (EPR, airflow, variable vane angle, and fan stall margin) and inlet parameters (inlet ramp angles and shock displacement ratio). The right-side propulsion system is characterized by similar results. With the PSC system engaged, the acceleration time was reduced by 14.8 sec or 8.5 percent from the baseline acceleration time.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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Maximum Thrust Mode Analysis (contd.)

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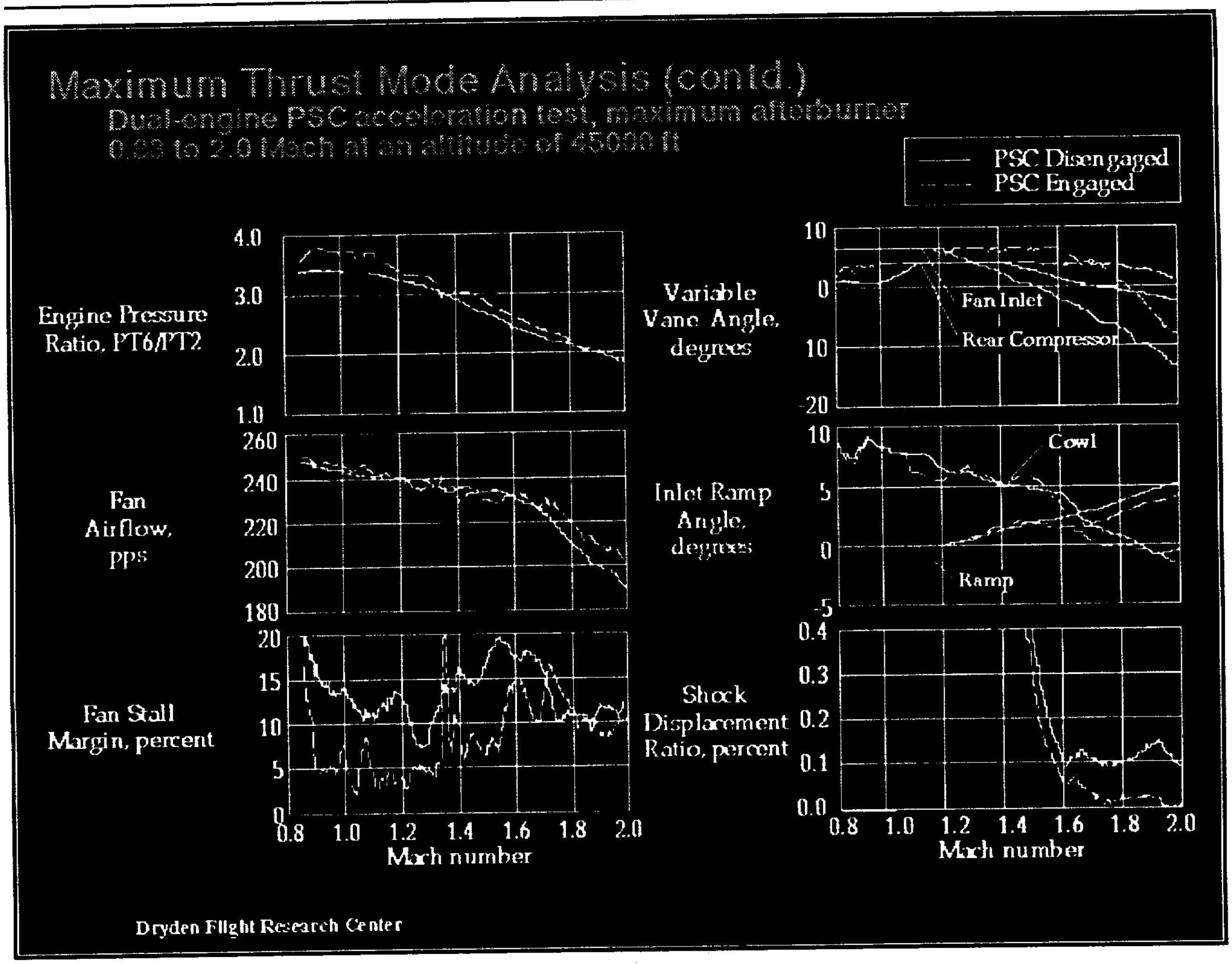

The manner in which the engines are optimized over the Mach 0.9 to Mach 2.0 range is typical for the maximum thrust mode. For the subsonic and supersonic region below Mach 1.80, the EPR trims contribute the most to increasing FNP; and above Mach 1.80, airflow uptrims command the most FNP increase. The variable vane angles of the fan and compressor are also trimmed to increase compression efficiency. Subsonically, the engine is driven to the minimum allowable fan stall margin. Supersonically, the inlets are driven to the maximum allowable airflow. In addition, PSC trims caused the FTIT to operate at its maximum limit for the entire acceleration.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

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Summary of Results for the Maximum Thrust Mode

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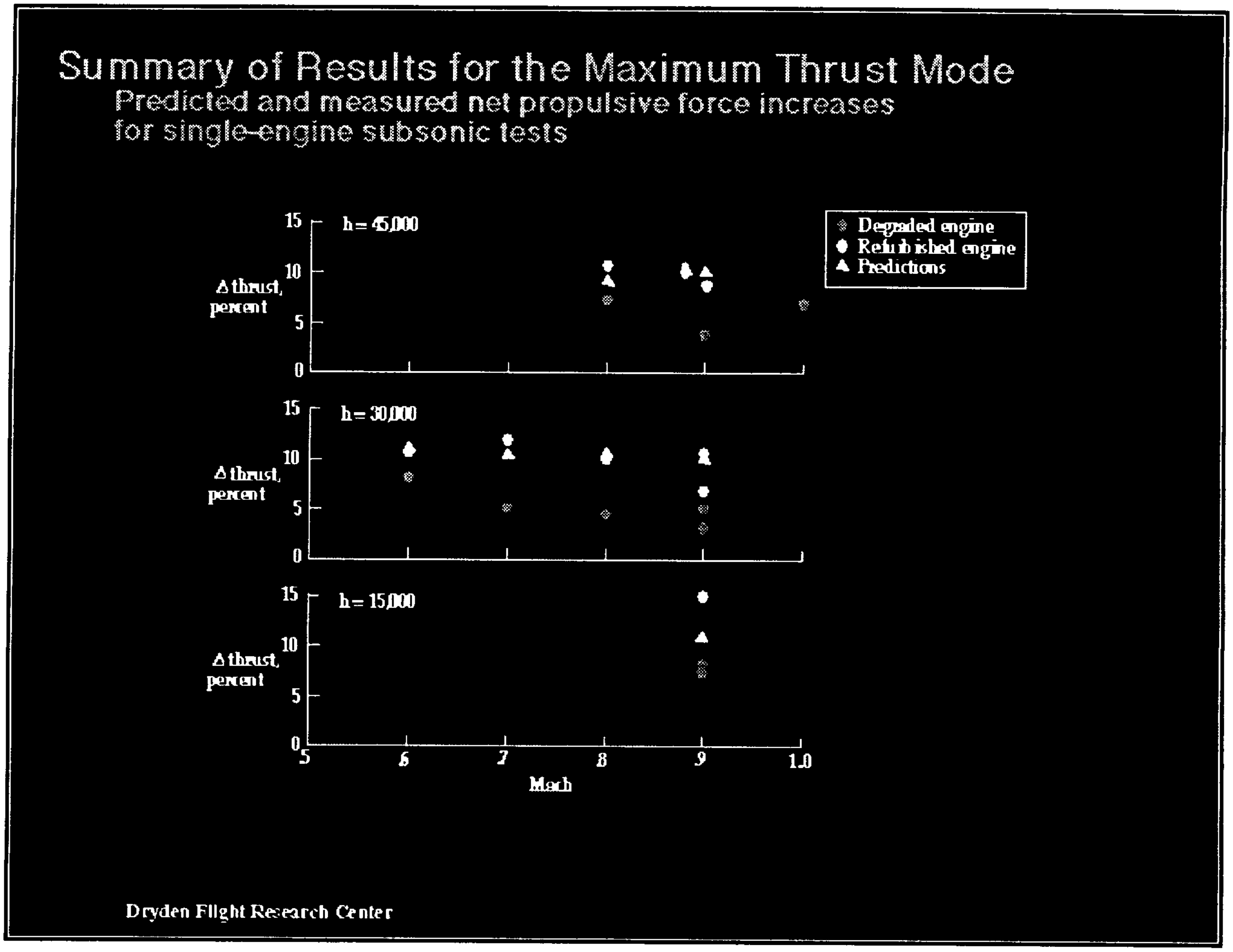

A comparison of measured and predicted thrust increases produced by the PSC system during single–engine subsonic testing is presented above for the test engine at military power setting as a function of flight condition. Data were collected at 15,000, 30,000, and 45,000 feet altitudes for the refurbished and degraded engines. For the refurbished engine at 30,000 ft, thrust increases average approximately 11 percent as Mach increases from 0.60 to 0.90 and compare very well with predictions. The degraded engine has significantly less thrust increase capability and diminishes with increasing Mach number. This level of thrust increases requires the engine to operate hotter. For the refurbished engine, FTIT in general is below the engine operating limit, with the PSC system engaged or disengaged. However, the degraded engine is operating hotter over the flight envelope to achieve a defined thrust level. In particular, the FTIT limit is generally restricting the amount of additional thrust increase.

The 45,000 ft thrust increase levels and trends are similar to those at 30,000 ft. At the 45,000 ft flight condition not as much data were collected since the aircraft cannot stabilize at the lower Mach numbers. The data are quite limited at 15,000 ft; however the thrust increases for the degraded engine are low because of the engine temperature limit being reached. At Mach 0.90, the refurbished engine has a thrust improvement of 15 percent, while the degraded engine has approximately half that amount. Overall, the maximum thrust mode performed well at military power and subsonic regime. To completely characterize the benefits of the PSC algorithm for the maximum thrust mode, two-engine performance is of importance since net aircraft performance is a primary interest.

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Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

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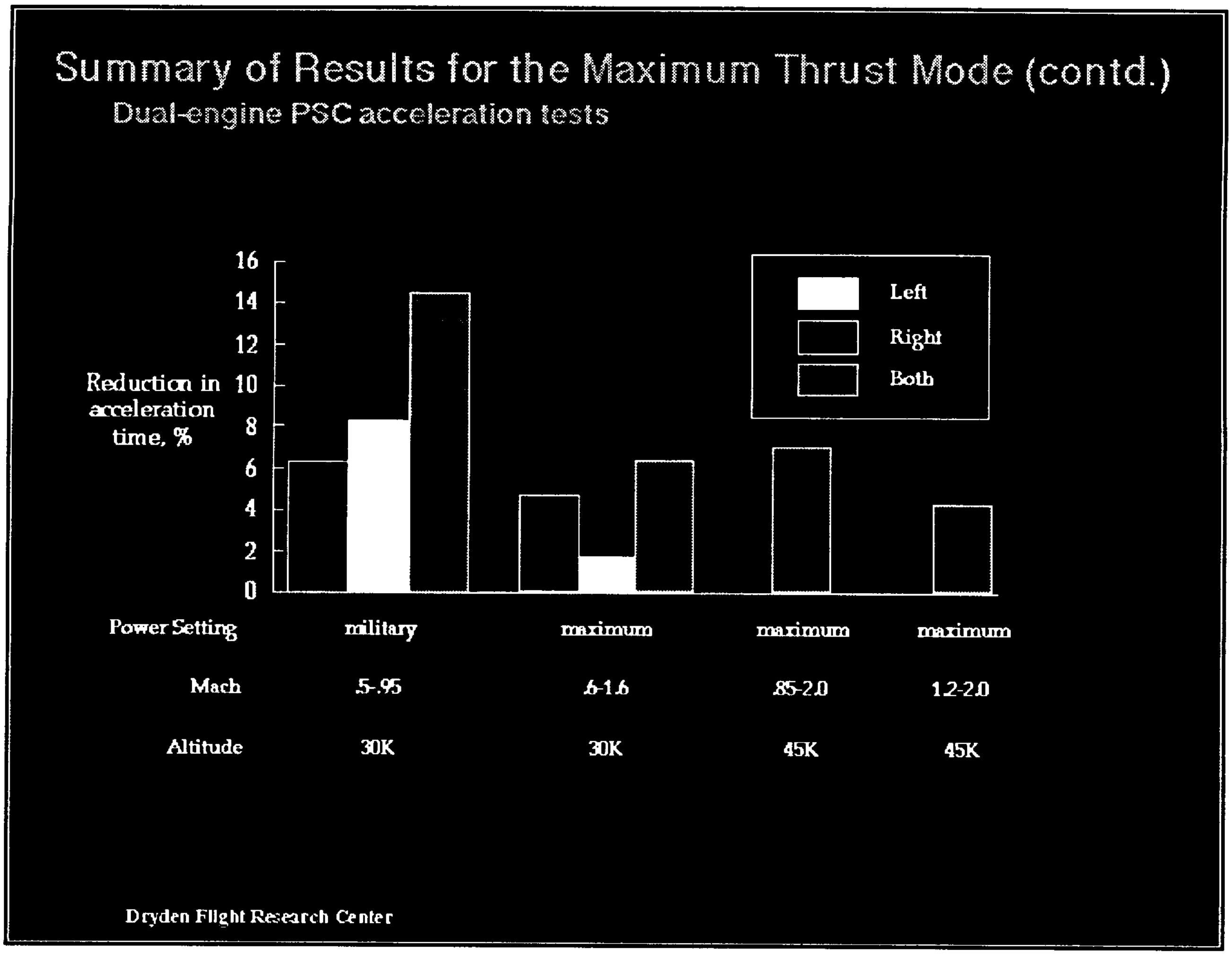

Measured reductions in acceleration times which resulted from the application of the PSC Maximum Thrust mode during the dual–engine test phase is presented **above** as a function of power setting and flight condition. Data were collected at altitudes of 30,000 and 45,000 feet at military and maximum afterburning power settings. The time savings for the supersonic acceleration is less than at subsonic Mach numbers because of the increased modeling and control complexity. In addition, the propulsion system was designed to be optimized at the mid supersonic Mach number range. Recall that even though the engine is at maximum afterburner, PSC does not trim the afterburner for the Maximum Thrust Mode.

Subsonically at military power, time to accelerate from Mach 0.6 to 0.95 was cut by between 6 and 8 percent with a single engine application of PSC, and over 14 percent when both engines were optimized. At maximum afterburner,the level of thrust increases were similar in magnitude to the military power results, but because of higher thrust levels at maximum afterburner and higher aircraft drag at supersonic Mach numbers the percentage thrust increase and time to accelerate was less than for the supersonic accelerations. Savings in time to accelerate supersonically at maximum afterburner ranged from 4 to 7 percent.

In general, the Maximum Thrust mode has performed well, demonstrating significant thrust increases at military and maximum afterburner power. Increases of up to 15 percent at typical combat–type flight conditions were identified. Thrust increases of this magnitude could be useful in a combat situation.

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Author: John S. Orme
e–mail: orme@alien.dfrf.nasa.gov

Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

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Author: Timothy R. Conners
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3324
Fax: (805)258-2842
Address: P.O. Box 273, MS D-2033, Edwards, CA 93523
e-mail: Tim_Conners@qmgate.dfrf.nasa.gov

Author: Steven G. Nobbs
Affiliation: McDonnell Douglas Corporation
Phone: (314)232-2717
Fax: (314)232-4141
Address: MC 1069020, P.O. Box 516, St. Louis, MO 63166
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

Author: John S. Orme
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3683
Fax: (805)258-3744
Address: P.O. Box 273, MS D-2033, Edwards, CA 93523
e-mail: orme@alien.dfrf.nasa.gov

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Abstract

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Aircraft with flight capability above Mach 1.4 normally have an RPM lockup or similar feature to prevent inlet buzz that would occur at low engine airflows. This RPM lockup has the effect of holding the engine thrust level at the intermediate power (maximum non–afterburning). For aircraft such as military fighters or supersonic transports, the need exists to be able to rapidly slow from supersonic to subsonic speeds. For example, a supersonic transport that experiences a cabin decompression needs to be able to slow/descend rapidly; and this requirement may size the cabin environmental control system. For a fighter, there may a desire to slow/descend rapidly, and while doing so to minimize fuel usage and engine exhaust temperature. Both of these needs can be aided by achieving the **minimum** possible overall net propulsive force. As the intermediate power thrust levels of engines increase, it becomes even more difficult to rapidly slow from supersonic speeds.

Therefore, a mode of the PSC system to minimize overall propulsion system thrust has been developed and tested. The Rapid Deceleration mode reduces the engine airflow consistent with avoiding inlet buzz. The engine controls are trimmed to minimize the thrust produced by this reduced airflow, and moves the inlet geometry to degrade the inlet performance. As in the case of the other PSC modes discussed earlier, the best overall performance (in this case the least net propulsive force) requires an integrated optimization of inlet, engine and nozzle variables. This paper presents the predicted and measured results for the supersonic minimum thrust mode, including the overall effects on aircraft deceleration.

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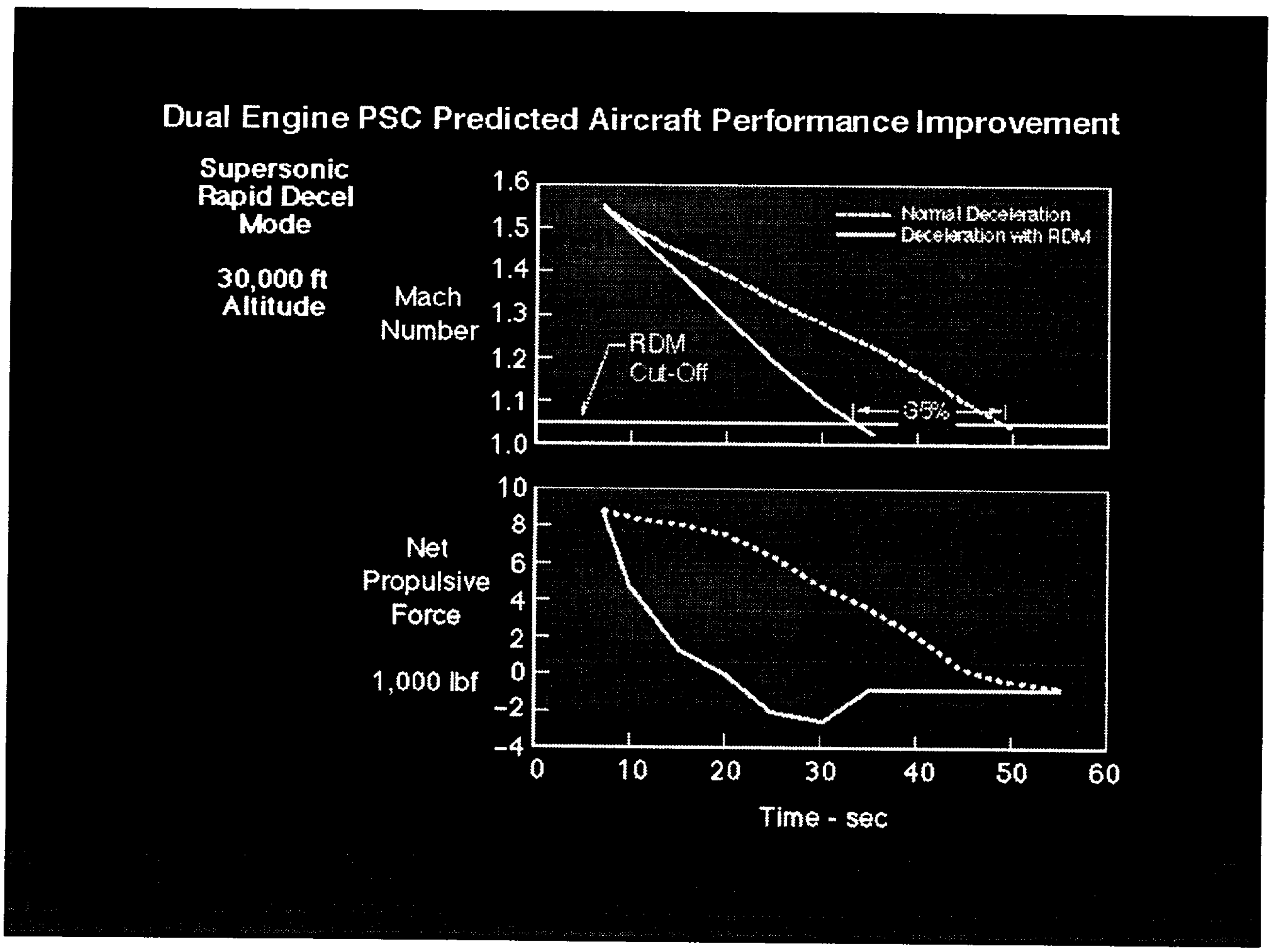
Author: Timothy R. Conners
e–mail: Tim_Conners@qmgate.dfrf.nasa.gov

Author: Steven G. Nobbs
e–mail: m236054%etd.decnet@mdcgwy.mdc.com

Author: John S. Orme
e–mail: orme@alien.dfrf.nasa.gov

Prediction of a Rapid Deceleration Mode Deceleration



In the supersonic rapid deceleration mode, thrust is minimized and drag maximized resulting in improved deceleration times.

An idle power deceleration with the Speedbrake retracted was simulated with the Six Degree of Freedom Simulation. An aircraft with PSC Supersonic Rapid Deceleration Mode engaged decelerates from 1.6 to 1.05 Mach number in 33 seconds where as a baseline aircraft takes 49 seconds. This is a 35% improvement in deceleration time.

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Author: Timothy R. Conners
e-mail: Tim_Conners@qmgate.dfrf.nasa.gov

Author: Steven G. Nobbs
e-mail: m236054%etd.decnet@mdcgwy.mdc.com

Author: John S. Orme
e-mail: orme@alien.dfrf.nasa.gov

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Prediction of Engine Controls for a Rapid Deceleration Mode Deceleration

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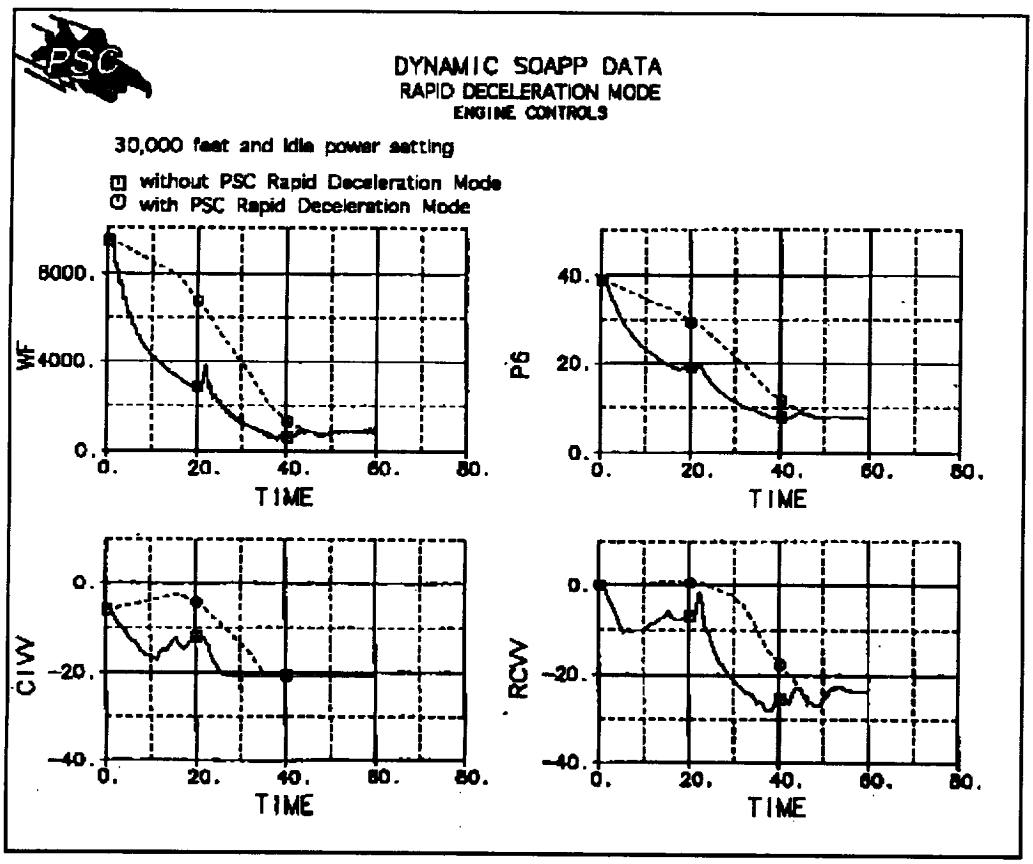

The Dynamic Propulsion System Simulation shows how Rapid Deceleration Mode (RDM) achieves these benefits for the 30K deceleration. Fuel flow (WF, pph) and turbine pressure (P6, lb/in2) were reduced. The fan and compressor vanes were trimmed in the cambered direction.

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Prediction of Inlet Controls for a Rapid Deceleration Mode Deceleration

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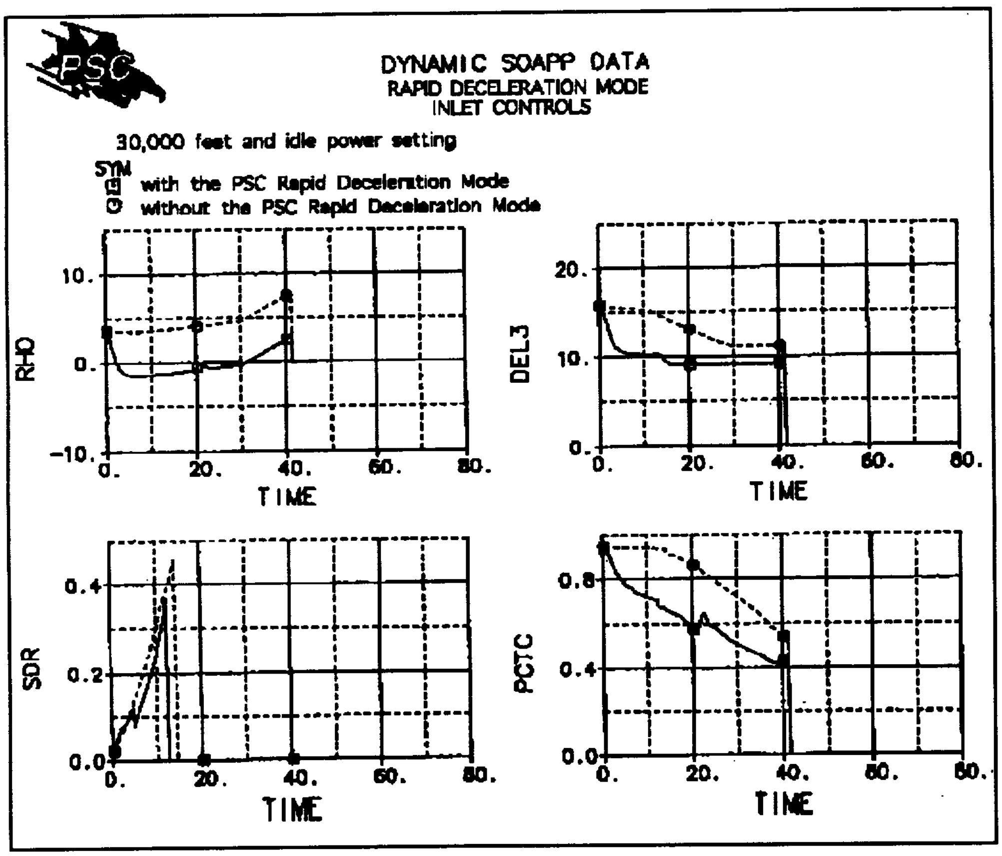

The inlet ramps were positioned to increase inlet and stabilator trim drag. The inlet cowl (rho, degrees) is rotated upward and the third ramp (DEL3, degrees) is moved out of the airflow.

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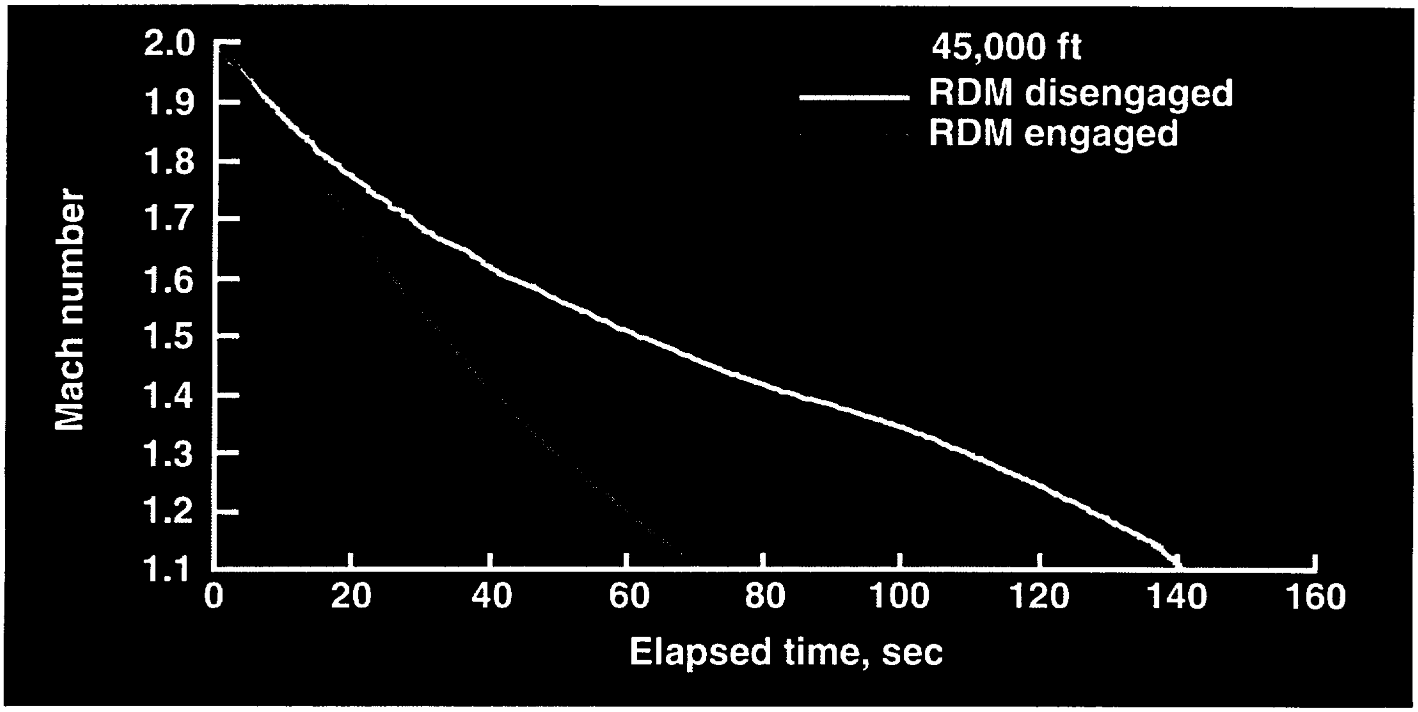
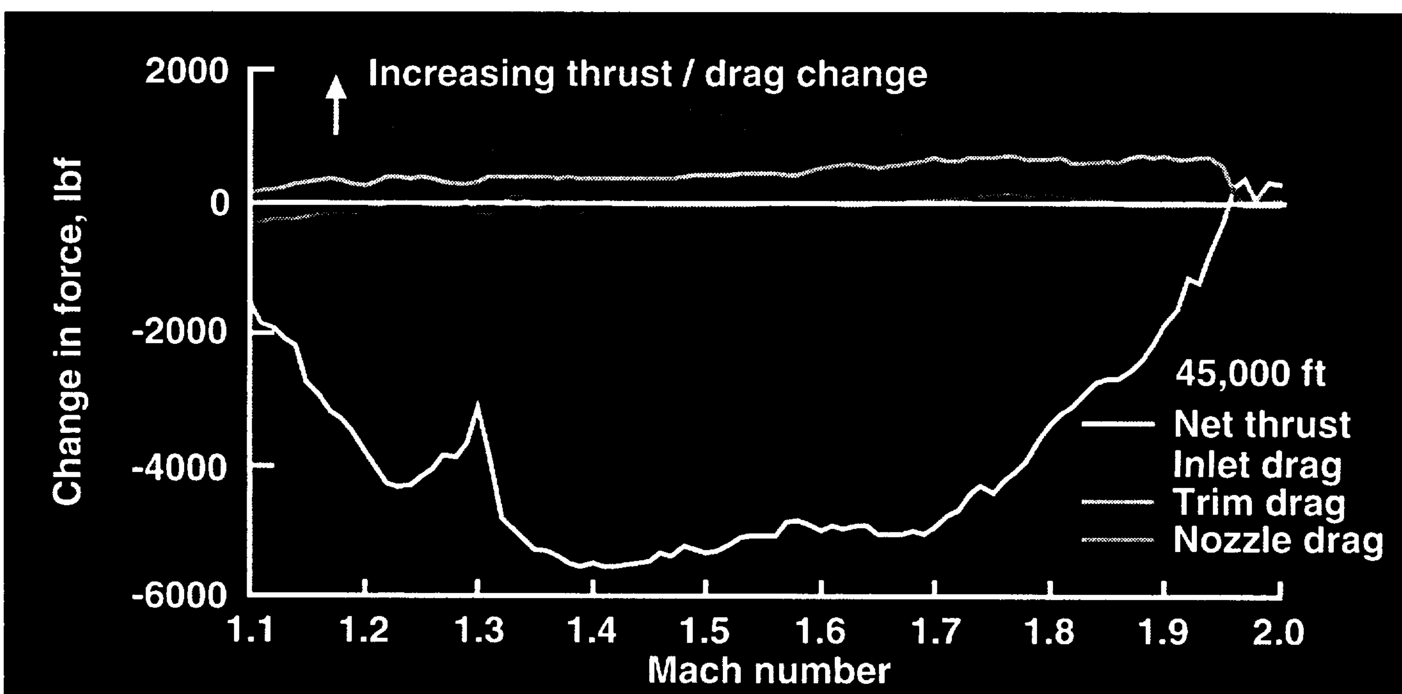
Author: Timothy R. Conners

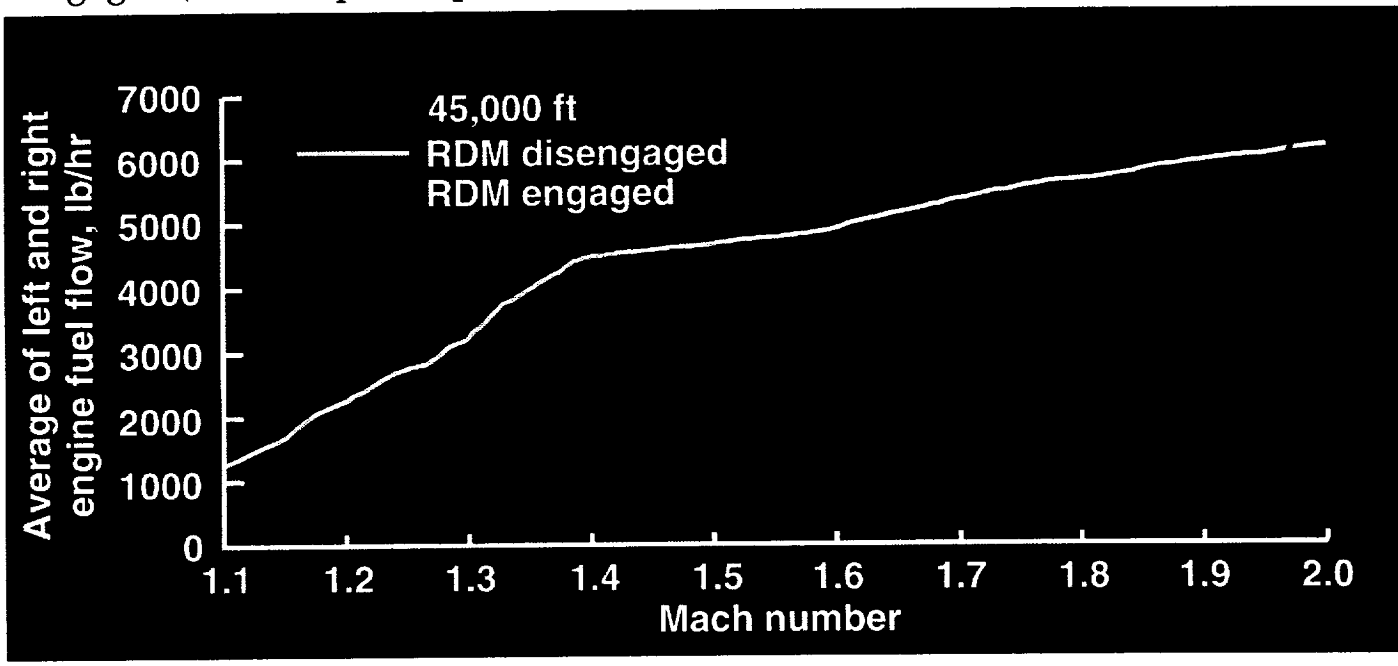
Results from the use of PSC RDM during a supersonic deceleration at 45,000 ft are presented in the figure below. As can be seen, RDM reduced the time to decelerate from Mach 2.0 to 1.1 by 50 percent (from 140 sec to 70 sec).



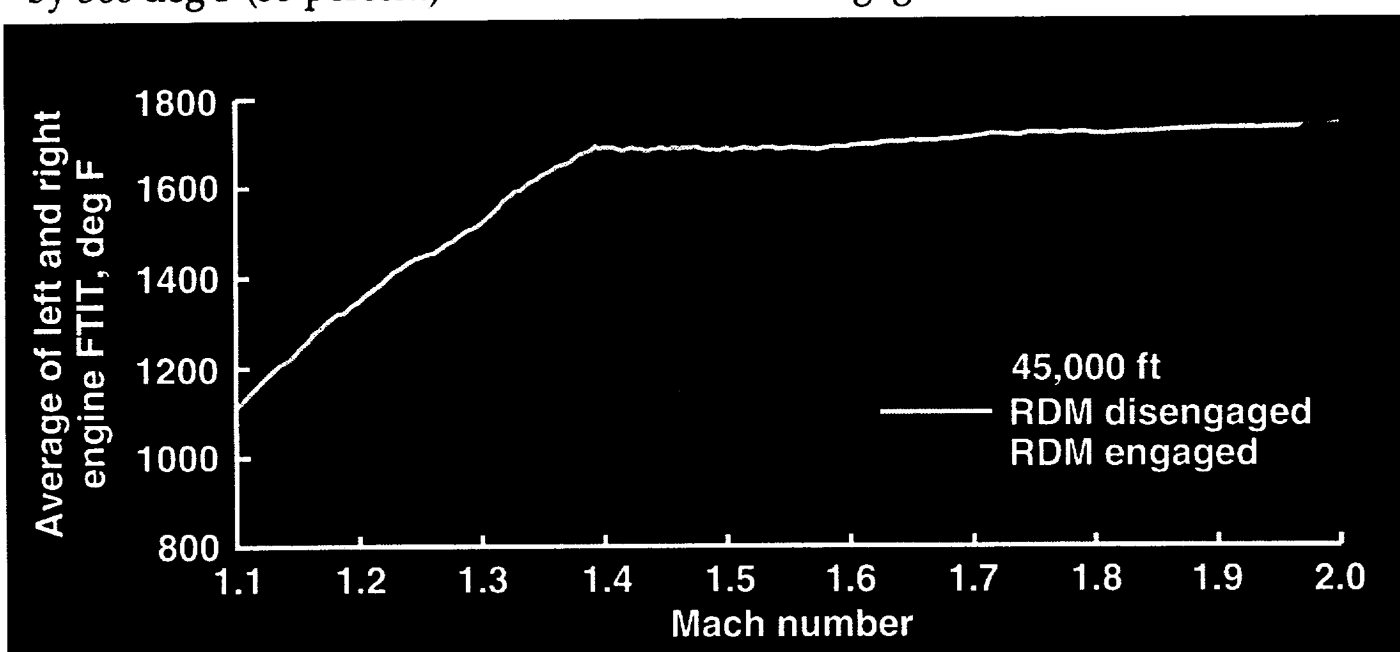
The figure below shows the change in component force and drag resulting from the use of RDM for the above test case. These values were estimated by the PSC on-board model. Net thrust was greatly reduced, primarily as a result of the reduction in engine airflow. Inlet drag was substantially increased by moving the inlet shock system further open, thereby increasing airflow spillage. Trim drag also increased as the inlet cowl was rotated upwards. The change in nozzle drag was minimal.



The figure below compares engine fuel flow as a function of Mach number for the 45,000 ft test condition, and shows the large reduction that occurs with RDM engaged (for example, 62 percent at Mach 1.4).



The following figure shows the correspondingly large decrease in engine operating temperature that occurs simultaneously. For example, FTIT is reduced by 560 deg F (33 percent) at Mach 1.4 with PSC engaged.



No inlet buzz problems occured using RDM. This mode successfully demonstrated the benefits of integrating the engine control with a thrust calculation algorithm and off-nominal inlet scheduling. Flexibility of PSC in effectively accommodating different performance goals was also proven. In this case, the antithesis of the maximum thrust mode drove the propulsion system to a minimum force value, constrained primarily to an accurate minimum airflow boundary.

Reference: *Orme, J. S. and Conners, T. R.; Supersonic Flight Test Results of a Performance Seeking Control Algorithm on a NASA F-15 Aircraft; AIAA-94-3210, June 1994.*

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"Thrust Stand Test"

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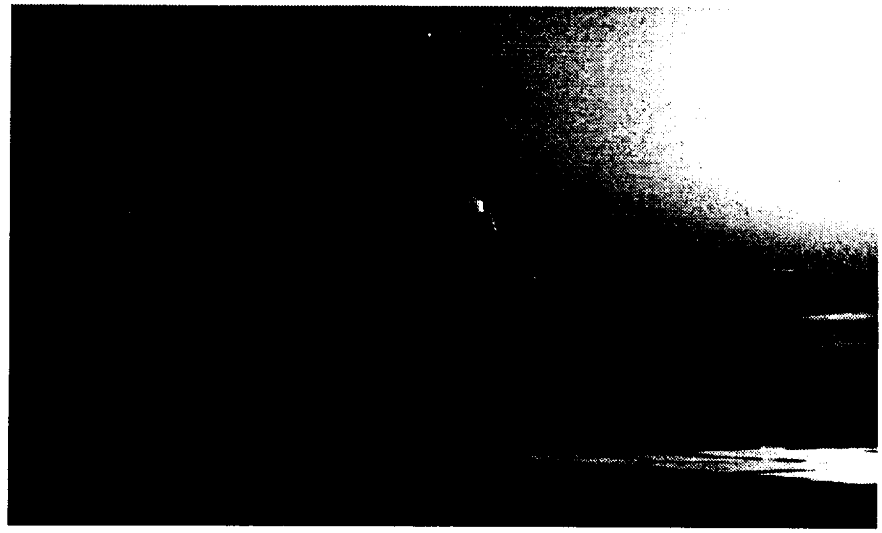
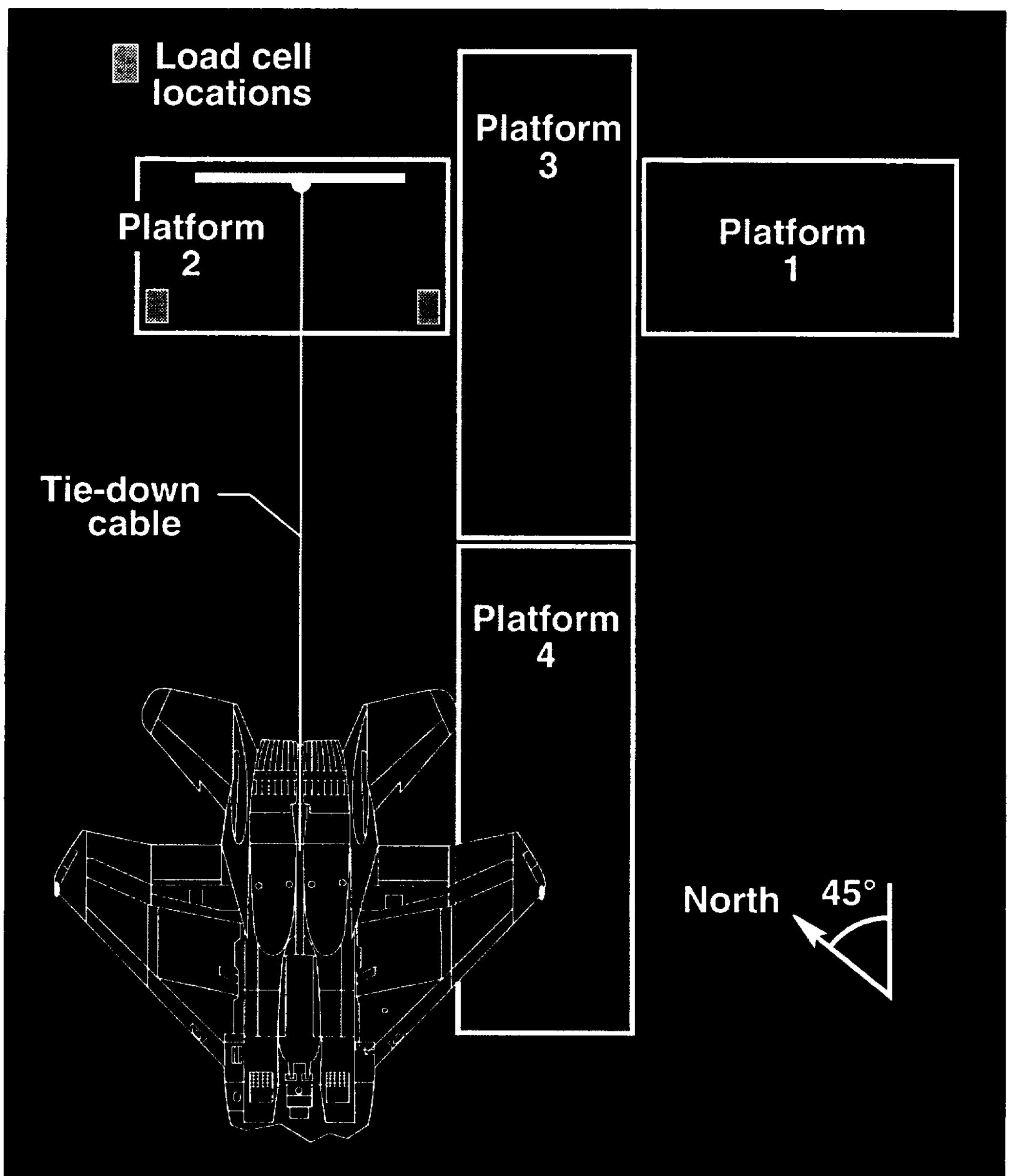
Author: Timothy R. Conners
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3324
Fax: (805)258-2842
Address: P.O. Box 273, MS D-2033, Edwards, CA 93523
e-mail: Tim_Conners@qmgate.dfrf.nasa.gov

Author: Steven G. Nobbs
Affiliation: McDonnell Douglas Corporation
Phone: (314)232-2717
Fax: (314)232-4141
Address: MC 1069020, P.O. Box 516, St. Louis, MO 63166

e-mail: m236054%etd.decnet@mdcgwy.mdc.com

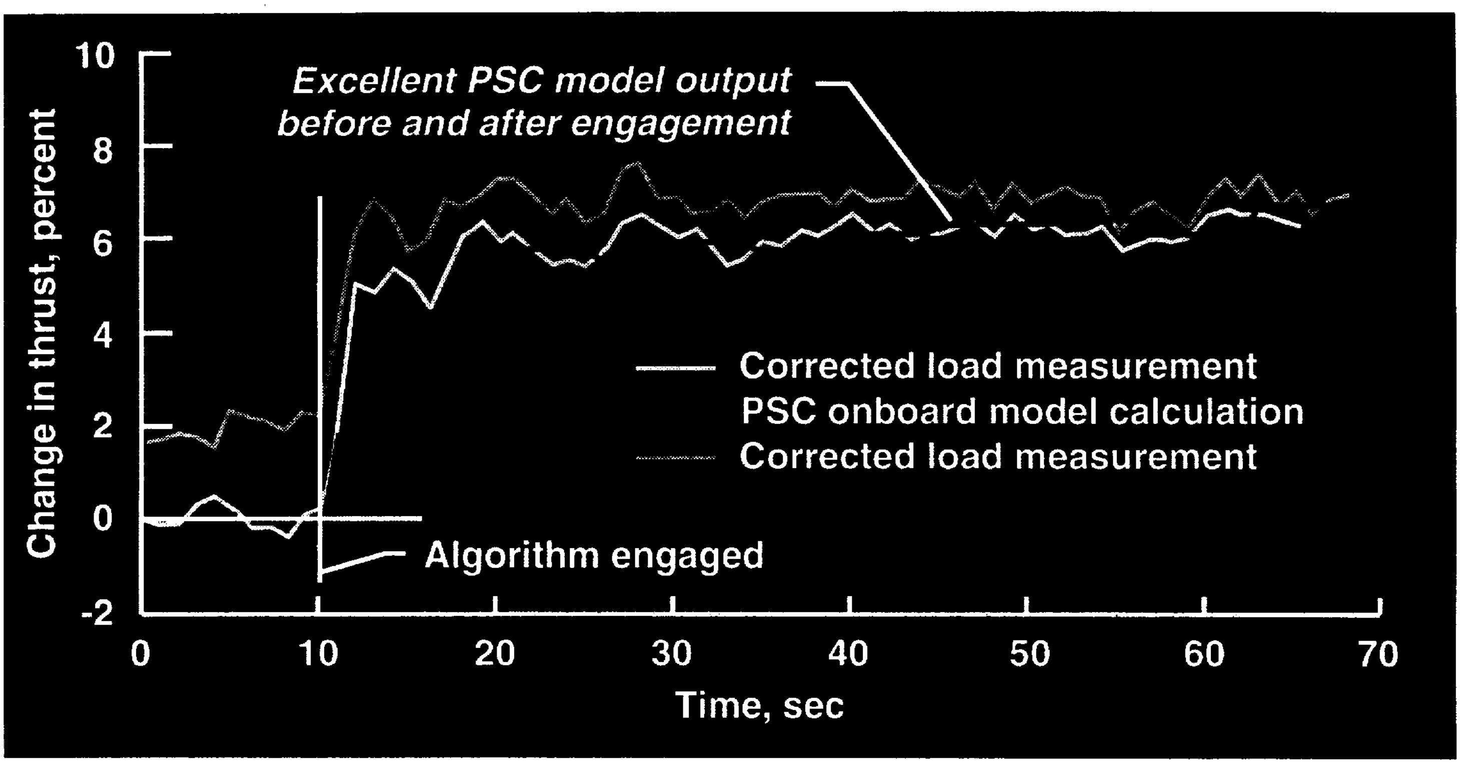
The PSC algorithm was tested in the F-15 at the Air Force horizontal thrust stand located at Edwards Air Force Base (see figure below for test set-up). There were two primary objectives: 1) to absolutely quantify the peformance benefits of PSC using the highly accurate thrust stand measurements, and 2) to directly compare the on-board model thrust estimates to these measurements.





In meeting the first objective, the PSC maximum thrust mode was directly observed to amplify engine thrust by an average of 10 percent at intermediate power and 6 percent at maximum power. PSC also generally performed well at holding constant nominal thrust when using the minimum fuel and minimum fan turbine inlet temperature modes. Bleed air extraction from the test engine was shown to have a substantial impact on the operation of the PSC algorithm.

The load cell measurements were also compared against estimations from several analytical engine performance models, including PSC's on-board estimate and a state-variable model (SVM) based technique. The figure below presents a comparison for a maximum thrust mode test point at maximum augmented power. Two important qualities for each model were assessed: the ability to calculate absolute thrust values, and the capability of measuring the performance across engine transients. In general, the on-board model displayed the best all-around ability at handling off-nominal transient operation and did very well at estimating the absolute net thrust. The SVM generally did not do as well at modeling the true engine performance change during engine transients.



The thrust stand provided the only practical means to compare analytically based thrust calculations with actual measured installed thrust. It proved to be an excellent platform for investigating the dynamic operation of PSC. It directly validated the predicted PSC performance improvements and verified the proper operation of the on-board thrust calculation.

Reference: *Conners, T. R.; Thrust Stand Evaluation of Engine Performance Improvement Algorithms in an F-15 Airplane; AIAA-92-3747 and NASA TM 104252, July 1992.*

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"Performance Seeking Control Excitation Mode"

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Author: Gerard Schkolnik
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258–3055
Fax: (805)258–3744
Address: P.O. Box 273, MS D–2033, Edwards, CA 93523
e–mail: Gerard_Schkolnik@qmgate.dfrf.nasa.gov

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"Performance Seeking Control Excitation Mode", page 1

Abstract

Flight testing of the Performance Seeking Control (PSC) Excitation mode was successfully completed at NASA Dryden on the F–15 highly integrated digital electronic control (HIDEC) aircraft. Although the Excitation mode was not one of the original objectives of the PSC program, it was rapidly prototyped and implemented into the architecture of the PSC algorithm, allowing valuable and timely research data to be gathered. The primary flight test objective was to investigate the feasibility of a future measurement–based performance optimization algorithm.

This future algorithm, called AdAPT, which stands for Adaptive Aircraft Performance Technology, generates and applies excitation inputs to selected control effectors. Fourier transformations are used to convert measured response and control effector data into frequency domain models which are mapped into state space models using multiterm frequency matching. Formal optimization principles are applied to produce and integrated, performance optimal effector suite. The key technical challenge of the measurement–based approach is the identification of the gradient of the performance index to the selected control effector. This concern was addressed by the Excitation mode flight test.

The AdAPT feasibility study utilized the PSC Excitation mode to apply separate sinusoidal excitation trims to two controls, one aircraft, inlet first ramp (cowl), and one engine, throat area. Aircraft control and response data were recorded using on–board instrumentation and analyzed post–flight. Sensor noise characteristics, axial acceleration performance gradients, and repeatability were determined. Results were compared to pilot comments to assess ride quality.

Flight test results indicate that performance gradients were identified at all flight conditions, sensor noise levels were acceptable at the frequencies of interest, and excitations were generally not sensed by the pilot.

Author: Gerard Schkolnik
e–mail: Gerard_Schkolnik@qmgate.dfrf.nasa.gov

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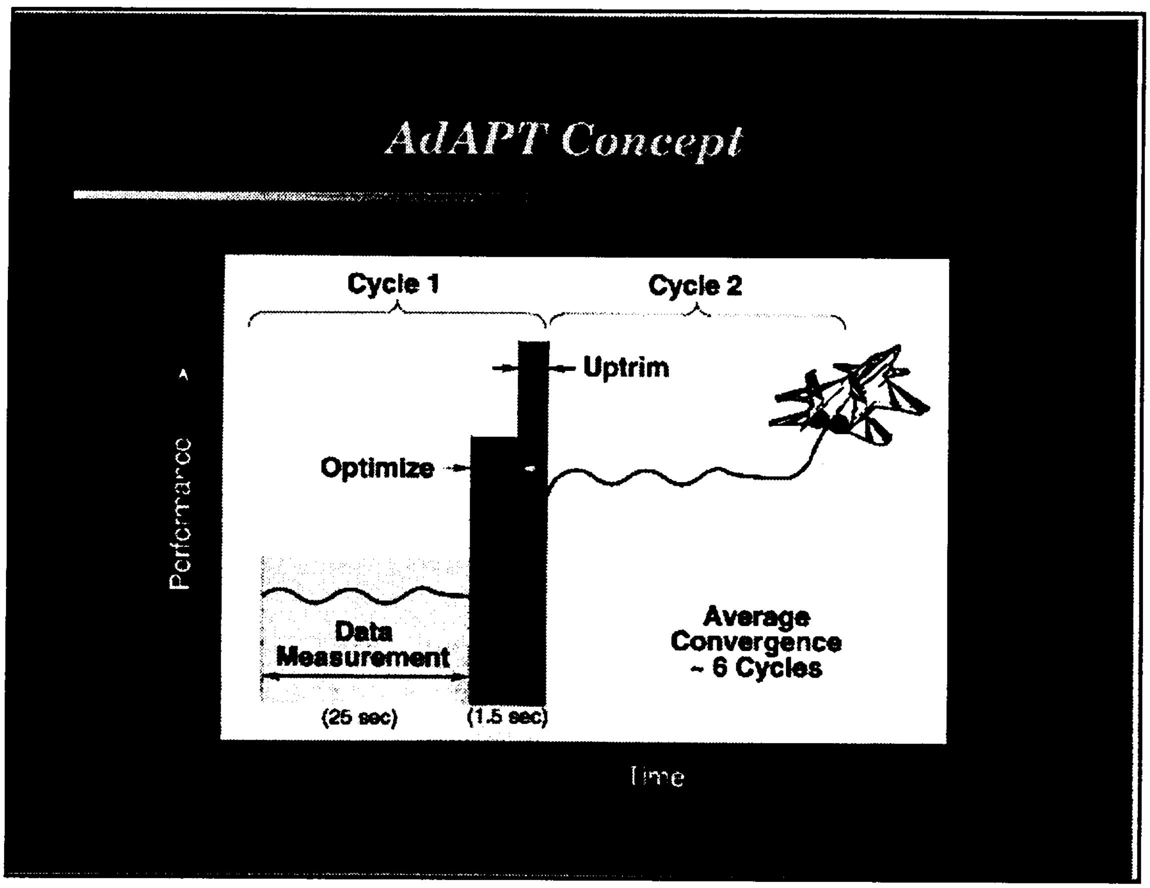
PSC Excitation Mode Testing



The PSC Excitation Mode was not part of the original PSC algorithm, but was added to investigate the feasibility of an adaptive measurement–based, algorithm that optimizes the aircraft and propulsion system in real–time during quasi–steady–state operation. The most important technical challenge for the measurement–based approach will be identifying the performance gradients without excessively disturbing the aircraft flight path. Other issues with this approach include the effects of noise or other extraneous inputs on the identification and the threshold sensitivity of the sensors. This new algorithm, Adaptive Aircraft Performance Technology (AdAPT), will be flight tested on a future program on a different aircraft.

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PSC Excitation Mode Implementation

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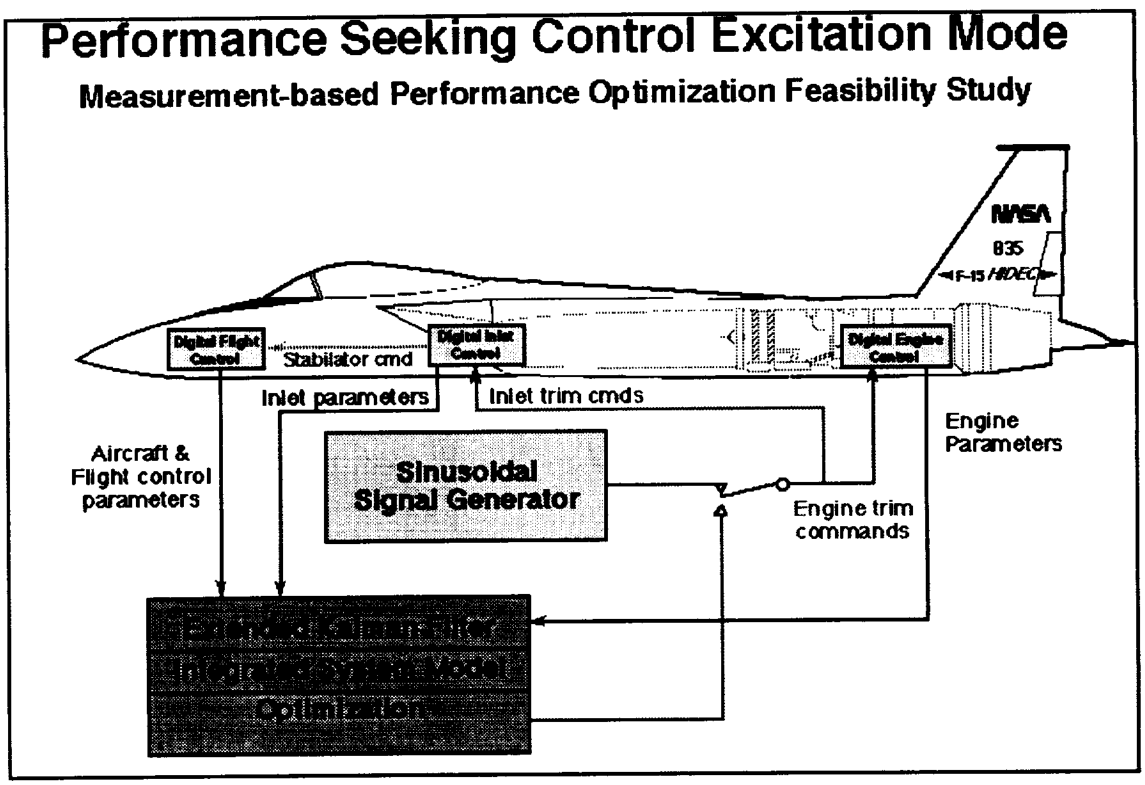

The implementation of the PSC Excitation Mode was based on the Minimum Fuel Mode. This allowed the operation of the algorithm at any power lever angle setting. PSC trim adders and multiplier options zeroed all trim outputs of the optimization and applied sinusoidal trims to the nozzle throat area and/or the inlet first ramp or cowl. Frequency and amplitude trim characteristics were selected inflight for each control via a variable gain structure. Aircraft controls and acceleration data from three longitudinal accelerometers were recorded on the instrumentation system for analysis postflight.

Maneuvers were flown across the subsonic and supersonic envelope of the F–15. Eleven test maneuvers were flown at nine flight conditions ranging from 0.7 Mach at 10,000 feet to 2.0 Mach at 45,000 feet. The eleven maneuvers were comprised of an amplitude parametric test, a frequency parametric test, and 9 standard tests. The standard test included an inlet excitation, a nozzle area excitation, and both controls excited simultaneously.

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Author: Gerard Schkolnik
e-mail: Gerard_Schkolnik@qmgate.dfrf.nasa.gov

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"Performance Seeking Control Excitation Mode", page 4

PSC Excitation Mode Analysis – Time Histories

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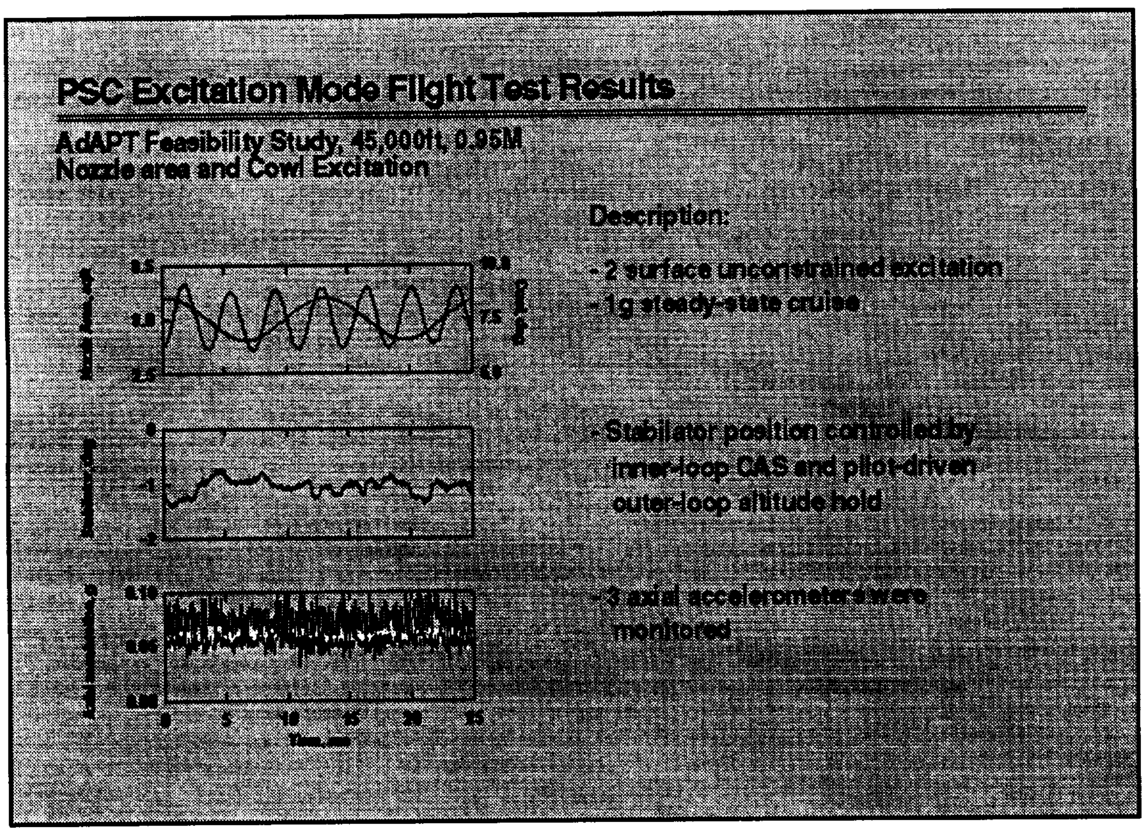

Time histories are shown for simultaneous cowl (inlet ramp) and throat area excitations at a flight condition of 45,000 feet and 0.95 Mach in the above figure. The first time history shows the excitations of the two controls, cowl and nozzle area; the maneuver lasted 25 seconds. The nozzle area was excited with a period of 12 seconds and an amplitude of +/– 0.2 square feet. The cowl was excited at a shorter period of 3.7 seconds and an amplitude of +/– 2 degrees. The second time history is of the stabilator position, which indicated how the controls are affecting stabilator position and, in turn, drag. The last time history shows the three longitudinal accelerometer traces for the same time period. One accelerometer has a much lower signal–to–noise ratio than the other two.

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PSC Excitation Mode Analysis – PSDs

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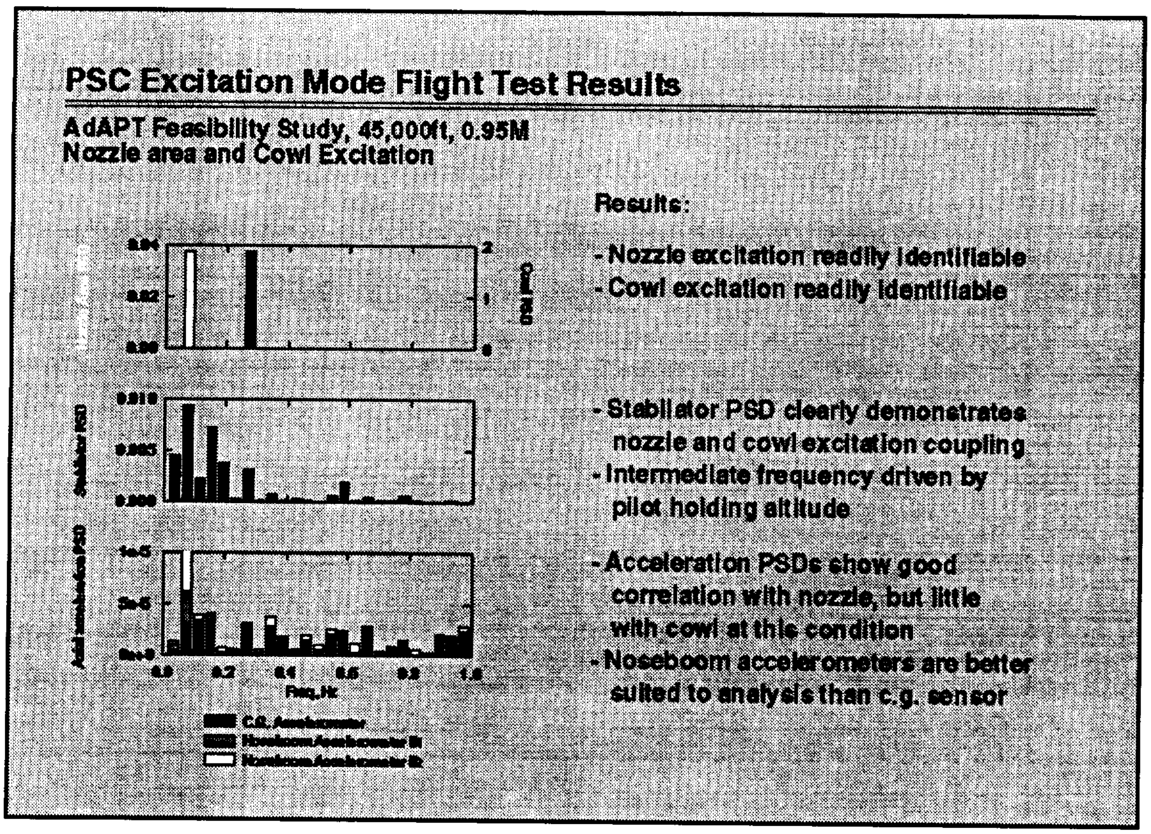

Power Spectral Densities (PSD, plots of amplitude of the Fast Fourier Transform, FFT, squared versus frequency) for the corresponding signals (see individual signals in previous figure) are presented in the above figure. The first PSD shows the distinct peaks of the two controls with no interference between the two. The second PSD indicates that at this condition the nozzle area had a greater effect on the stabilator drag than cowl. The third PSD indicates that the two noseboom accelerometers clearly sensed the nozzle area excitation, but did not sense the cowl excitation. These PSDs are a direct indication of the quality of the identification of the performance gradients. Also, noise levels were observed to be low to frequencies beyond any planned excitation. By comparison, the c.g. accelerometer had unacceptable performance with high noise levels starting at very low frequencies making the identification difficult. Overall, the results show that the identification is readily possible and virtually imperceptible to the pilot and not affected by simultaneous excitations.

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Author: Gerard Schkolnik
e–mail: Gerard_Schkolnik@qmgate.dfrf.nasa.gov

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"Performance Seeking Control Excitation Mode", page 6

PSC Excitation Mode Results

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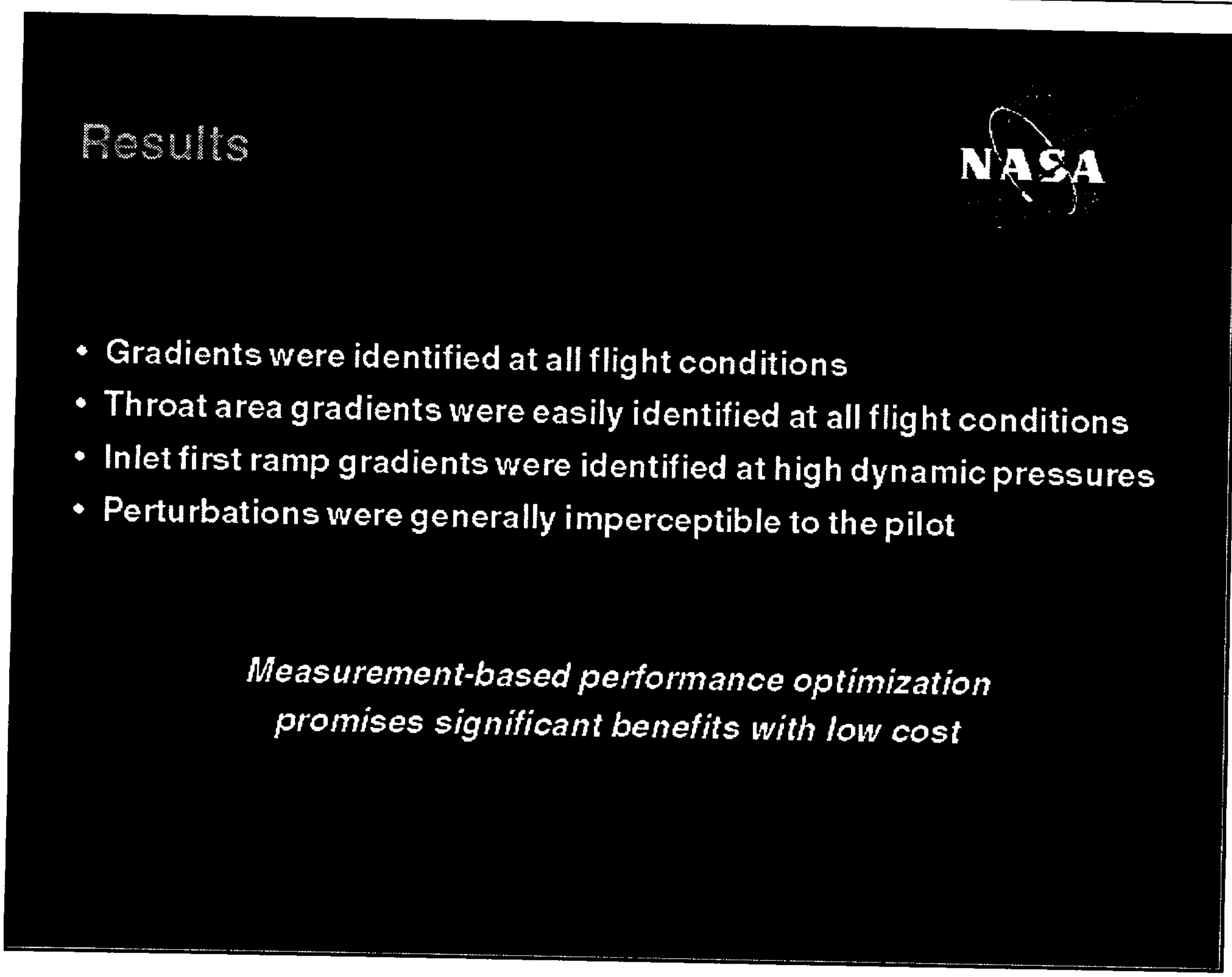

Overall, gradients were successfully identified at all conditions. As expected at low dynamic pressures where the inlet ramp is ineffective, the inlet ramp gradient was within the noise level. At higher dynamic pressures, the inlet ramp gradient was easily identified. The nozzle throat area gradient was identifiable at all conditions. Simultaneous excitations of both controls produced gradients that were nearly identical to those performed separately. Pilot comments with respect to disturbance to flight path indicated that the excitation was generally not perceptible, and when perceptible, it was insignificant.

The development of measurement–based performance optimization promises to produce significant benefits with little additional cost. This flexible approach allows all aircraft, commercial and military, subsonic and supersonic to attain an optimum configuration.

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Author: Gerard Schkolnik
e–mail: Gerard_Schkolnik@qmgate.dfrf.nasa.gov

NASA Dryden Flight Research Center

"PSC Asymmetric Thrust Alleviation Mode"

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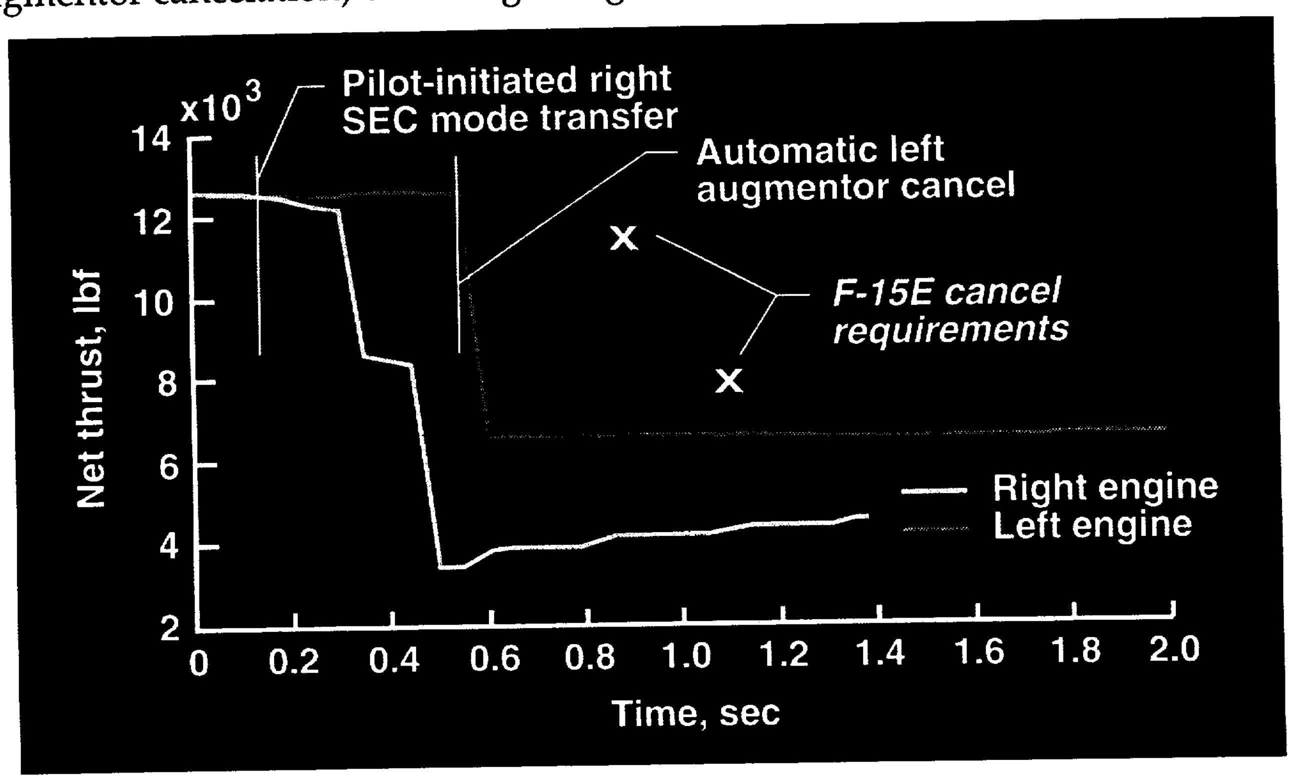
Author: Timothy R. Conners
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258-3324
Fax: (805)258-2842
Address: P.O. Box 273, MS D-2033, Edwards, CA 93523
e-mail: Tim_Conners@qmgate.dfrf.nasa.gov

Asymmetric thrust alleviation is the ability to reduce large yaw excursions resulting from thrust asymmetry. This capability is particularly important in high thrust, multi-engine aircraft that experience reduced lateral-directional stability at high dynamic pressure. An example is the F-15E with F100-PW-229 engines, in which structural damage or aircraft departure can occur at high Mach numbers if a single augmentor fails and the rapid yaw excursion is not arrested.

The PSC asymmetric thrust alleviation (PATAL) mode, unlike other methods in use, employs digital communication to detect an augmentor blow-out or fault, and then sends a military power autothrottle command to both engines. The engines remain in primary mode, unless the fault that caused the loss of augmentation was a secondary (SEC) mode transfer. In this case, the good engine remains in primary. The primary objective of testing this mode was to verify that augmentation was canceled quickly enough to avoid unacceptably large yaw excursions.

The PATAL mode was successfully tested at 31,000 ft, Mach 0.93. The mode was expcted to be tested at higher dynamic pressures to measure its effectiveness at reducing yaw excursions following a similated augmentor fault, but the retirement of the HIDEC aircraft precluded this. At the 31,000 ft/0.93 condition, yaw excursions resulting from augmentor-out are small. However, because the time delay of the autothrottle command is independent of Mach number, the actual flight test timing results were none-the-less significant.

Plotted in the figure below is post-flight calculated net thrust versus time following a pilot-initiated secondary mode transfer (with corresponding augmentor cancelation) on the right engine at the above flight condition.



There is no asymmetric thrust problem at 0.9 Mach for the F-15. However, in order to evaluate the timing results, F-15E high dynamic pressure thrust roll-off requirements, extrapolated from 30,000 ft, Mach 2.0, are also plotted on the figure. The F-15 HIDEC results meet these timing constraints.

The PATAL mode does not utilize the modeling and optimization logic in the PSC algorithm, but it does take advantage of its integrated digital framework. It is another example of the advatages to be gained from integrating avionics and propulsion systems, and it further illustrates the flexibility of the HIDEC aircraft.

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Author: John S. Orme
Affiliation: NASA Dryden Flight Research Center
Phone: (805)258–3683
Fax: (805)258–3744
Address: P.O. Box 273, MS D–2033, Edwards, CA 93523
e–mail: orme@alien.dfrf.nasa.gov

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Adaptive Features

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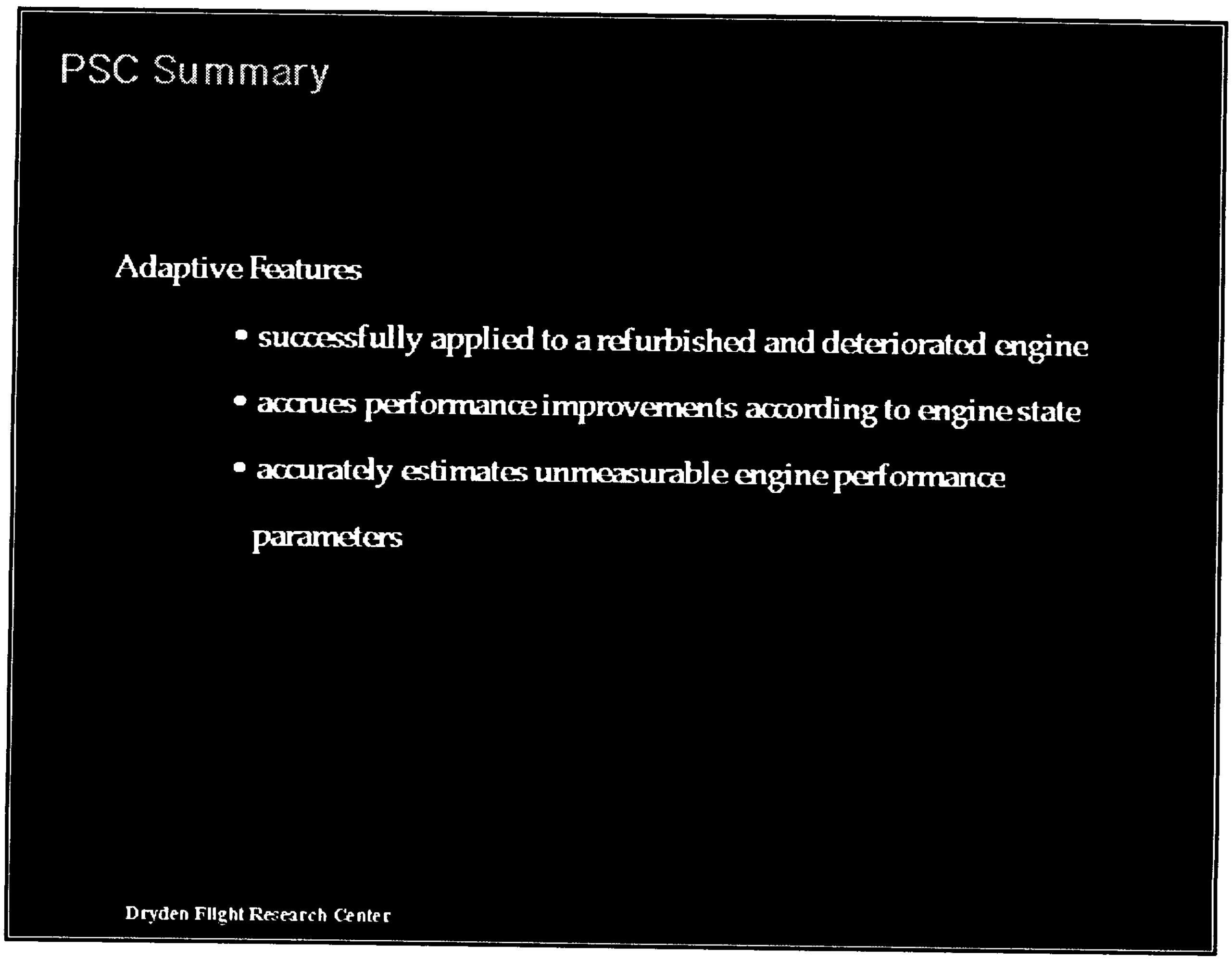

The Performance Seeking Control algorithm optimizes total propulsion system performance. This adaptive, model–based optimization algorithm has been successfully flight demonstrated on two engines with differing levels of degradation. Models of the engine, nozzle and inlet produce reliable, accurate estimates of engine performance. But, because of an observability problem, component levels of degradation cannot be accurately determined.

Depending on engine–specific operating characteristics PSC achieves various levels performance improvement. For example, engines with more deterioration typically operate at higher turbine temperatures than less deteriorated engines. Thus when the PSC maximum thrust mode is applied, for example, there will be less temperature margin available to be traded for increasing thrust.

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Author: John S. Orme
e–mail: orme@alien.dfrf.nasa.gov

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Performance Improvements

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PSC Summary

Performance Improvements

- exceptionally stable algorithm operation
- Maximum Thrust mode increases thrust up to 15% subsonically and 10% supersonically improving aircraft acceleration
- Minimum Fan Turbine Inlet Temperature mode can reduce temperature by over 100 °F extending engine life
- Minimum Fuel mode saves as much as 2% at dry power and 10% at afterburning power settings during cruise
- During supersonic decelerations the Rapid Deceleration mode cut time-to-decel by 50%

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Flight results show substantial benefits from the F–15 PSC algorithm. The PSC system benefits in general accrue from more accurate, real–time knowledge of various safety margins – that is, where the system currently is and where it can safely go. The PSC system takes advantage of this difference to maximize benefits. To its credit, the system operated in an exceedingly safe manner. No unrecoverable stalls, engine over–temps, or ingested shocks occurred over the 72 PSC test flights. In one instance, however, because of unsteady conditions, just after engaging the system, PSC caused a self–clearing pop–stall of the fan and immediately the system automatically disengaged. Also, during optimizations in which the fan turbine inlet temperature was driven to its maximum limit, the limit was exceeded transiently, but never more than by 10 deg.F. The pilots who flew with the PSC system characterize its operation as exceptionally reliable and were most impressed with its acceleration and deceleration performance.

In the Maximum Thrust mode, increases of up to 15 percent at subsonic and 10 percent at supersonic flight conditions were identified. Thrust increases were achieved essentially by trading available fan stall margin and operating at higher turbine temperatures. The Maximum Thrust mode reduced the time to accelerate by 15 percent at military power and between 4 and 7 percent at maximum afterburner. Performance improvements of this magnitude could be useful in a combat situation.

The Minimum Fan Turbine Inlet Temperature mode demonstrated temperature reductions exceeding 100 deg.F at high altitudes. If temperature were the only factor affecting engine life, these reductions would more than double engine life. In addition, lower operating temperatures could mean less required engine maintenance. The primary means of accomplishing the decreases in temperature were by reducing trim drag and lessening the thrust required for cruise.

Savings in fuel consumption of up to 2 percent in the subsonic regime and almost 10 percent supersonically were observed in the Minimum Fuel mode. Fuel consumption improvements like these could offer significant cost savings and/or range improvements to commercial airlines or the military. A large portion of the fuel savings are attained by down trimming the afterburner and also by reducing trim drag. Thrust was maintained in both the Minimum Fan Turbine Inlet Temperature mode and the Minimum Fuel mode as evidenced by the constant flight condition.

Supersonic decelerations with the PSC Rapid Deceleration mode produced dramatic results. At 45,000 feet, time to decelerate from Mach 2 to 1.1 was reduced by 50 percent. At 30,000 feet, time to decelerate was cut by approximately 30 percent. For in–flight emergencies, the benefits of this mode include increased controllability and safety. For military aircraft flying supersonic intercept missions, rapid deceleration gives the pilot increased control when engaging the adversary. Reducing infrared signature by lowering engine exhaust temperature may also be desired.

Overall, the PSC system can provide significant benefits for economy and performance. As a design tool, PSC could be used to reduce aircraft weight. PSC offers advantages to existing commercial subsonic and high performance military aircraft, as well as any future aircraft including the High Speed Civil Transport aircraft. For existing aircraft, PSC performance could be gained without any weight penalty. PSC could be used as a low cost and low weight retrofit to an entire class of aircraft. If PSC were incorporated in the design stage, the resulting configuration would reflect PSC's contribution by reductions in weight, maintenance costs, and performance.

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Algorithm Flexibility

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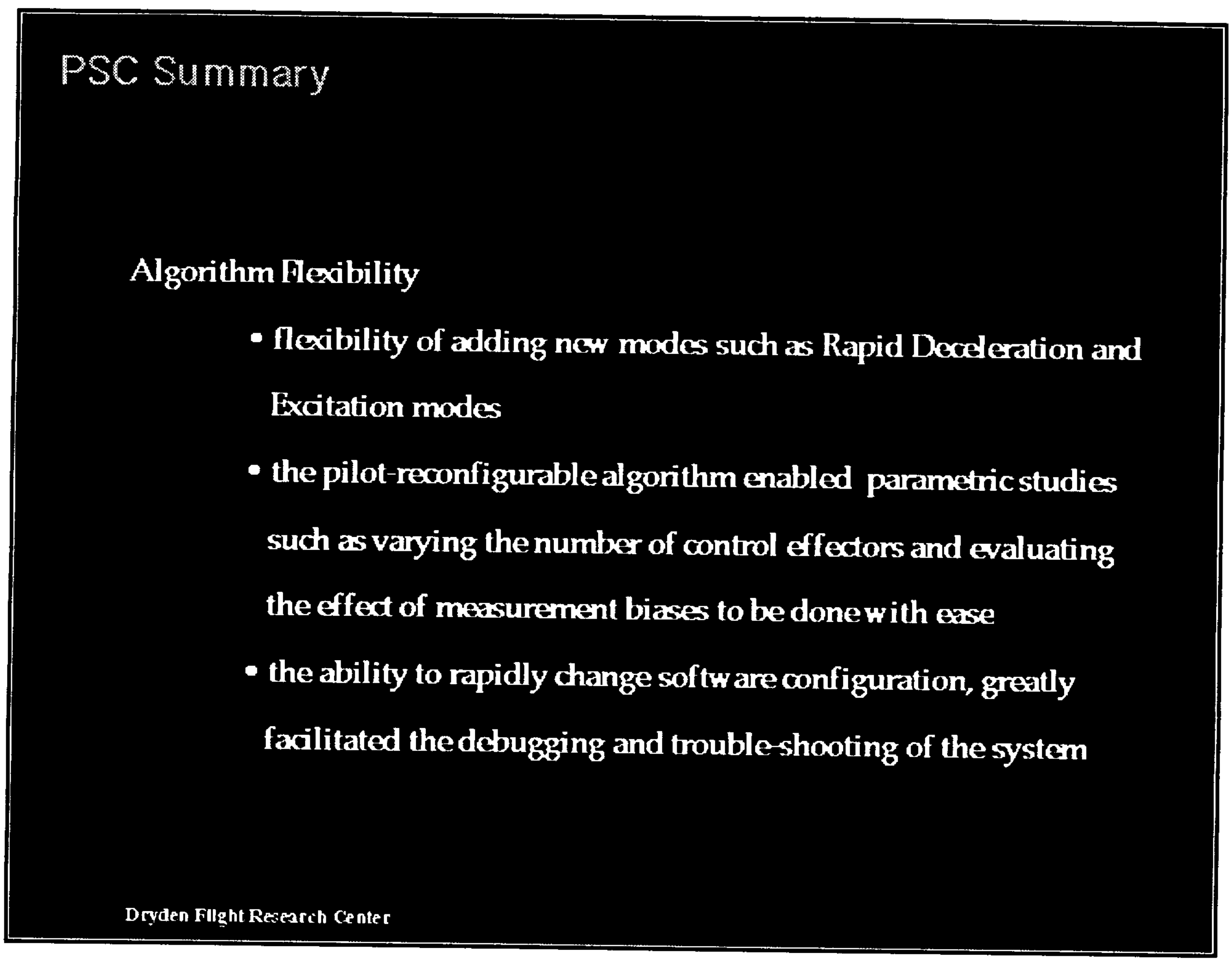

The flexibility of the PSC algorithm, its architecture and implementation contributed greatly to a successful test program. The ability to rapidly change software configuration, greatly facilitated the debugging and trouble–shooting of the system. Two new modes which weren't even considered in the initial PSC design were added with very little difficulty, the Rapid Deceleration and PSC Excitation modes. The performance objective of the PSC algorithm can be changed very easily as was the case in the Rapid Deceleration mode where the performance index was just the opposite sign of the Maximum Thrust mode. In addition, the ability for the pilot select the algorithm configuration via the Navigation Control Unit (NCI) allowed for numerous parametric studies to be conducted. Changing the number of control effectors and the measuring the effect of biases, for example, would have been extremely cumbersome if a new OFP had to be released each time configuration changed.

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Author: John S. Orme
e–mail: orme@alien.dfrf.nasa.gov

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The Future

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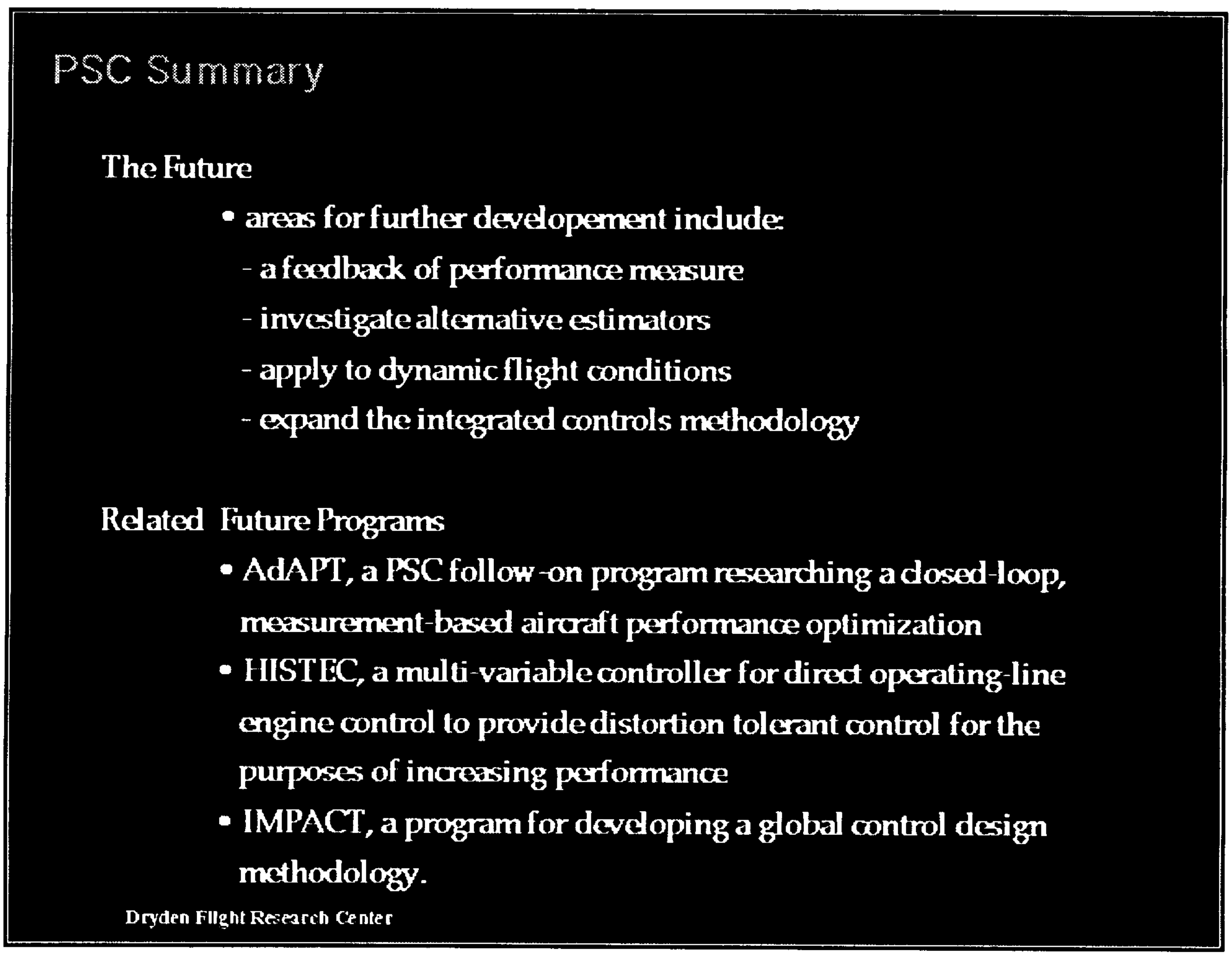

The F–15 PSC program developed a technical approach and methodology that can enhance the performance of high–performance and transport aircraft. The PSC algorithm as it was implemented on the F–15, however, requires accurate models that predict actual flight hardware performance operation. In addition, the adaptive estimation technique depends on accurate measurements of the inputs and outputs of the system being optimized. Because of the model–based open–loop approach used by the F–15 PSC, errors in modeling and measurements produce estimated optimal trim commands rather than measurement–based, true optimal trim commands. To improve system performance, several improvements could be made. By increasing the number of measurements and adding feedback, the system would rely less on the models and would simultaneously improve modeling accuracy. Alternative estimators to the Kalman filter should also be explored; the dynamic Kalman filter employed for PSC was unnecessarily complicated and had an observability problem. At some point in the future, it mat be desired to expand the valid aircraft maneuvering envelope for PSC beyond just quasi steady–state to more dynamic conditions. It would also be of interest to expand the integrated controls methodology to include more direct aerodynamic control effectors in the PSC optimization such as stabilator and ailerons.

Some of the areas for further research mentioned above are currently being addressed in related programs. A joint NASA, USAF, MDA, and P&W program called Adaptive Aircraft Performance Technology (AdAPT) is a follow–on PSC project. AdAPT will continue to advance the optimal performance technology base with a performance optimization algorithm that is measurement–based and includes feedbacks. The modified F–15 Short Take–off and Landing/Maneuvering Technology Demonstrator (S/MTD) aircraft will be used to demonstrate this technology. Initial planning is directed at quasi–steady optimization modes such as minimum fuel consumption at constant thrust or maximum thrust for a fixed fuel flow. The AdAPT optimization approach uses measurement feedback of performance metrics to ensure optimality. The AdAPT algorithm primarily optimizes with aerodynamic effectors to achieve its results, but also will control an axi–symmetric pitch/yaw vectoring nozzle.

Two other planned programs are related to the PSC research. The High Stability Engine Control (HISTEC) will investigate a multi–variable controller for direct operating–line engine control to provide distortion tolerant control for the purposes of increasing performance. Integrated Methodology for Propulsion and Airframe Control Technology (IMPACT) is a program for developing a global control design methodology. The idea of IMPACT is to capitalize on the inherent coupling between the engine and airframe.

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Author: John S. Orme
e–mail: orme@alien.dfrf.nasa.gov

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Final Thoughts

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The Performance Seeking Control experience is an excellent example of how flight test research benefits emerging technologies. The close–knit relation between working partners in government and industry has been mutually beneficial. From the PSC flight test program a high risk technology was demonstrated and matured to the extent that industry is already commercializing it. The typical development cycle time for a new high risk technology such as PSC is anywhere from 7 to 10 years. Even before the test program ended in 1993, portions of the PSC technology were being incorporated as a standard part of new military aircraft engines. This demonstrates the value of flight test research. The government gained experience with a new technology and fulfilled its mission of technology transfer. Without NASA's aid, MDA and P&W probably would not have developed the PSC technology to the point where commercial products result because the costs and risks are just too high.

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Author: John S. Orme
e–mail: orme@alien.dfrf.nasa.gov

PCA Session Information

As a result of several accidents in which all or major parts of the flight control system was lost, NASA Dryden investigated the capability for a "Propulsion Controlled Aircraft" (PCA) system, one which used only engine thrust for flight control.

Initial flight studies with the pilot manually controlling the throttles and all flight controls locked in the NASA F-15 showed that it was possible to maintain gross control. For instance, a climb could be initiated by adding an equal amount of power to both engines. Bank control could be achieved by adding power to one engine and reducing power to the opposite engine. Using these techniques, altitude could be maintained within a few hundred feet and heading to within a few degrees. These same flights showed that it was extremely difficult to land on a runway. This was due to the small control forces and moments of engine thrust, difficulty in controlling the phugoid oscillations, and difficulty in compensating for the slow engine response. Studies in flight simulators at Dryden and at McDonnell Douglas were able to duplicate the flight results. These simulators also established the feasibility of a PCA mode, shown below, using feedback of parameters such as flight path angle and bank angle to augment the throttle control capability and to stabilize the airplane.

The NASA F-15 was an ideal testbed airplane for this research. The HIDEC digital engine controls, digital flight controls, general-purpose computer and data bus architecture minimized the equipment that had to be added for PCA. The only equipment added to the airplane was a control panel containing 2 thumbwheels, one for flightpath command, and the other for bank angle command. These papers will describe the design, development, and flight test results.

Agenda

Frank W. Burcham Jr., "Background and Principles of Throttles-Only Flight Control"

Edward A. Wells, James M. Urnes, Sr., "Propulsion Controlled Aircraft Design and Development"

Frank W. Burcham Jr., Trindel A. Maine, "Flight Test of a Propulsion Controlled Aircraft System on the NASA F-15 Airplane"

Stephen Corda, Mark T. Stephenson, Frank W. Burcham Jr., "Dynamic Ground Effects Flight Test of the NASA F-15 Airplane"

PCA Session Information (Concluded)

Agenda (Concluded)

Trindel A. Maine, Frank W. Burcham Jr., Peter Schaefer, John Burken, "Design Challenges Encountered in the F-15 PCA Flight Test Program"

Frank W. Burcham Jr., "F-15 PCA Conclusions and Lessons Learned"

Session Chair

Chair: Bill Burcham
Affiliation: NASA Dryden Flight Research Center
Phone: 805-258-3126
Fax: 805-258-3744
Address: M. S. D2033, P. O. Box 273, Edwards, CA 93523-0273
e-mail: Bill_Burcham@QMGATE.DFRF.NASA.GOV

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NASA Dryden Flight Research Center

"Background and Principles of Throttles–Only Flight Control"

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Author: Frank W. Burcham Jr.
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3126
Fax: 805–258–3744
Address: M. S. D2033, P. O. Box 273, Edwards, CA 93523–0273

e-mail: Bill_Burcham@QMGATE.DFRF.NASA.GOV

Background and Principles of Throttles-Only Flight Control

Frank W. Burcham

NASA Dryden Flight Research Center
Edwards, CA

Abstract

There have been many cases in which the crew of a multi-engine airplane had to use engine thrust for emergency flight control. Such a procedure is very difficult, because the propulsive control forces are small, the engine response is slow, and airplane dynamics such as the phugoid and dutch roll are difficult to damp with thrust. In general, thrust increases are used to climb, thrust decreases to decend, and differential thrust is used to turn. Average speed is not significantly affected by changes in throttle setting. Pitch control is achieved because of pitching moments due to speed changes, from thrust offset, and from the vertical component of thrust. Roll control is achieved by using differential thrust to develop yaw, which, through the normal dihedral effect, causes a roll. Control power in pitch and roll tends to increase as speed decreases. Although speed is not controlled by the throttles, configuration changes are often available (lowering gear, flaps, moving center-of-gravity) to change the speed. The airplane basic stability is also a significant factor. Fuel slosh and gyroscopic moments are small influences on throttles-only control. The background and principles of Throttles-Only flight control are described in this paper.

Background and Introduction

The crew of a multi-engine aircraft with a major flight control system failure may use throttle manipulation for emergency flight path control. Differential throttle control generates yaw, which through dihedral effect, results in roll. Collective throttle inputs may be used to control pitch. Crews of DC-10, B-747, L-1011, and C-5A aircraft have used throttles for emergency flight control, ref 1.

To investigate the use of engine thrust for emergency flight control, the National Aeronautics and Space Administration's Dryden Flight Research Center (NASA Dryden) at Edwards, California, has been conducting a study including flight, ground simulator, and analytical studies. One objective is to determine the degree of control power available with engine thrust for various classes of airplanes. This objective has shown a surprising amount of control capability for most multi-engine airplanes, ref 2.

A second objective was to provide awareness of throttles-only control capability and suggested manual throttles-only control techniques for pilots. Dryden conducted simulation and flight studies of several airplanes, including the B-720, Lear 24, F-15, B-727, C-402, and B-747, refs 2&3. A third objective was to investigate possible augmented control modes that could be developed for future airplanes. An augmented control system that uses pilot flight path inputs and airplane sensor feedback parameters to provide appropriate throttle commands for emergency landings was developed. This augmented system was evaluated on a B-720 transport airplane simulation, ref 4, and a simulation of a conceptual megatransport, ref 5.

Recently, simulation studies and flight tests have been conducted to investigate the details of throttles-only control for the F-15 airplane, and to investigate the performance of a PCA (Propulsion Controlled Aircraft) augmented system. The PCA system was installed on the NASA F-15 research airplane. The objectives of the flight program were to demonstrate and evaluate PCA performance in up-and-away and landing approach flight, over the speed range from 150 to 190 knots at altitudes below 10,000 ft. There was also an option, if PCA performance was adequate, to attempt PCA landings.

The F-15 has since completed a 36 flight series of tests, including actual landings using PCA control. Recoveries from upset conditions including 90 deg bank at a 20 deg dive have also been flown. Altitudes to 38,000 ft and speeds up to 320 knots were flown. Six guest pilots have flown the PCA system.

The papers to follow present the principles of throttles-only flight control, flight tests of manual and augmented propulsion-only flight control for the F-15, the PCA design, development, and implementation, test techniques, and results, and pilot comments.

In this paper, the principles of throttles-only flight control are presented. These principles are rather simple but are not well-understood becuase the effects are so much smaller than normal flight control forces that they are often ignored.

Bank Angle Control

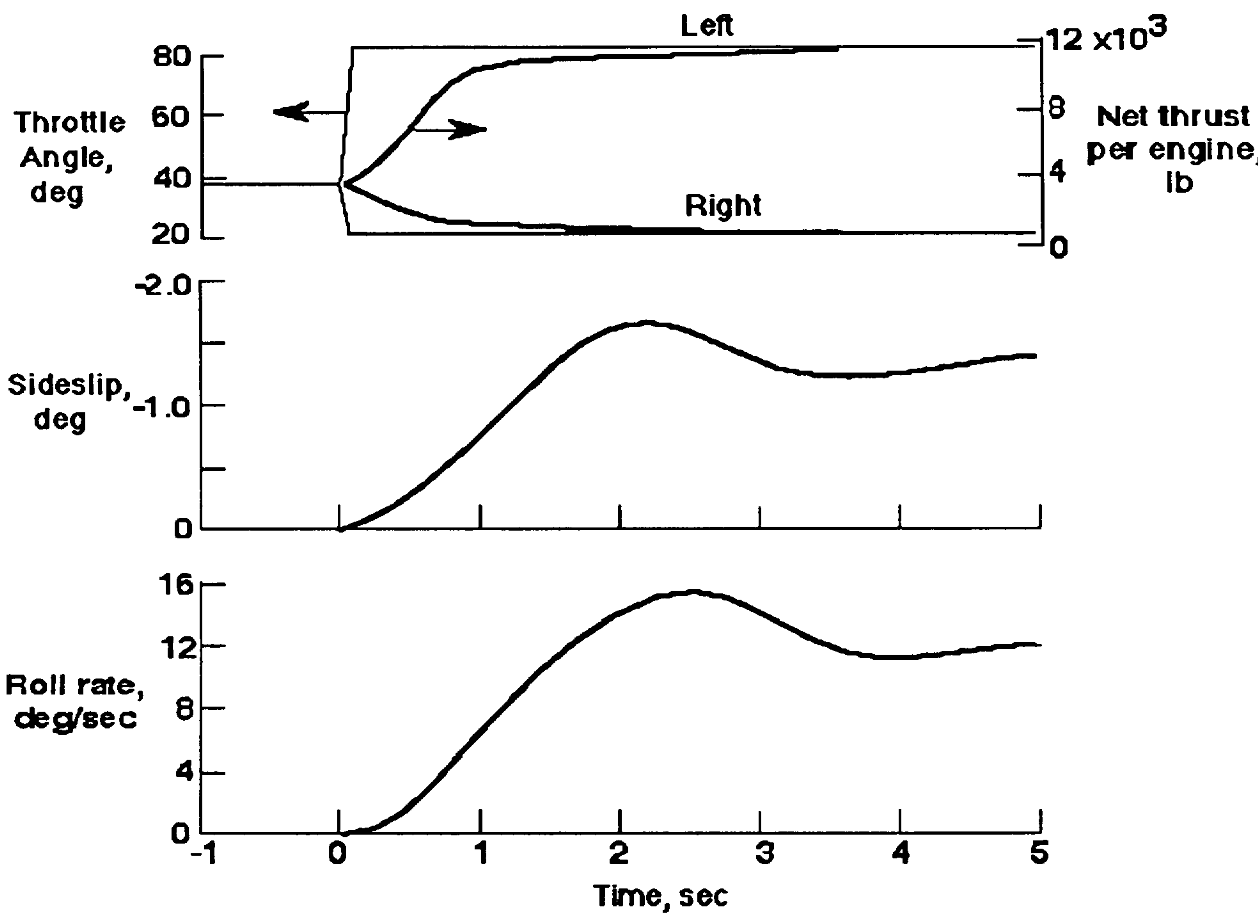
As shown below, bank angle is controlled by using differential thrust, which generates sideslip. The sideslip, through the dihedral effect present on the F-15 and most airplanes, results in roll rate. Roll rate is controlled to establish a bank angle which results in a turn and change in aircraft heading.

Full differential thrust for the F-15 yields a roll rate of about 15 deg/sec at a speed of 170 kts. Because bank angle is controlled by sideslip with throttles-only flight control, the turns are typically not properly coordinated.

Throttles-Only Roll Control

F-15, 170 knots

NASA 93-30

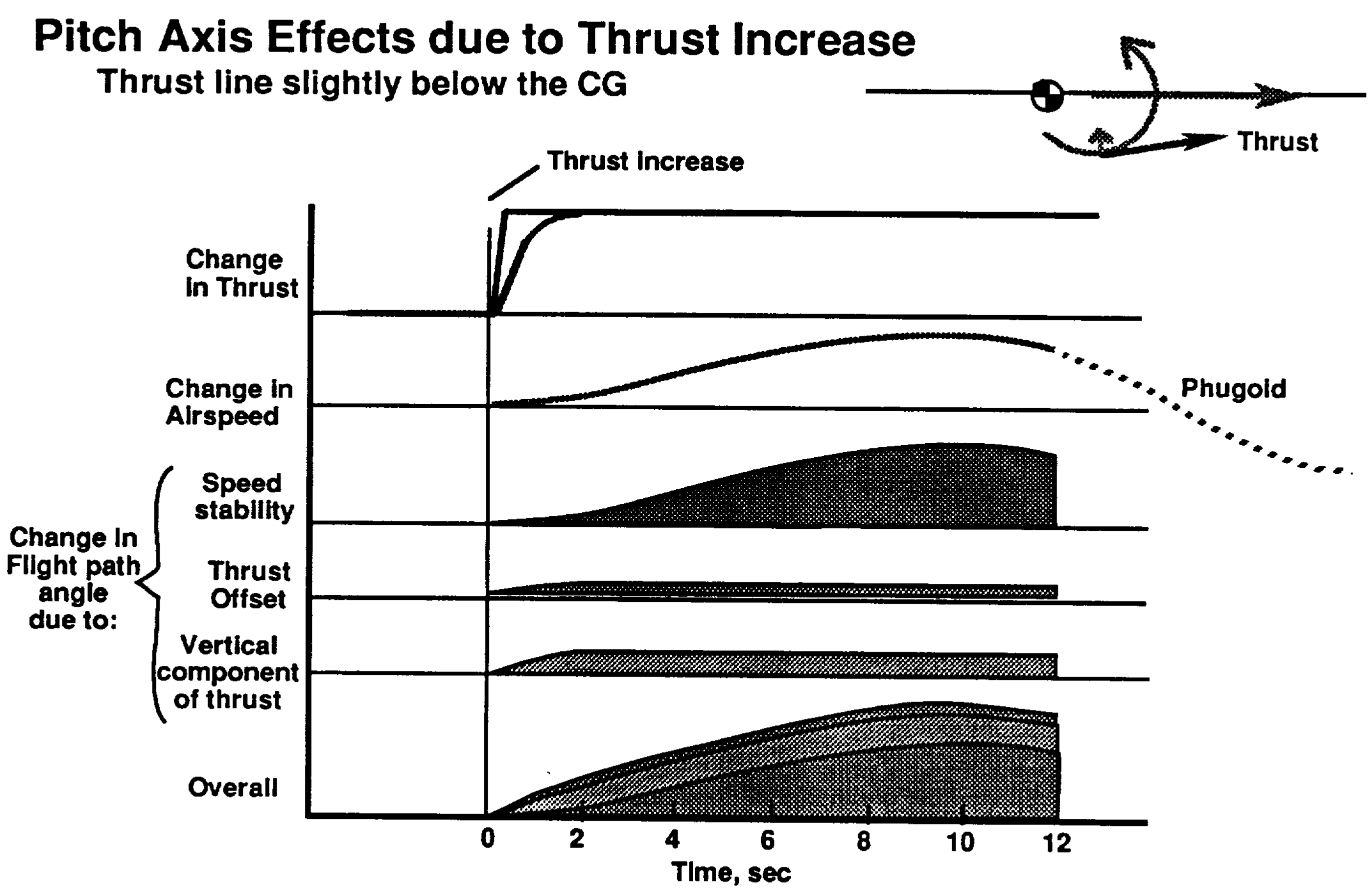


Principles of throttles-only control - Pitch axis

For pitch control due to throttle changes; several effects occur, as shown below.

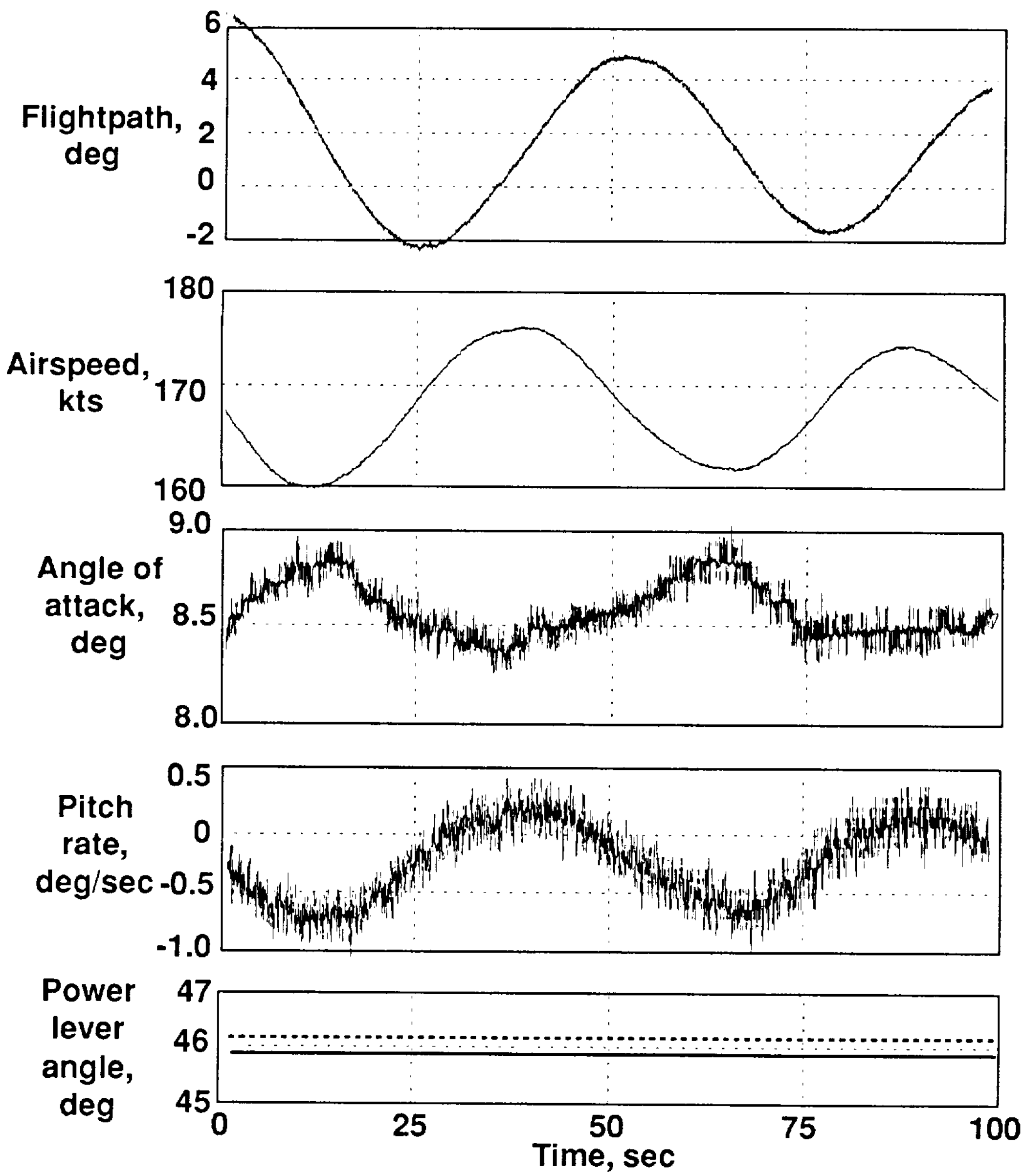
1. *Flight path angle change due to speed stability.* Most stable airplanes, including the F-15 exhibit positive speed stability. Over a short period of time (approx 15 sec), a thrust increase will cause a speed increase, which will cause a lift increase. With the lift being greater than the weight, the airplane will climb, which causes a pitch rate increase. (If allowed to continue for a longer period of time, this effect will be oscillatory, see "phugoid" on the next page. The degree of change to the flight path angle is proportional to the difference between the initial trim airspeed and the current airspeed, hence, the flight path angle tends to increase as speed increases.
2. *Pitching moment due to thrust line offset.* If the engine thrust line does not pass through the center of gravity (CG), there will be a pitching moment introduced by thrust change. For many transport aircraft, the thrust line is below the CG, and increasing thrust results in a desirable nose-up pitching moment, the magnitude being a linear function of the thrust change. This is the desirable geometry for throttles-only control, because a thrust change immediately starts the nose in the same direction as will be needed for the long term flight path angle change. The effect is more a function of change in thrust than in change in speed, and occurs near the time of the thrust increase. For the F-15, the thrust line passes within plus or minus an inch of the vertical CG, depending on fuel quantity, and this effect is small.
3. *Flightpath angle change due to the vertical component of thrust.* If the thrust line is inclined to the flight path, as is commonly the case, an increase in thrust will increase the vertical component of thrust, which will cause a direct increase in vertical velocity, ie, rate of climb, and a resulting increase in flightpath angle. For a given aircraft configuration, this effect will increase as angle of attack,(a) increases (ie, as speed decreases)

For the F-15, the combined effects of the engine thrust is to produce a nose up pitching response that peaks at approximately 2 deg/sec for a throttle step from power for level flight (PLF) to intermediate power on both engines.



Phugoid

The phugoid is the longitudinal long period oscillation of an airplane. It is a motion in which kinetic and potential energy (speed and altitude) are traded. The phugoid oscillation is excited by a pitch, or velocity change, and will have a period of approximately a minute, and may or may not damp naturally. An example of an F-15 phugoid with the gear down and flaps up is shown below. The oscillation was excited by a step increase in thrust, which results in an oscillatory climb with very light damping. Although a very low amplitude phugoid is usually considered to be a constant angle of attack maneuver, if the amplitude is not small, there can be significant angle of attack variations resulting from pitch rate damping, as shown in this example. Properly sized and timed throttle inputs can be used to rapidly damp unwanted phugoid oscillations; these techniques are discussed in ref 2 and 3, and shown on the next page



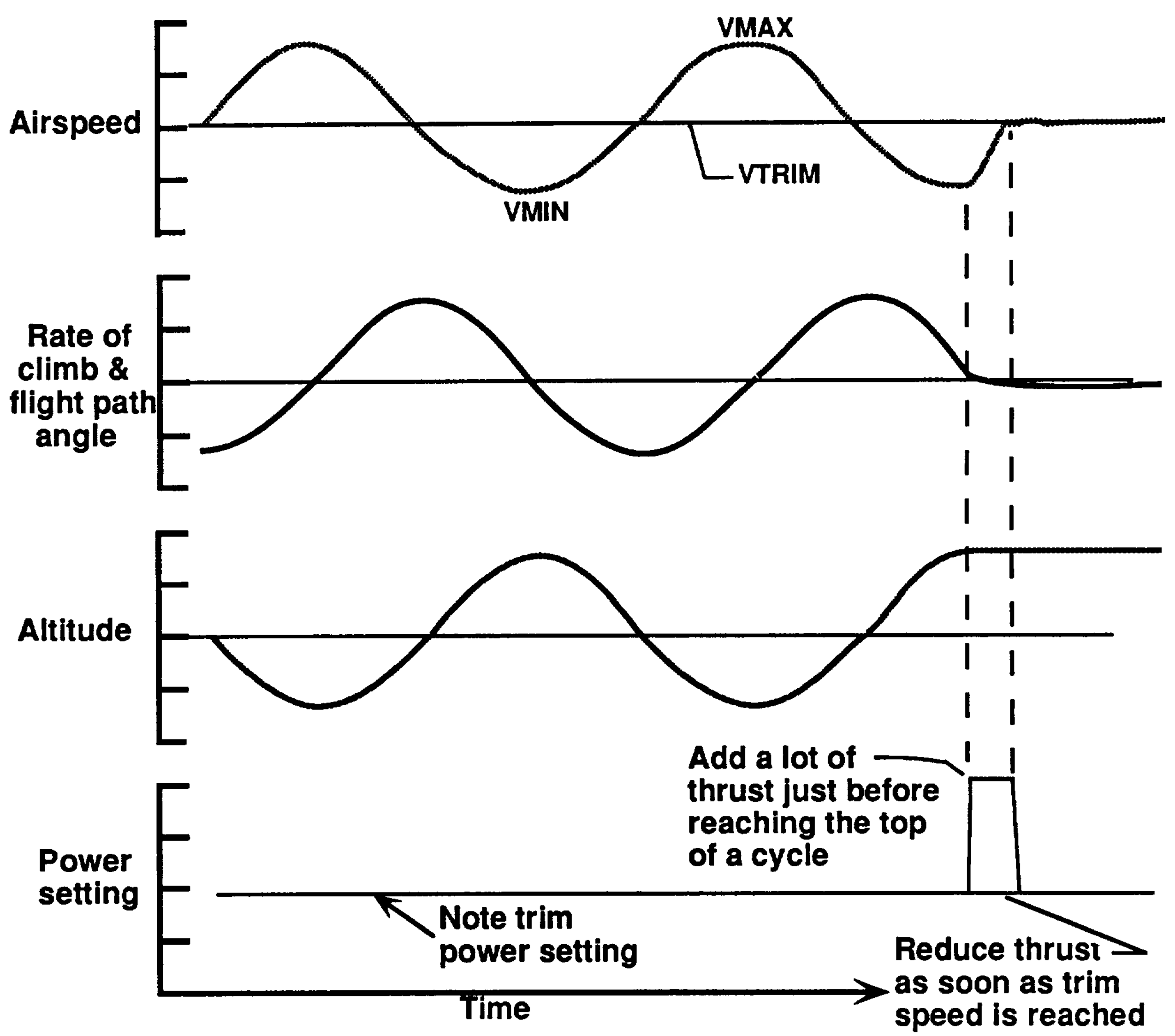
Manual Phugoid Damping Technique

The phugoid, a pitch oscillation in speed and altitude, may be damped with a properly timed and sized throttle input

Suggested technique for damping a phugoid oscillation

1. Determine trim speed from the average of VMAX and VMIN (set bug)
2. Observe trim power setting (EPR or %N1 or %N2) (set bug)
3. Just prior to reaching the top of a cycle, sharply increase power setting (to get speed back to the trim speed as the flight path is approximately level)
4. As soon as the speed increases to the trim speed, rapidly reduce power setting to trim

The phugoid oscillation should now be much smaller

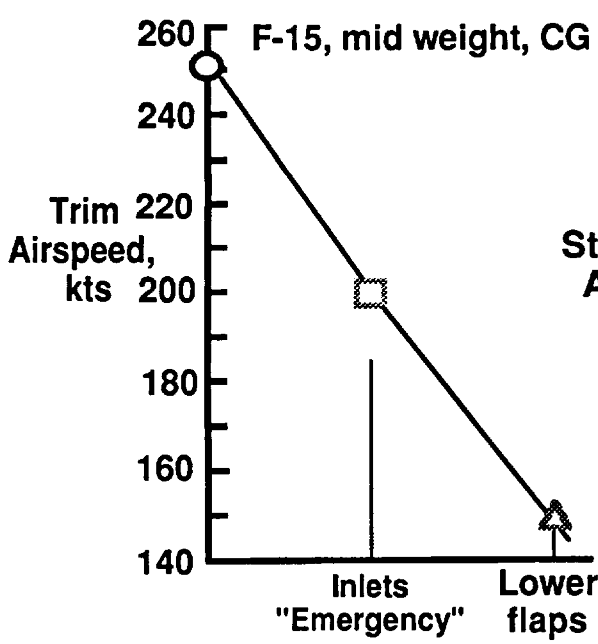


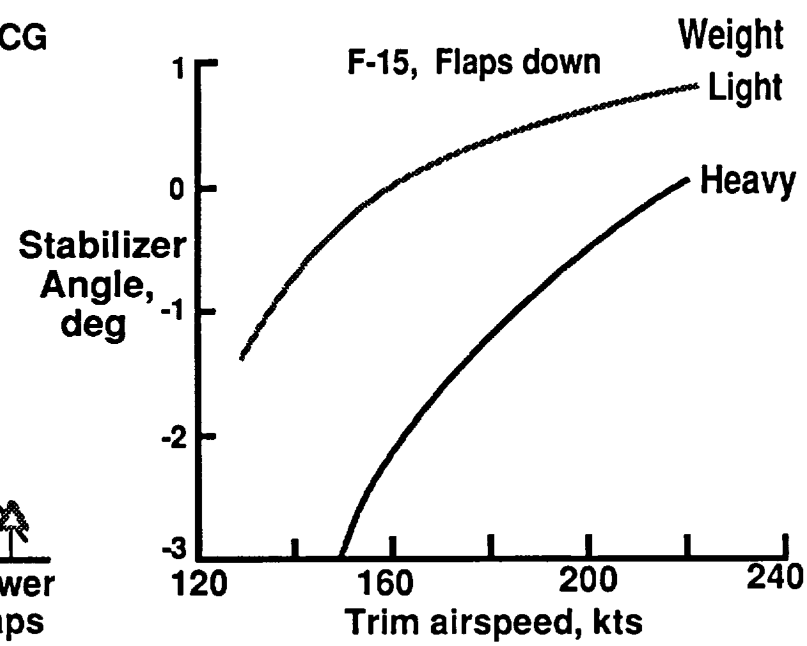
Speed control

Once the flight control surfaces of an airplane are locked at a given position, the trim airspeed of most airplanes is only slightly affected by engine thrust. Retrimming to a different speed may be achieved by other techniques, such as variable stabilizer control, center-of-gravity (CG) control, lowering of flaps, landing gear, and reducing weight. In general, the speed will need to be reduced to an acceptable landing speed; this implies developing nose-up pitching moments. Methods for doing this include moving the CG aft, lowering of flaps, extending the landing gear, or burning off or dumping fuel. Shown below are some of these effects for the F-15.

Trim speed is affected by changes in weight. As weight is reduced (such as by burning fuel), (assuming that the CG remains constant) the lift remains constant , so the airplane tends to climb. To maintain level flight, the throttle setting must be reduced to reduce speed until lift and weight are again in balance. For the F-15, flying at low speed and approaximately level flight, this effect reduces trim speed by approximately 1 knot every 1 to 2 minutes.

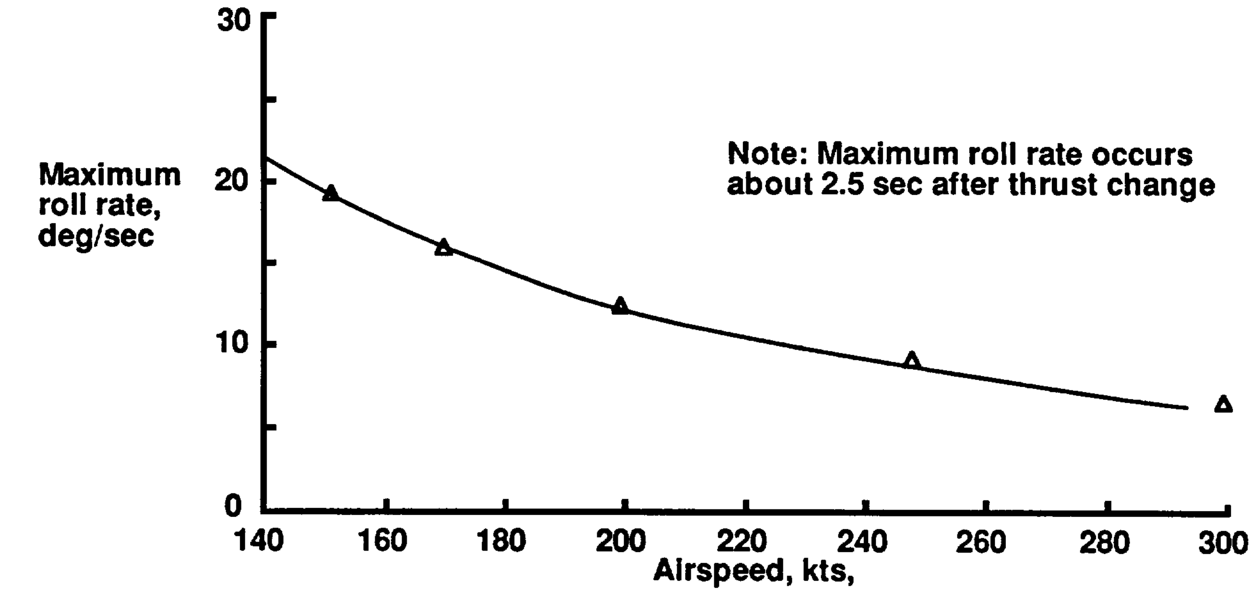
Other effective ways of slowing the F-15 include moving the air inlets to the full-up emergency position, and lowering the flaps. Landing gear extension on the F-15 has essentially no effect on trim speed. Center of gravity control using fuel transfer was studied for the F-15 and was feasible, but was not implemented due to funding constraints.

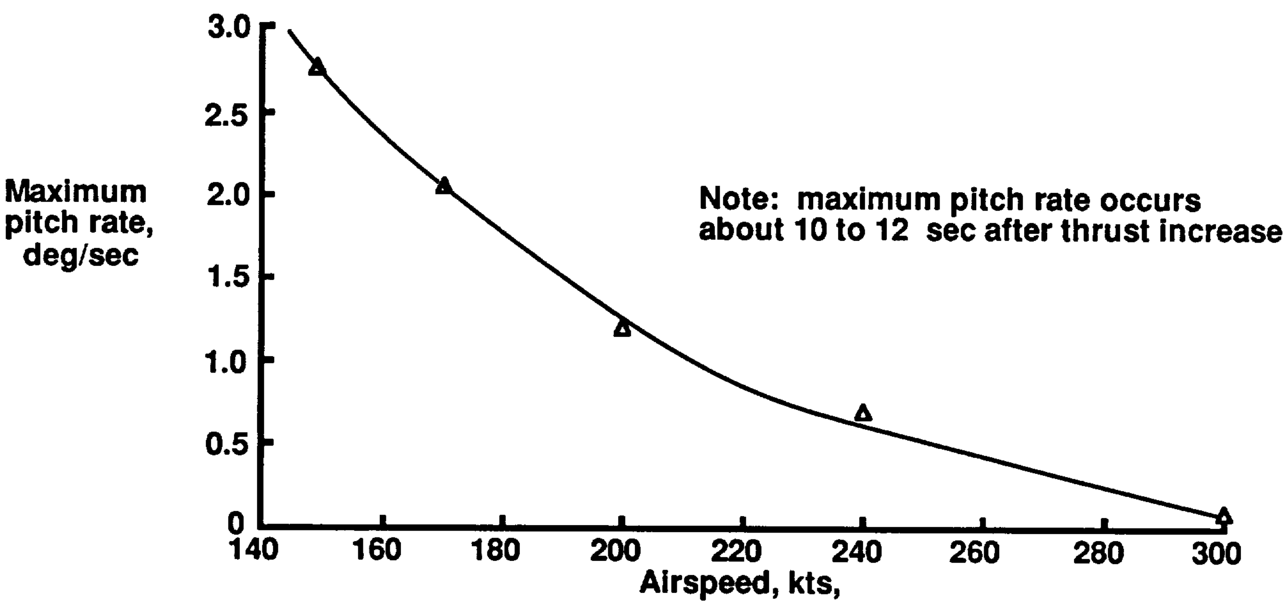




Speed effects on propulsive control power

The propulsive forces (differential thrust for yaw for lateral control and collective thrust for flightpath control) tend to be relatively independent of speed, whereas the aerodynamic restoring forces that resist the propulsive forces are proportional to the dynamic pressure, which is a function of speed squared. This relationship results in the propulsive control power being approximately inversely proportional to the speed. The figure below shows these effects for the F-15. The maximum roll rate for a full differential thrust step varies from 8 deg/sec at 300 kts to 18 deg/sec at 150 kts. The maximum pitch rate, occurring approximately 8 sec after the throttles were stepped from power for level flight (PLF) to intermediate, varies from 0 at 300 kts to 2 deg/sec at 170 kts.





Airplane Stability

The flight controls-failed stability of an airplane is an important consideration for throttles-only control. Large transport airplanes typically have good basic static stability. Yaw dampers may be used for increasing the dutch roll mode stability, but good pitch, roll, and yaw static stability is usually built in. This stability remains if the flight control system should be lost. For fighter airplanes, the airframe may have lower levels of static stability, with adequate stability being achieved with mechanical and/or electronic stability augmentation. Thus in the case of flight control system failure in a fighter, the basic short period stability may be considerably reduced, and the control requirements for a PCA system will be more difficult. (The previous comments do not apply to the long-period phugoid stability which will likely be a problem for both fighter and transport aircraft)

References for PCA Background and Principles

1. F. W. Burcham Jr., Trindel Maine, C. Gordon Fullerton, and Ed Wells: Preliminary Flight Results of a Fly-By-Throttle Emergency Flight Control System on an F-15 Airplane, NASA TM 4503, 1993

2. Burcham, Frank W. Jr., and Fullerton, C Gordon: Controlling Crippled Aircraft - With Throttles, NASA TM-104238, Sept 1991.

3. Dornheim, Michael A.: " Research Pilot Devises Rules of Thumb for Engine-Only Control of Disabled Aircraft", Aviation Week and Space Technology, June 24, 1991, pp 43.

4. Gilyard, Glenn B., Joseph L. Conley, Jeanette L. Le, and Frank W. Burcham, Jr., "A Simulation Evaluation of a Four-Engine Jet Transport Using Engine Thrust Modulation for Flightpath Control, AIAA-91-2223, June 1991.

5. Gerren, Donna: Design, Analysis and Control of a Large Transport Aircraft Utilizing Engine Thrust as a Backup System for the Primary Flight Controls. NASA CR-192938, Mar 1993

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NASA Dryden Flight Research Center

"Propulsion Controlled Aircraft Design and Development"

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Author: Edward A. Wells
Affiliation: McDonnell Douglas Aerospace, New Aircraft & Missile Products
Phone: 314–234–4082
Fax: 314–232–4141
Address: P.O. Box 516; MC 1069020, St. Louis, MO 63166–0516
e–mail: M226336%ETD.DECNET@MDCGWY.MDC.COM

Author: James M. Urnes, Sr.
Affiliation: McDonnell Douglas Aerospace, New Aircraft & Missile Products
Phone: 314–234–3775
Fax: 314–232–4141
Address: P.O. Box 516; MC 1069020, St. Louis, MO 63166–0516
e–mail: STREETER@D318.AVLABS.MDC.COM

Propulsion Controlled Aircraft Design and Development

Edward A. Wells
James M. Urnes, Sr.

McDonnell Douglas Aerospace

This paper describes the design, development, and ground testing of the Propulsion Controlled Aircraft (PCA) flight control system. A backup flight control system which uses only engine thrust, the PCA system utilizes collective and differential thrust changes to steer an aircraft that experiences partial or complete failure of the hydraulically actuated control surfaces. The objective of the program was to investigate, in flight, the throttles-only control capability of the F-15, using manual control, and also an augmented PCA mode in which computer-controlled thrust was used for flight control. The objective included PCA operation in up-and-away flight and, if performance was adequate, a secondary objective to make actual PCA landings.

The PCA design began with a feasibility study which evaluated many control law designs. 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. A flight test baseline configuration was selected based on projected flight performance, applicability to transport and fighter aircraft, and funding cost. During the PCA software and hardware development, the initial design was updated as data became available from throttle-only flight experiments conducted by NASA on the F-15. This information showed basic airframe characteristics that were not observed in the F-15 flight simulator and resulted in several design changes. After the primary objectives of the PCA flight testing were accomplished, additional PCA modes of operation were developed and implemented. The evolution of the PCA system from the initial feasibility study, control law design, simulation, hardware-in-the-loop tests, pilot-in-the-loop tests, and ground tests is presented in this paper

DESIGN OF THE PCA SYSTEM

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. 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.

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.

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. Use of the center control stick was eliminated because control column motion would require an automatic cancellation of the mechanical control system outputs in order to maintain fixed control surfaces during the flight test. There were no other suitable controllers available in the F-15 cockpit, so three possibilities were examined; a side mounted force joystick, a side mounted displacement joystick, and a pair of side mounted thumbwheels. Some key characteristics of the three remaining candidates are listed below.

- Miniature Force Joystick
  +/- 3.1 lbs full scale
  spring loaded to center
  1 inch stick handle length

- Miniature Displacement Joystick
  +/- 30 deg full scale
  spring loaded to center
  1.5 inch stick length

- Thumbwheels
  +/- 175 deg full travel
  not spring loaded to center
  detent at center of travel

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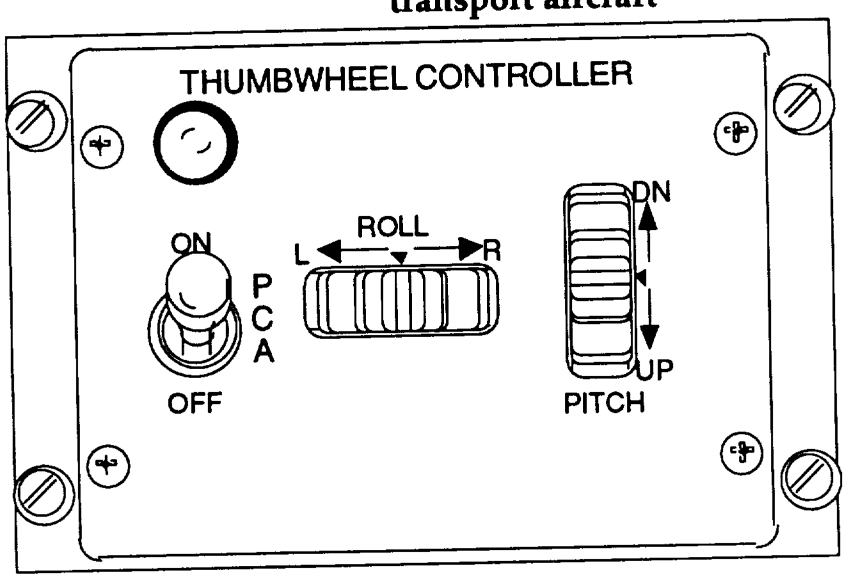
  - spring loaded to center
  - 1.5 inch stick length
- Thumbwheels
  - +/- 175 deg full travel
  - not spring loaded to center
  - detent at center of travel

Joystick - Thumbwheel Comparison

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. The Thumbwheel Controller Panel (TCP) is shown in the figure below 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 **Small size of handle** **Small range/poor resolution** **Incremental command hard to attain**	**Thumbwheels remain where set** **Thumbwheels used in prev pgm** **Large range/good resolution** **Incremental commands easy**
Virtually no pitch/roll isolation	**Separate pitch and roll thumbwheels**
Ability to hold command during flight questioned	**Not required to hold thumbwheel so aircraft motion does not affect command, Similar controls used in transport aircraft**



Thumbwheel Control Panel

PCA Control Law Development Trade Studies

Several trade studies were performed during the development of the PCA control laws. One study focused on the importance of augmenting the phugoid frequency versus the phugoid damping. Because flight data had shown that it was very difficult to damp phugoid oscillations using manual throttle inputs, augmenting the phugoid damping was one of the early design goals. The value of augmenting the phugoid frequency, however, was an unknown 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 pilot rating 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 summarized below.

Variations Tested	Parameter Yielding Improvement	Cooper-Harper Rating Improvement
Flight Path Angle vs Flight Path angle Rate Stick Command	Flightpath 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

Results of Four Trade Studies

PCA Control Law Development - Longitudinal Feedback Trade Study

The feasibility study also examined the selection of longitudinal feedback parameters. 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.

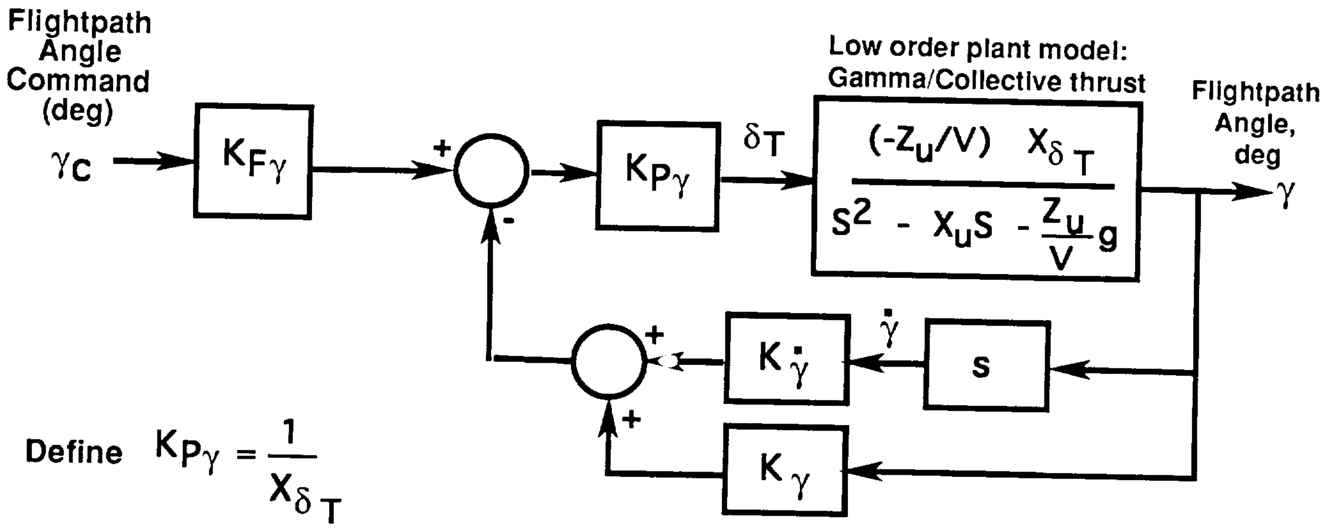
Phugoid Dynamics

Feedback (to thrust)	Low Speed		High Speed	
	Damping	Frequency	Damping	Frequency
Flightpath Angle	—	Good	—	Fair - large gain req'd
Flightpath Angle Rate	Good	—	Fair - large gain req'd	—
Pitch Rate	Good - Wings Level		Fair - large gain req'd	
Airspeed	Good - Need Reference		Good - Need Reference	

Results of Longitudinal Feedback Selection Trade Study

Longitudinal Model Design

Once the requirements were defined, design of the control law gains could begin. The linear, low order model of the airframe is shown below in the upper figure. As shown in the lower figure, 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). 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.



Define $K_{P\gamma} = \dfrac{1}{X_{\delta T}}$

Actual Closed Loop Transfer Function

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

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

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

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

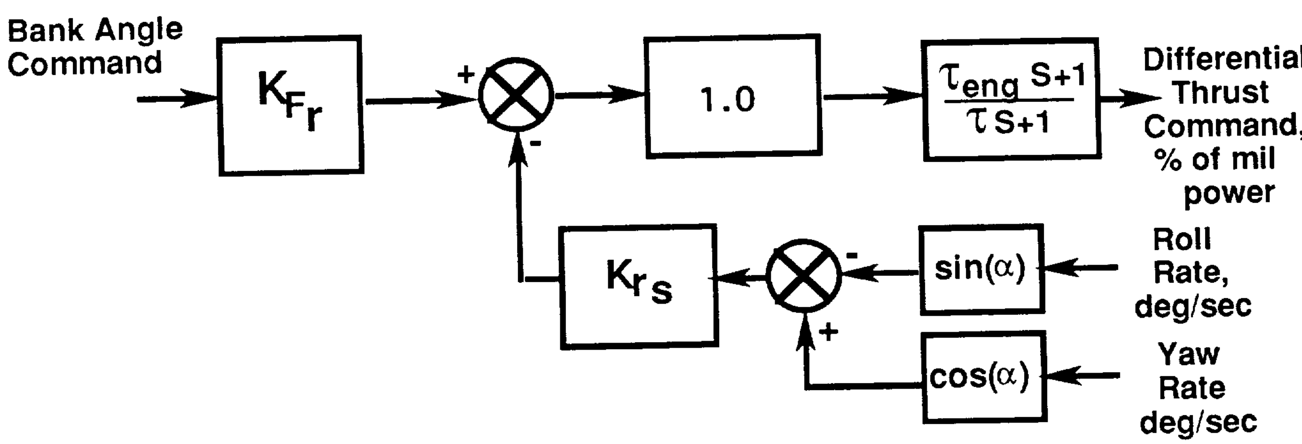
Equate Actual and Desired Numerator

$$\frac{Z_u}{V}K_{F\gamma} = -W^2 \longrightarrow K_{F\gamma} = -W^2\frac{V}{Z_u}$$

Longitudinal Gain Determination

PCA Control Law Development - Lateral Axis

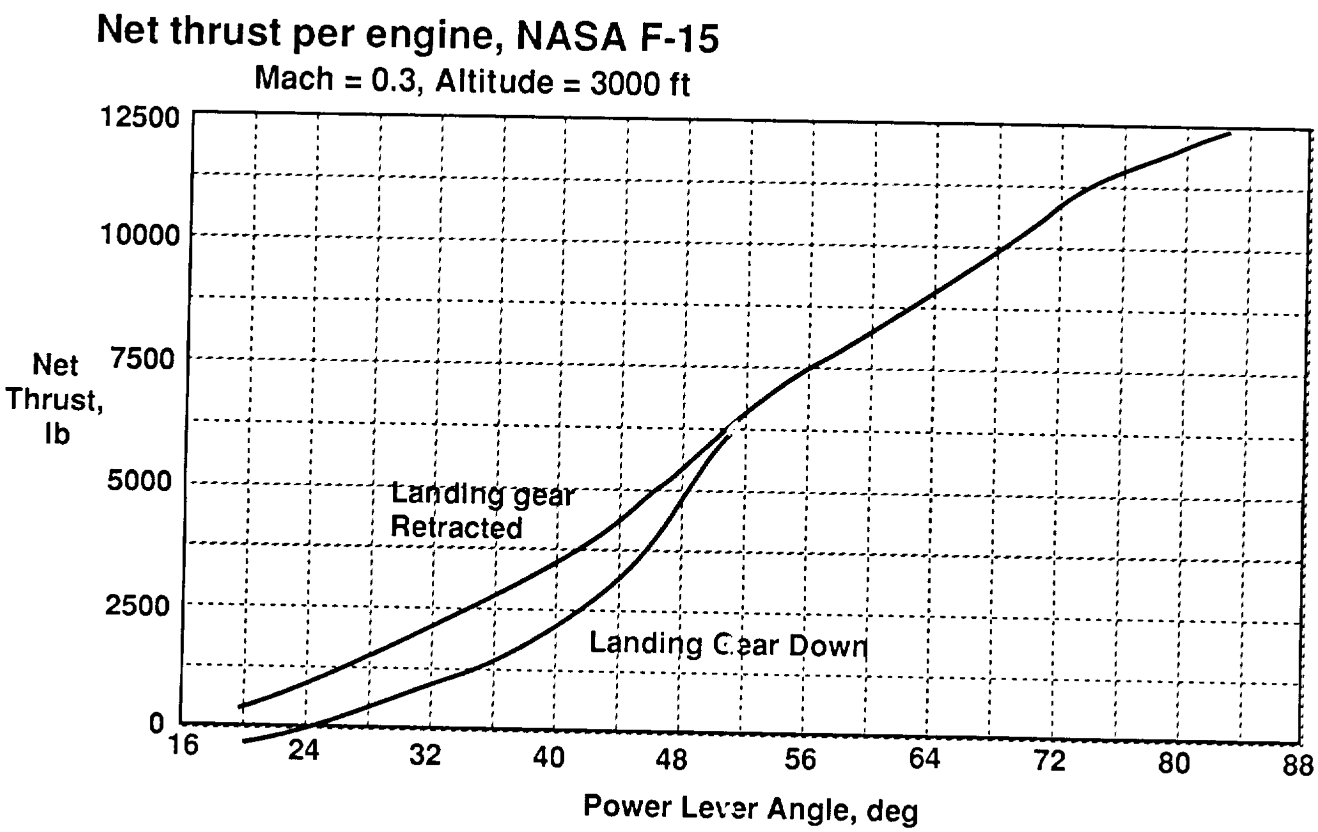
For the lateral control law, stability axis yaw rate was the feedback incorporated to dampen the dutch roll mode and provide a turn rate reference. The gain was selected to maintain a flat frequency response for as high a frequency as possible. Additionally, a lead-lag filter was developed using an engine time constant of 1.3 seconds. Schedules were developed to automatically adjust the control law gains for weight and airspeed variations. This control performed well in the F-15 linear simulation.



Lateral Control Law Block Diagram

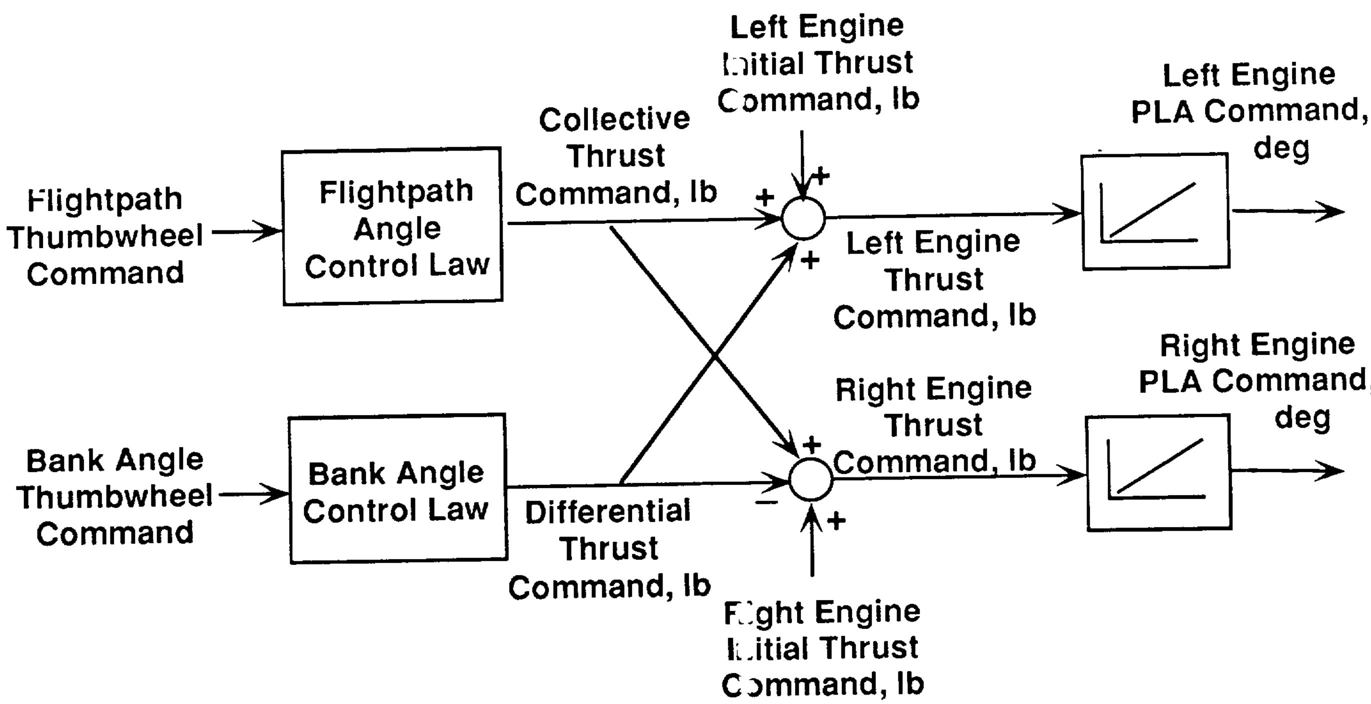
Engine thrust versus power lever angle

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 engine digital controllers were designed to accept PLA commands. This function was developed using design point data (188 knots at 3000 feet) from the engine model. With the landing gear retracted, the thrust per engine varies from about 500 lb at idle to about 12,000 lb at intermediate power (the maximum limit for PCA operation). With the landing gear down, there is a feature called idle area reset (IAR) that, to reduce thrust, opens the nozzle as PLA is reduced below 50 deg. The effect of this IAR is to make the thrust non-linear and to have a relatively steep slope in the PLA range from 40 deg to 50 deg. This is the PLA range for most PCA operation.



Thrust-PLA Function Integration into PCA Control Law

The thrust versus PLA function from the previous page was integrated into the PCA control laws as shown below. The resulting control law performance in the non-linear simulation was compared to linear results. In almost all cases, an excellent match was obtained between the non-linear simulation and the linear results and was ready to be tested with NASA pilots in the manned simulator.



PCA Control Law - Sensitivity Analysis

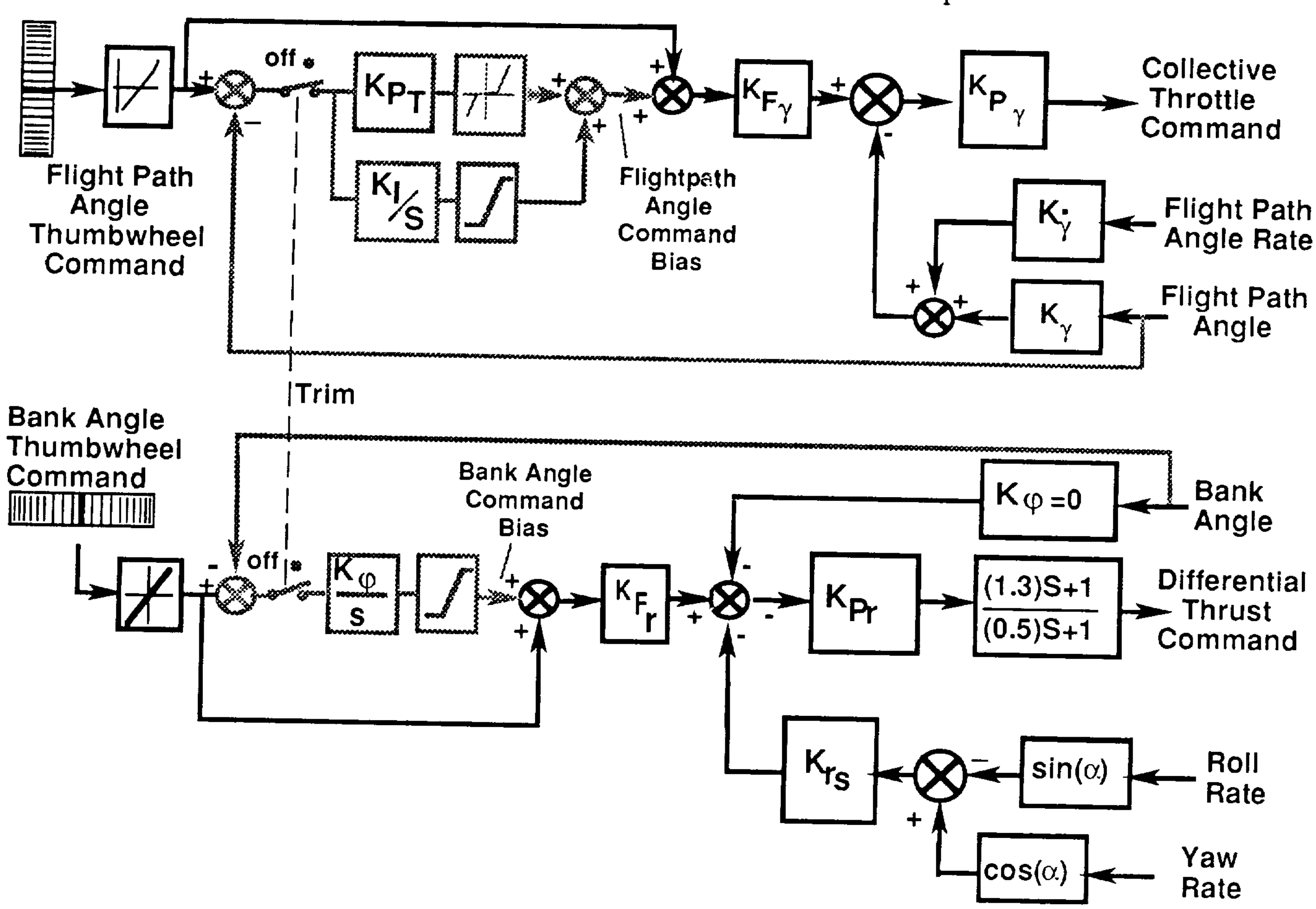
Using the manned simulator, a study was conducted to determine how sensitive PCA performance was to a number of parameter variations. The effects of fifteen parameters were examined during tests with two NASA pilots. The result was that performance was not significantly degraded for any of the parameter 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.

PCA Control Law -Trim requirement

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 adding forward path integrators to the baseline PCA control law, but the feasibility study showed that this type of addition could result in larger overshoot, longer settling time, and reduced performance overall. 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.

PCA Control Law with Trim

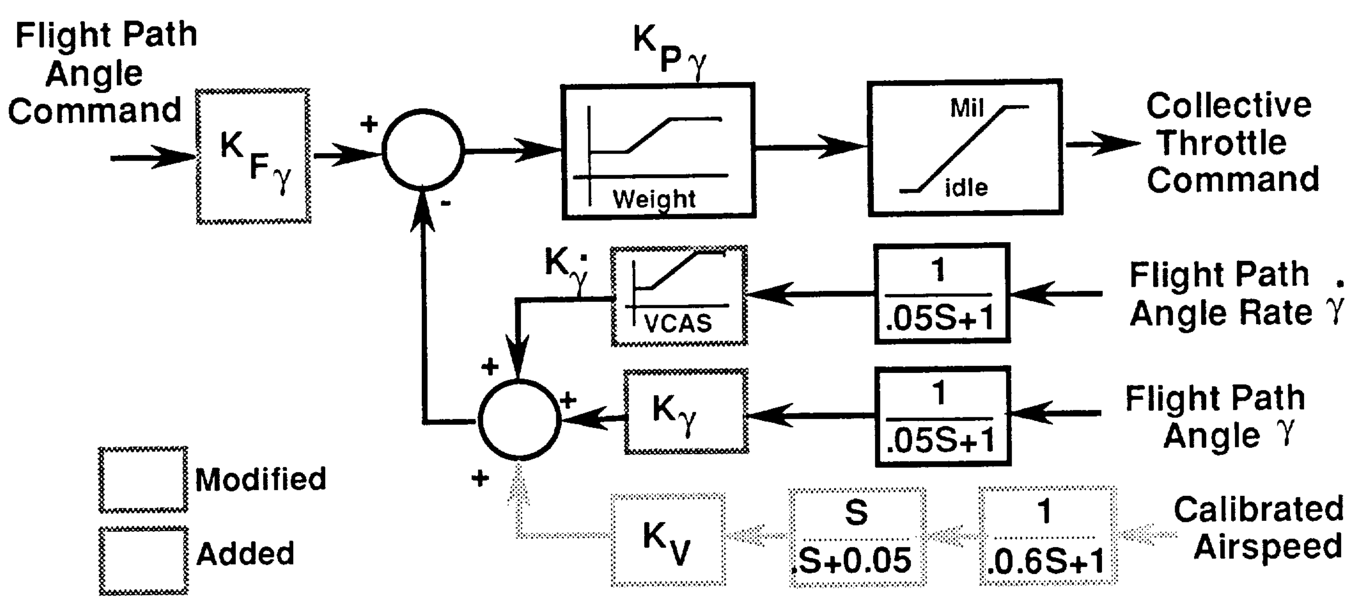
A two step trim mode was developed for the PCA control law. The trim mode would execute when the PCA system was initially coupled and then turn itself off when the aircraft was sufficiently trimmed. For this mode, a proportional plus integral path was added to the baseline longitudinal control law and an integral path was added to the lateral control law. 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. 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.



Inlet Airflow Effect

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 developed from the flight and wind tunnel data, shown in the flight test paper. As shown in that paper, this pitching moment increment resulted in a satisfactory comparison between the six-degrees-of-freedom simulation and the flight data.

The existence of this phase reversal caused a re-assessment of the longitudinal control law. A velocity feedback path was added to improve PCA performance at the higher airspeed conditions where the inlet airflow effect was important. Characteristics such as the reversal due to inlet airflow have relatively minor effect when the normal flight control system is operating, but have a more pronounced impact during propulsion-only control.

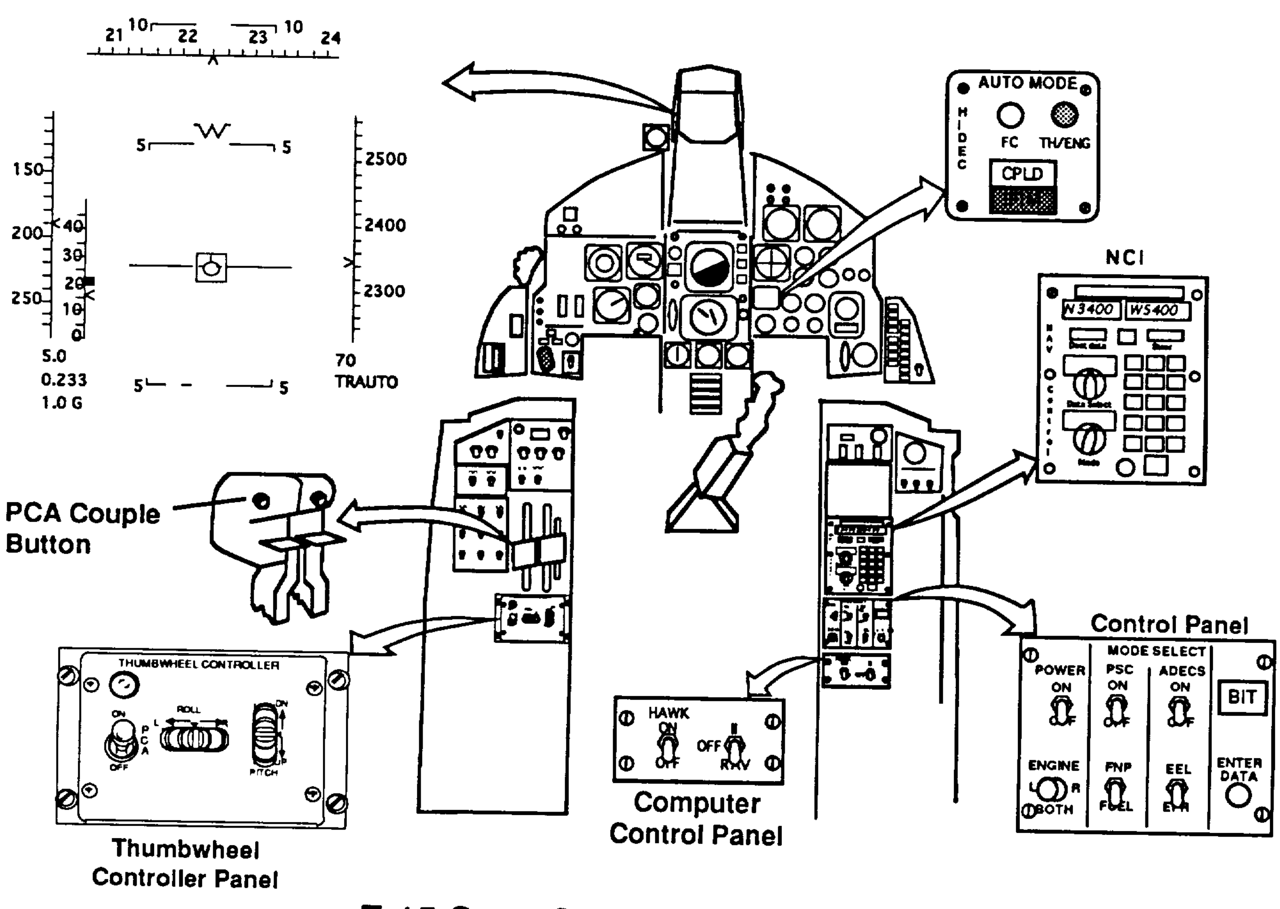


Control Law Modification for Inlet Airflow Effect

PCA Cockpit Control and Display Development

The pilot was able to interact with the PCA demonstration system through several cockpit components. Shown below is 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.

The PCA demonstration provided 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 illuminated when the PCA system was coupled and the red IFIM light illuminated if the In-Flight Integrity Management software detected a system failure. The green TH/ENG light was illuminated when the PCA switch was on.

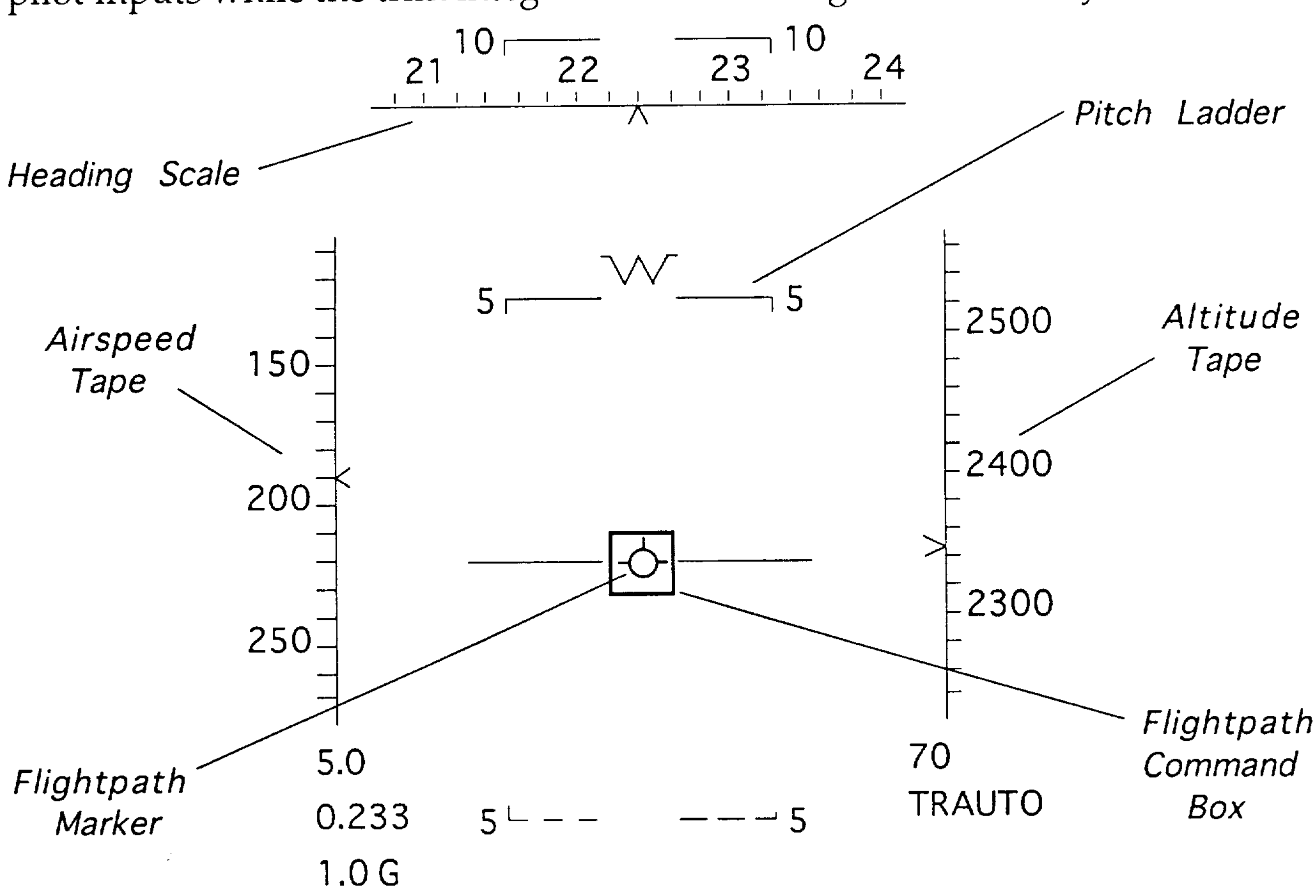


F-15 Crew Station for PCA Testing

PCA HUD Display

The PCA command box was drawn on the HUD while the system was coupled and would flash while the trim control laws were executing. It can be seen centered on the velocity vector in Figure 16. In the lower right corner of the HUD a mnemonic was displayed which indicated the position of the PCA trim switch: TROFF when the PCA trim was off; TRAUTO when the PCA trim was in the automatic mode; TRON when the PCA trim was on. A radar altimeter reading in feet above ground level was 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

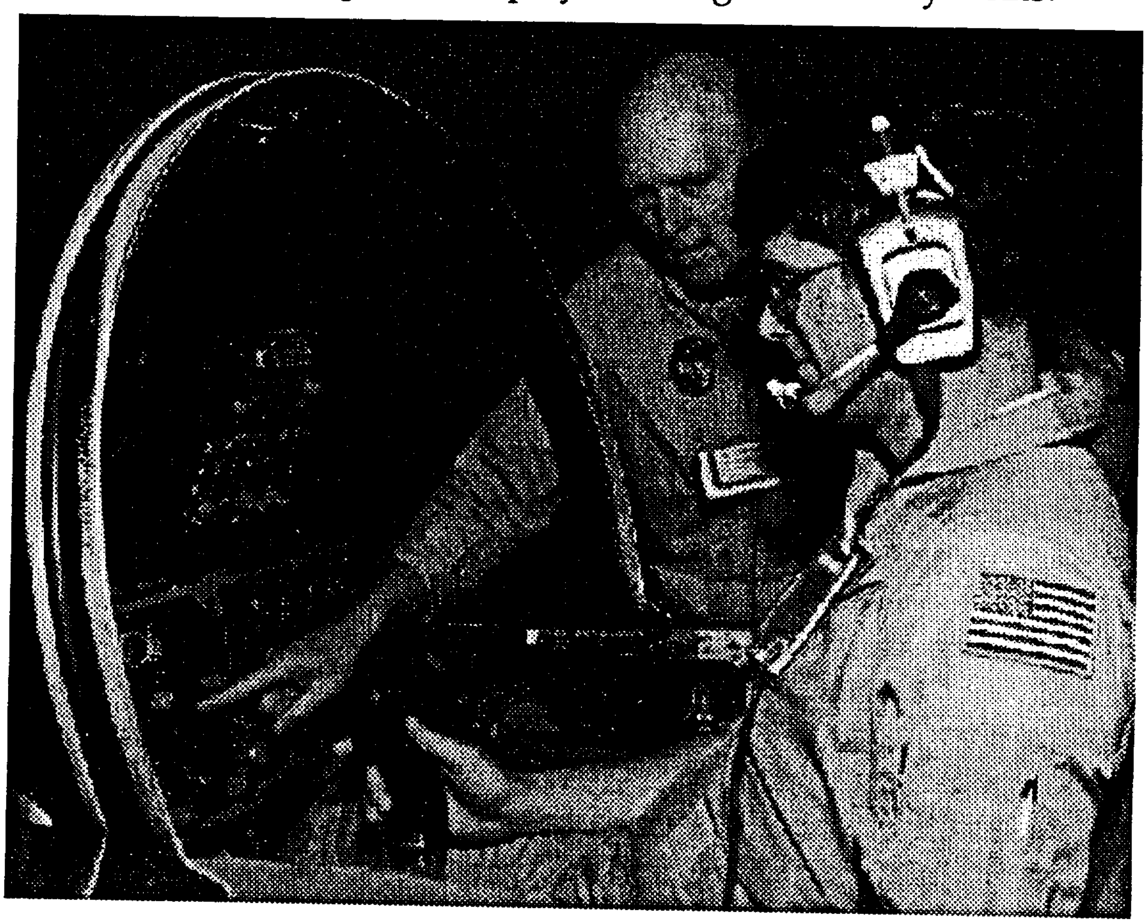


PCA Heads Up Display

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.

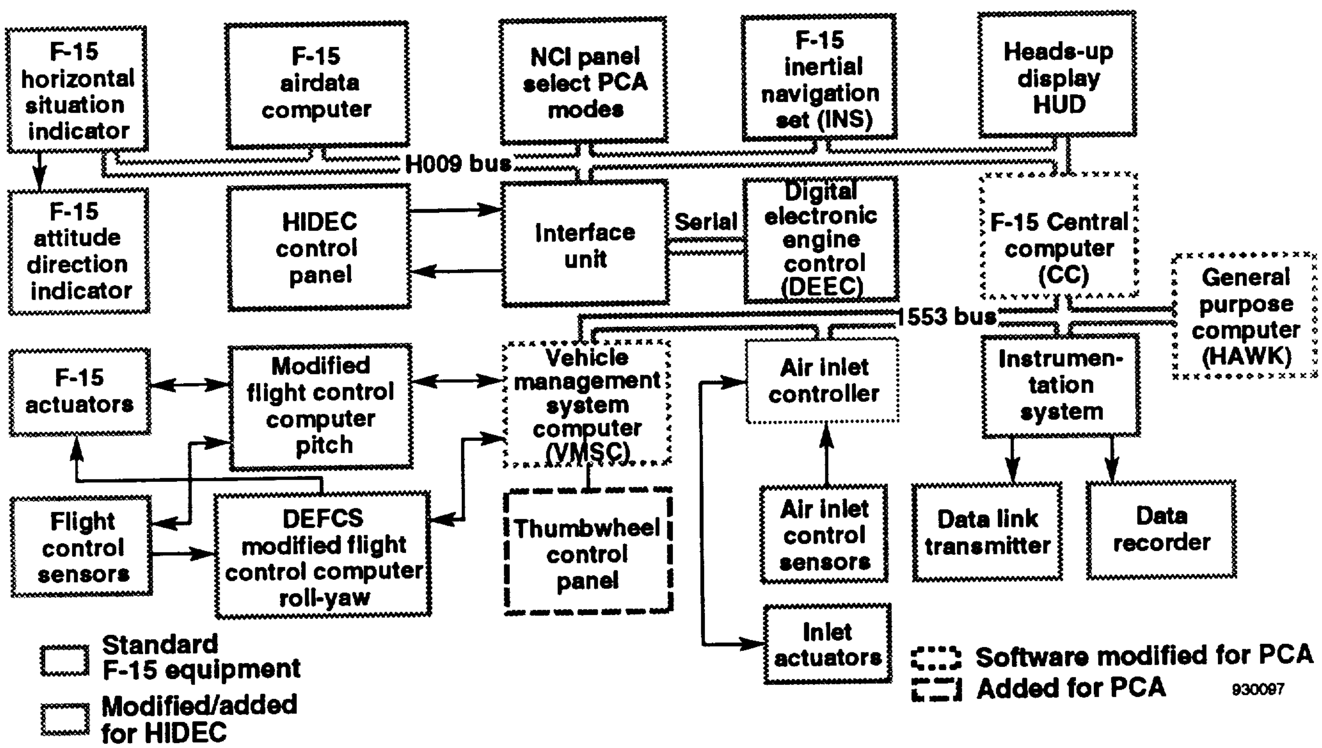


PCA Software tests in the MDA Simulator

PCA Implementation

PCA Hardware Development

The PCA system was installed on the F-15 HIDEC airplane using much of the already then-existing hardware and system interfaces. The only hardware added were the pitch and roll thumbwheels, as shown below.



PCA Hardware Implementation on the F-15

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 general-purpose research (Hawk) computer. 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.

Flight Software

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 a 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 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. Shown below are 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.

Signal Monitor Limits	Input Biases	Input Scale Factors
Noise Filters	Envelope Limits	Flight Path Rate Calculation
Weight Input	Signal Channel(s)	Fuel Flow Source
Control Law Gains	PLA Step Biases	Gain Schedule Input Source
Wash-out Filters	Control Law Modes	Trim Control Law Modes
		Thumbwheel Scale Factors

NCI-Selectable parameters

Flight Software (Continued)

In addition to the IFIM logic in the Central Computer(CC), 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.

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 inertial navigation set(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.

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 wire bundle. The software for the VMSC and the Hawk was transported to the NASA Dryden Flight Research Center (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.

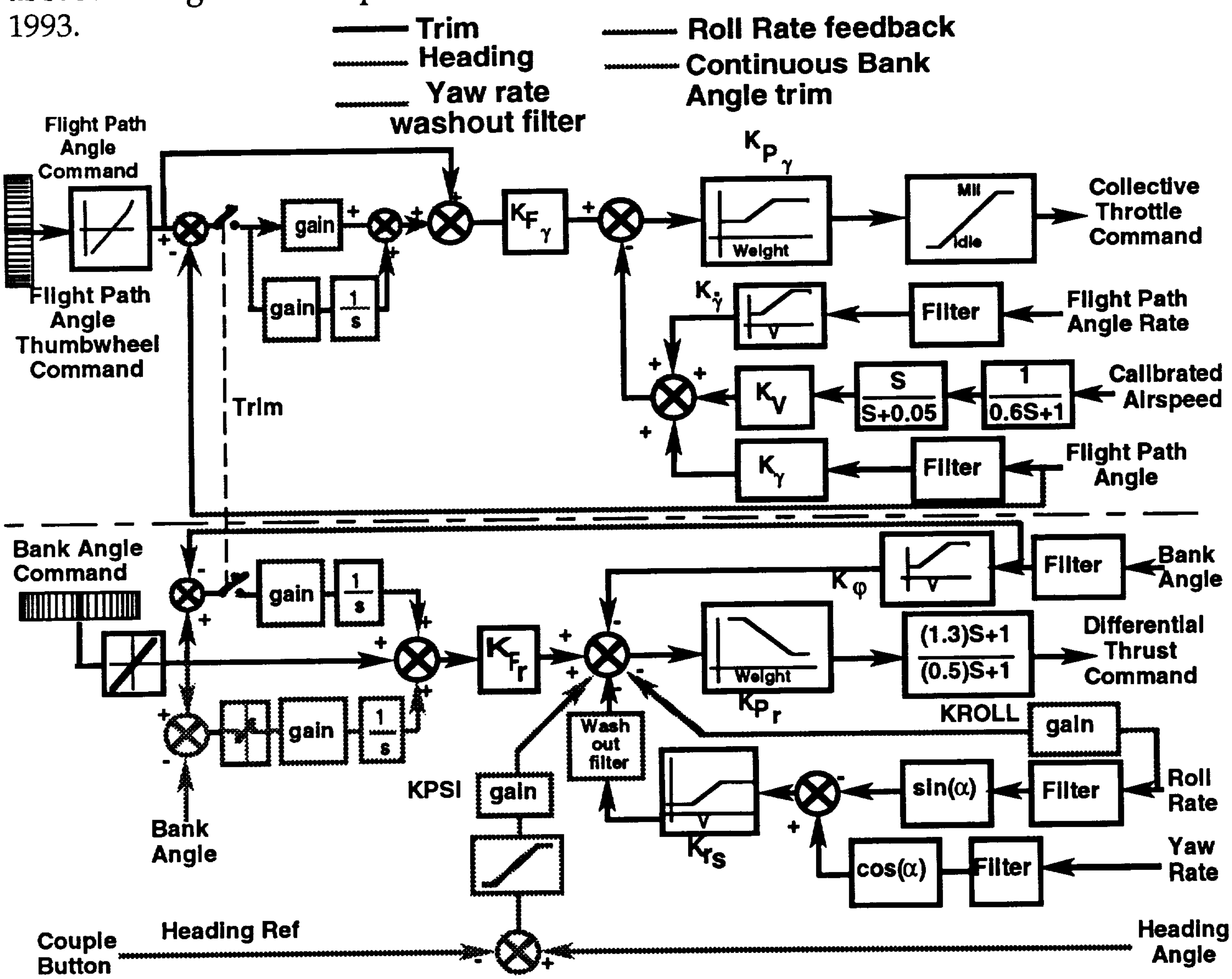
Ground testing at NASA-Dryden consisted of a series of five tests: Instrumentation, Functional, Radiation, Electromagnetic Interference (EMI) and Combined Systems Test. The Instrumentation Test verified that the aircraft telemetry system and the PCA system were working together correctly. The Functional 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.

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 already 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 was a valuable tool during integration and ground testing as well as flight development.

Additional Software Development

After the PCA-controlled landings, and 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, 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 only significant software change required to test this mode was the ability to operate PCA with one engine at idle power.

There were several features added to the PCA software, as shown below. The most significant 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.



PCA Logic block diagram additions including Heading mode

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NASA Dryden Flight Research Center

"Flight Test of a Propulsion Controlled Aircraft System on the NASA F-15 Airplane"

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Author: Frank W. Burcham Jr.
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3126
Fax: 805–258–3744
Address: M. S. D2033, P. O. Box 273, Edwards, CA 93523–0273
e–mail: Bill_Burcham@QMGATE.DFRF.NASA.GOV

Author: Trindel A. Maine
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3794
Fax: 805–258–3744
Address: M. S. D2033, P. O. Box 273, Edwards, CA 93523–0273
e–mail: tam@alien.dfrf.nasa.gov

Flight Test of a Propulsion Controlled Aircraft System on the NASA F-15 Airplane

Frank W. Burcham
Trindel A Maine

NASA Dryden Flight Research Center

Abstract

Flight tests of the PCA system on the NASA F-15 airplane evolved as a result of a long series of simulation and flight tests. Initially, the simulation results were very optimistic. Early flight tests showed that manual throttles-only control was much more difficult than the simulation, and a flight investigation was flown to acquire data to resolve this discrepancy.

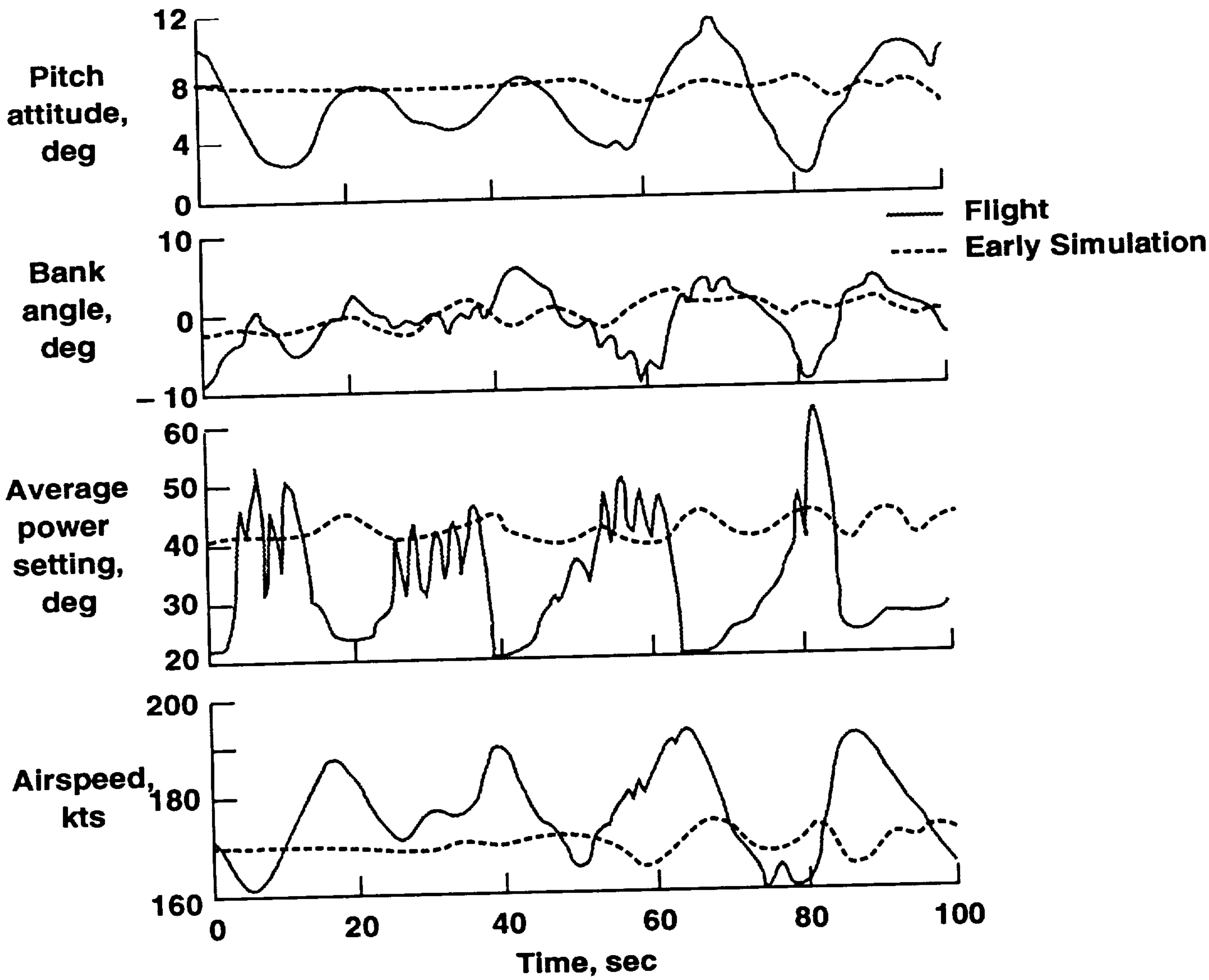
The PCA system designed and developed by MDA, and described in the previous paper, evolved as these discrepancies were found and resolved, requiring redesign of the PCA software and modification of the flight test plan. Small throttle step inputs were flown to provide data for analysis, simulation update, and control logic modification.

The PCA flight tests quickly revealed less than desired performance, but the extensive flexibility built into the flight PCA software allowed rapid evaluation of alternate gains, filters, and control logic, and within 2 weeks, the PCA system was functioning well. The initial objective of achieving adequate control for up-and-away flying and approaches was satisifed, and the option to continue to actual landings was achieved.

After the PCA landings were accomplished, other PCA features were added, and additional maneuvers beyond those originally planned were flown. The PCA system was used to recover from extreme upset conditions, descend, and make approaches to landing. A heading mode was added, and a single engine plus rudder PCA mode was also added and flown. The PCA flight envelope was expanded far beyond that originally design for. Guest pilots from the USAF, USN, NASA, and the contractor also flew the PCA system and were favorably impressed.

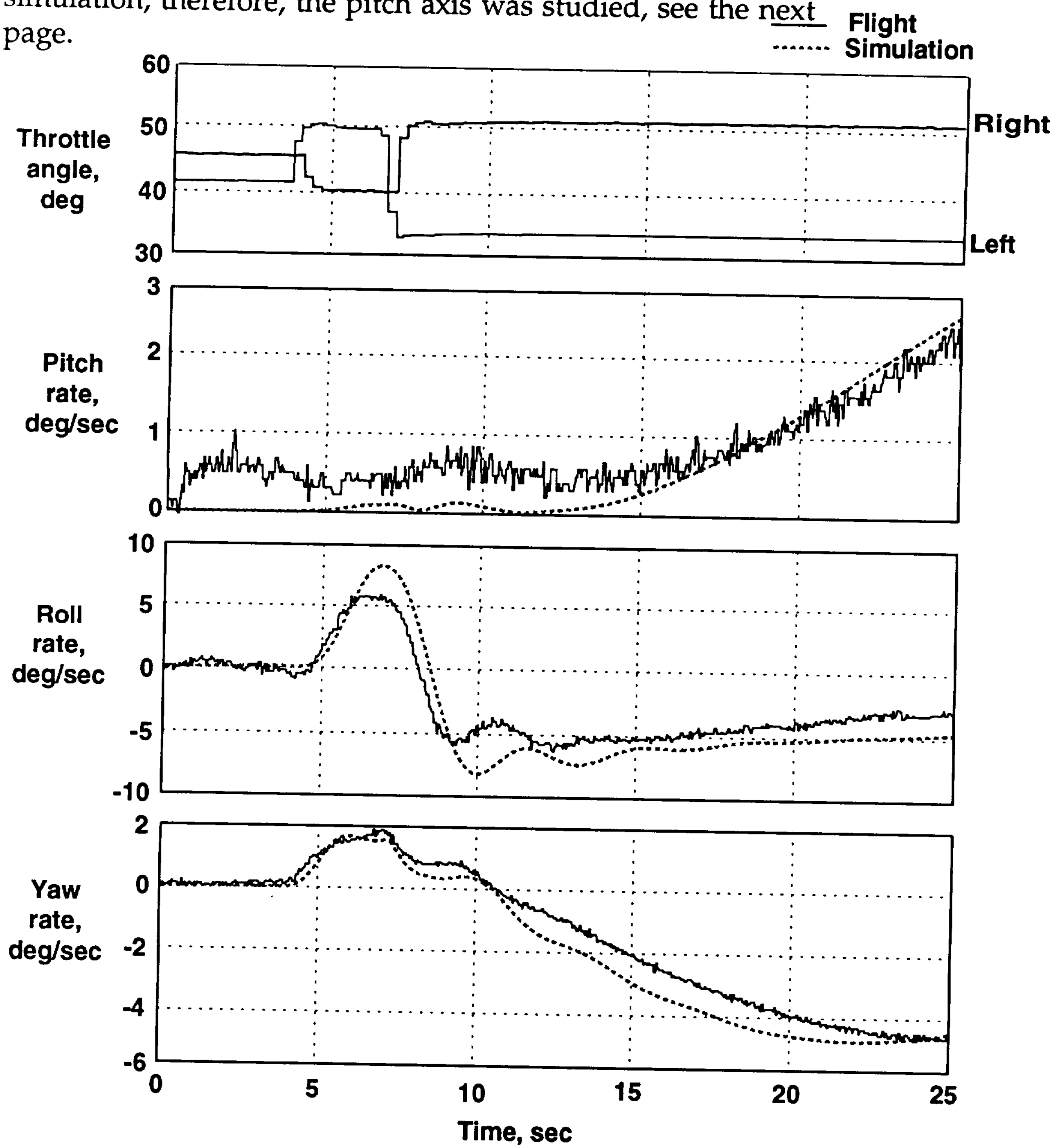
Comparison of Early Simulation and Flight Approach

The early F-15 throttles-only simulation at Dryden showed that manual throttles-only approaches were difficult initially, but after some practice, pilots became proficient enough to make successful landings every time. First attempts at manual approaches in the NASA F-15 airplane were made, and were surprisingly unsuccessful, even after much practice. Shown below is a comparison of a flight and simulation approach at the same conditions; the much poorer performance in the airplane is clearly evident. The video shows a typical example. The basic airplane stability in the "CAS-off Pitch and roll ratios emergency" mode and "inlets emergency" mode was lower than in the simulation. The pilot had great difficulty in stabilizing on the desired flightpath, and had the throttles on the idle stop part of the time. The airplane would not stay wings-level for more than a few seconds. The pilot rated the chances of a safe throttles-only landing in the airplane at zero. The reasons for the simulation-to-flight discrepancies had to be resolved prior to designing the PCA logic.



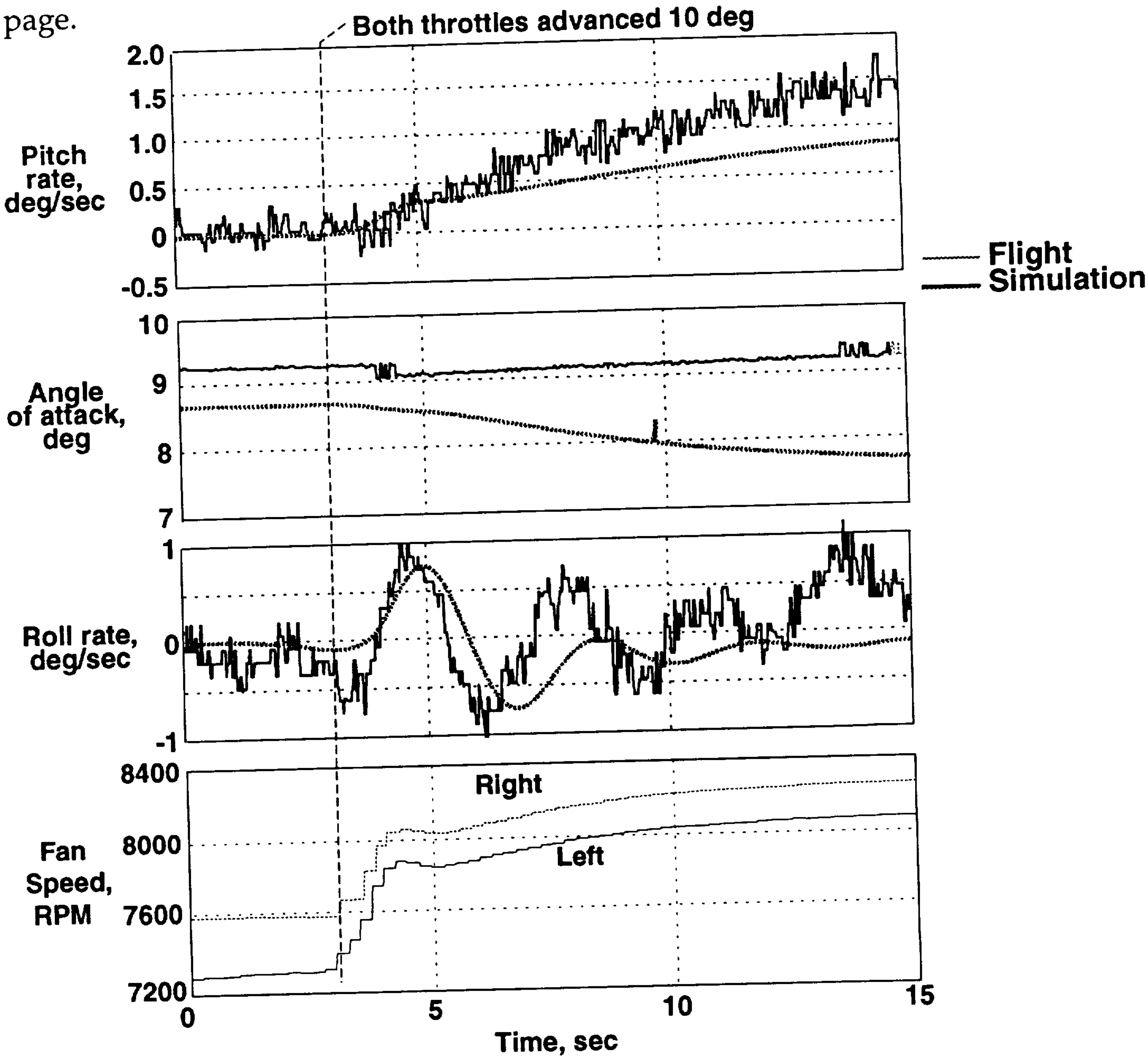
Differential Throttle Step Tests

Small step inputs in throttle settings were made to obtain data to compare to the simulation. A typical differential throttle roll test case is shown below. The pilot initially split the throttles approximately 2 inches and held that for 3 seconds, then split the throttles 2 inches in the opposite direction. The flight-to-simulation yaw rate match is very good. The resulting roll rate oscillations were comparable in frequency and damping in both the flight and the simulator response, although the roll rates are higher in the simulation than in the flight data. This good agreement does not explain the discrepancy between flight and simulation, therefore, the pitch axis was studied, see the next page.



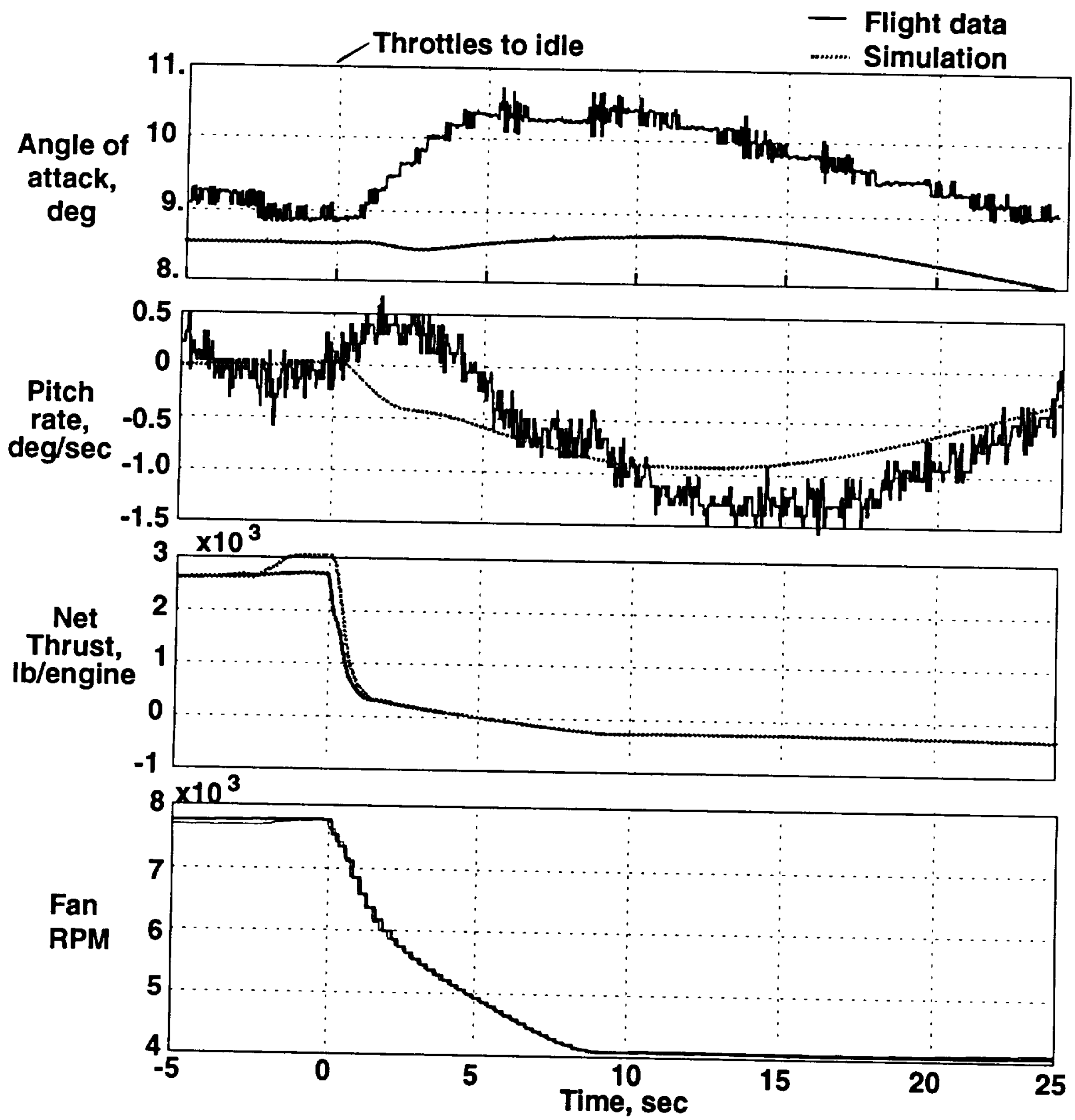
Small Step Throttle Increase

Results of tests in which the throttles were both increased about 10 deg from the level flight setting, shown below, showed the expected pitch up, although less than the simulation predicted. The measured angle of attack varied only slightly, and did not display the reduction seen in the simulation. The small roll oscillation in the simulation matched closely that seen in flight. The flight fan speed data show that the right throttle was increased slightly more than the left. (The presence of a roll response from what was supposed to be a small pitch input is indicative of a problem that contributes to difficulty in flying manual throttles-only control, that is, inability of the pilot to make perfectly equal throttle inputs, or, if he does, that the engine thrust changes are not equal) Next, small throttle decreases were tested, as shown on the next page.



Step Throttle Reduction

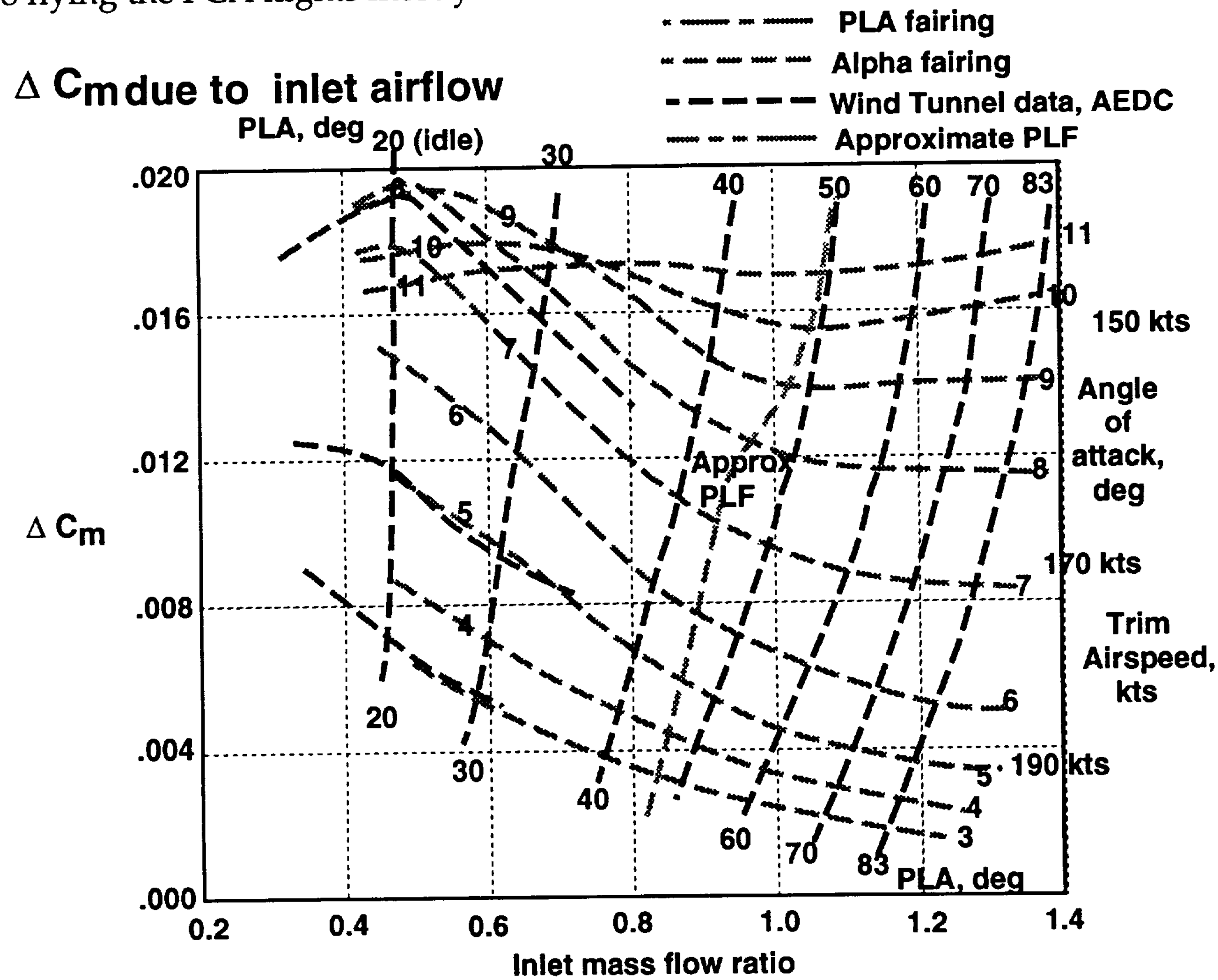
Differential throttle steps and throttle increase steps shown on the 2 previous pages agreed fairly well with simulation. Shown below is a typical step PLA reduction. The pitch rate comparisons of flight and simulation data are shown where both throttles were reduced from PLF to idle. While the long term response of the flight data was the expected pitch-down, there was a significant initial pitch-up. There was also a significant increase in angle of attack. Data at other flight conditions also showed the same initial pitch-up and angle of attack increase. These results called attention to what appears to be a serious discrepancy between the simulation and flight. Although thrust falls off rapidly (due to the nozzle opening), fan RPM decays slowly, taking almost 9 sec to stabilize, due to the slow respose of the "non-production" engine control logic. Fan rpm, which is proportional to engine (and inlet) airflow, and angle of attack show a direct inverse relationship. Because of this trend, inlet wind tunnel test data reports were examined.



Inlet Airflow Effect on Pitching Moment

Wind tunnel data from an AEDC test showed a significant airflow effect on pitching moment, shown below. Unfortunately, it was a Mach number of 0.6, rather than the desired 0.25. Using data from the throttle step tests shown in the previous pages, along with other data, some of which was not available until the last PCA flights, the curves shown below were developed. Also plotted are the power lever angle (PLA) values, and the angle of attack values for level flight conditions over a range of speeds. Typical power for level flight (PLF) is also shown, varying between 45 and 50 deg for the flaps-down configuration.

These data show that at the low inlet mass flow ratios and low angles of attack, there is an adverse negative slope (decreasing throttle pitches the nose up). This causes the observed pitchup with the throttle step to idle, and the difficulty in manual throttles-only control that the pilots found in the airplane. The next page shows the throttle step with this inlet effect in the simulation. The data below also show that at higher angles of attack above 10 deg, and at higher mass flow ratios above 1, (which occur at lower speeds) that the inlet effect becomes less adverse, and possibly even favorable (positive slope). Decreasing speed at a fixed PLA also increases capture area ratio. Both of these effects would result from lower speed, thus the improved control at 150 kts, where the slope of $\Delta Cm/\alpha$ is near zero. This led to flying the PCA flights mostly at 150 kts.

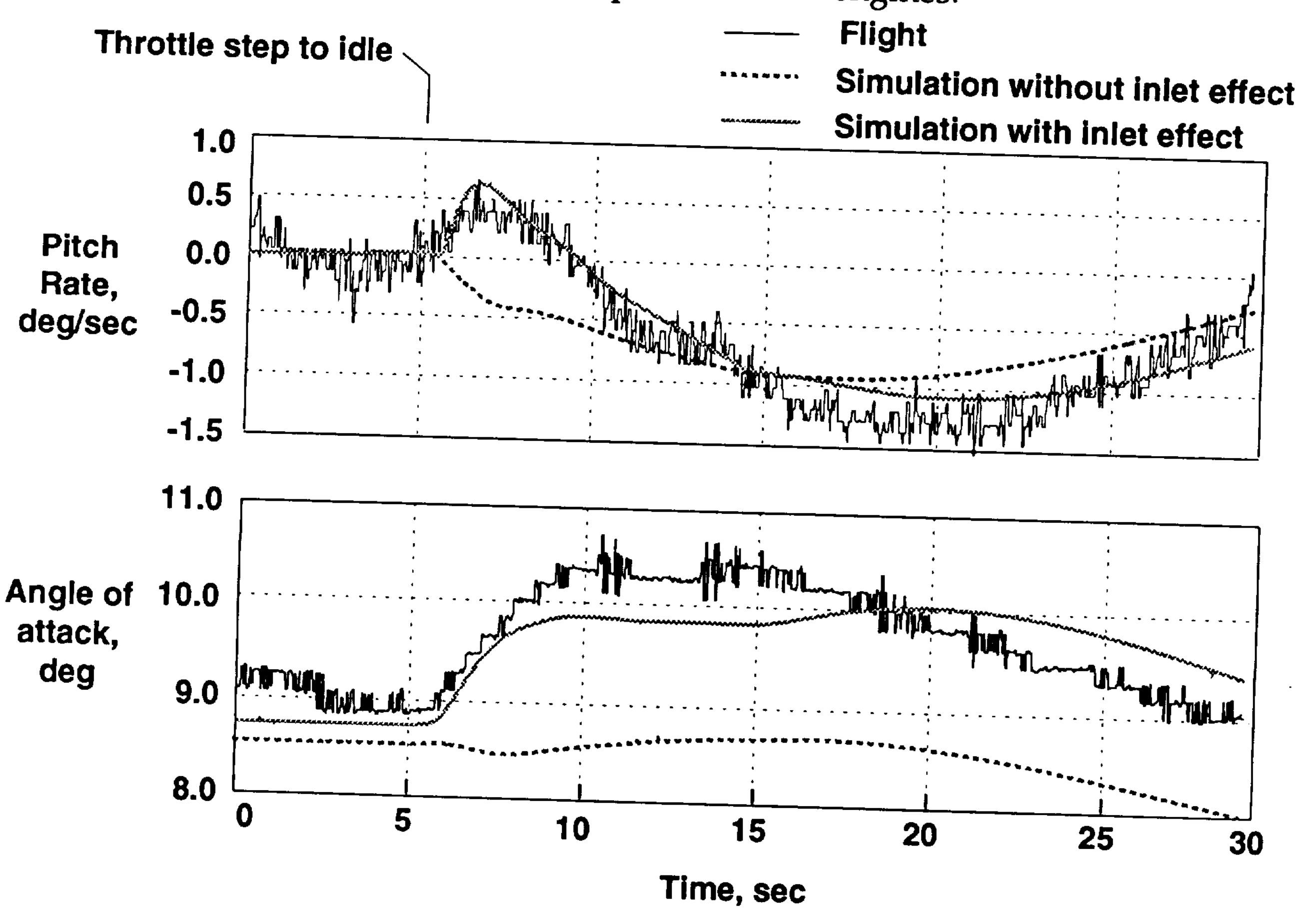


Flight and Simulation Match with Inlet Airflow Effect Modeled

With the inlet airflow effect from the previous page included, the agreement between the simulator and flight results was substantially improved. The results of this inlet airflow effect are shown below, the same flight data shown two pages earlier. The initial changes in pitch rate and angle-of-attack are now properly modeled. With this match in-hand, the Dryden and MDA simulations were modified to incorporate the inlet effect, and the control laws were redesigned to add velocity feedback in the flightpath control logic.

The simulation with this effect added, showed many of the characteristics of the flight data; poor phugoid damping, a pitch PIO (pilot induced oscillation) tendency, sluggish response to pitch inputs, and an initial response in the opposite direction to that desired. The simulation match to the flight data was markedly improved.

The inlet airflow effect was very small, and would often be neglected in an airplane simulation. However, when the only moments being used for control are the small moments from the propulsion system, normally neglected effects may become significant. This is particularly true for airplanes with highly integrated propulsion systems such as fighters where inlet /airframe interactions are strong. It would likely be less true for subsonic airplanes with pod-mounted engines.



F-15 Throttles-Only Control Simulation Upgrades

The inclusion of the inlet airflow effect was only one of many simulation upgrades required for the PCA flight evaluation. The list below summarizes the major changes to the NASA Dryden simulation in the order in which they were made. At the beginning of the throttles-only studies, the Dryden F-15 simulation consisted of a 6 degree of freedom fixed base piloted simulation, with a high-fidelity aerodynamic data base, and lower fidelity flight control system and engine models. The aero database assumed the inlets were operating on their nominal schedules.

Some of the additions were minor and had only a small effect, while others were major, and required continued iteration as additional data became available. Some of the inlet effects upgrades were not finalized until after the flight program was completed and the envelope expansion flight data became available.

The most significant additions included the improved engine dynamics model, the PCA logic, and the inlet airflow effects model. The availability of a highly flexible simulation was critical in the development of the PCA concept for the F-15.

Initial F-15 Six degree of freedom non-linear simulation with nominal inlet schedules, engine modeled from net thrust tables with first order lags.

- **Lock control surfaces at any given position**
- **Incorporate augmented control laws from NASA B-720**
- **Incorporate variable inlet effects on lift, drag**
- **Separate gross thrust and ram drag terms**
- **Add thumbwheels for control inputs**
- **Incorporate horizontal CG effects**
- **Incorporate vertical CG effects as a function of fuel quantity**
- **Model CAS-off stick fixed pitch and roll ratios emergency control system**
- **Add ground effect model**
- **Add landing gear model**
- **Improve engine dynamics (Ed Wells model)**
- **Add gyroscopic moments**
- **Add non-linear inlet airflow effects**
- **Add flight path command box to HUD**
- **Add McAir control laws and trimming**
- **Incorporate trim-while-fly**
- **Incorporate velocity feedback, variable inertias**
- **Incorporate 3 trim options**
- **Incorporate "help" path to control law**
- **Incorporate improved CG, inertias, weight for F-15 835**
- **Incorporate revised ground effect model**
- **Incorporate heading mode**
- **Incorporate added bank angle control logic features**
- **Incorporate updated inlet effects models**

PCA Flight Evaluation

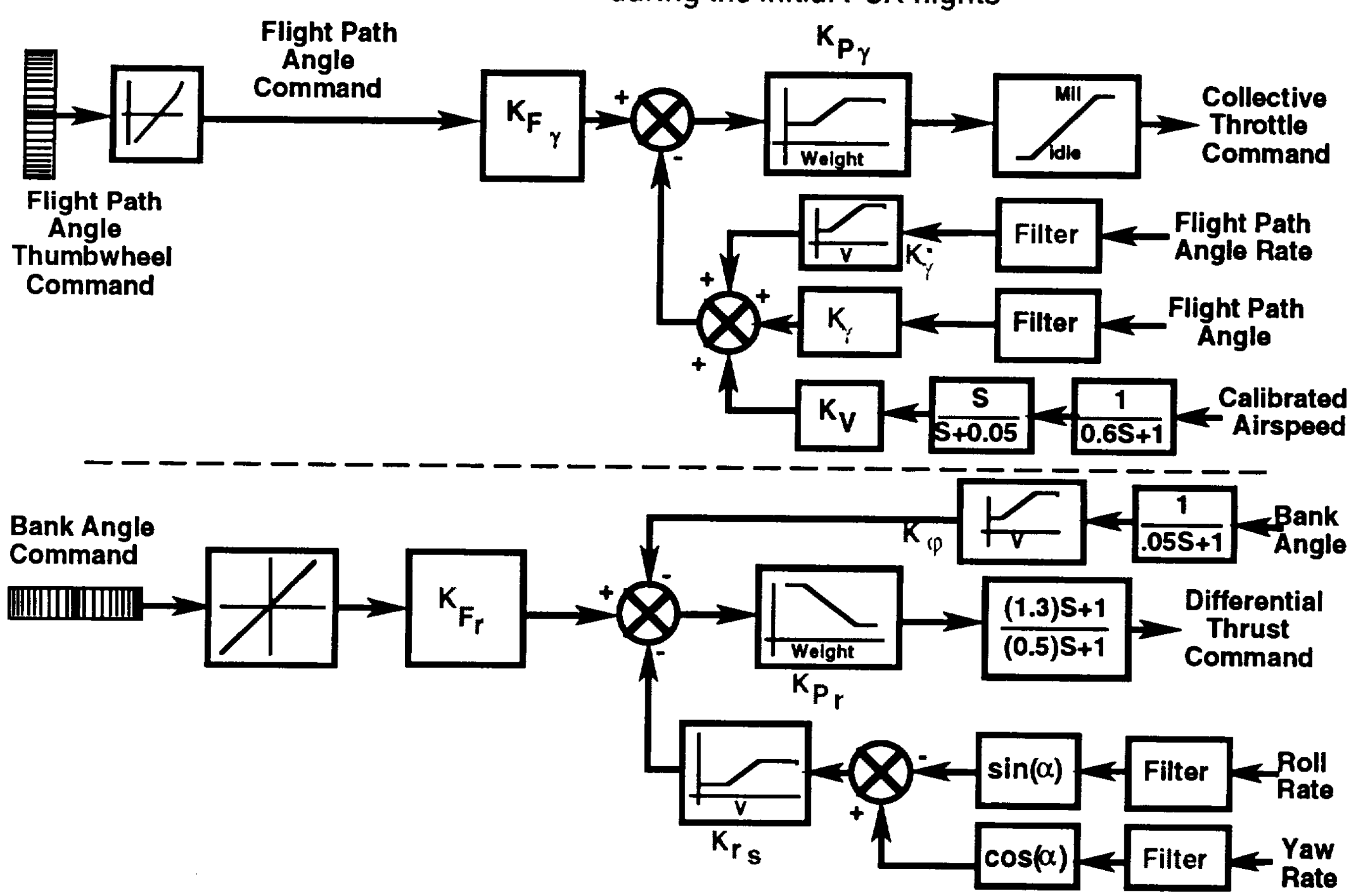
With a reasonably good match between simulation and flight data, the PCA control laws were finalized as shown below and the software and hardware-in-the-loop tests were performed, as outlined in the preious paper. Following the ground tests, the first PCA flight was flown in Jan 1993. The first flight was mostly devoted to showing that the many safety features worked as planned, and that the PCA system could always be disengaged. All worked as expected.

Toward the end of the first flight, the PCA system was engaged, allowed to trim, and was briefly evaluated at an altitude of 10,000 ft and 150 kts. Initial performance was less than desired, particularly in the lateral axis. With the extensive flexibility of the flight software, the real-time monitoring capability, and the pilot's ability to make changes through the NCI panel, it was possible to quickly make changes and evaluate the results. The parameters shown shaded below were changed.

PCA pitch performance was reasonably good, only small gain change was made. In the lateral axis, the previously unused bank angle feedback was increased, while the yaw rate feedback was filtered and reduced. The thumbwheel gains were also adjusted. A typical evaluation consisted of making a change, evaluating performance in level flight with small step inputs. Then, a closed loop tracking task was tried, typically tracking a road from an altitude of about 3000 above ground level(AGL). If the results were promising, a simulated or actual approach was then flown. If not, further adjustment were made. After 5 flights, the pilots and engineers were happy with the PCA performance, and approaches to lower altitudes were flown, with the pilot taking over with the stick at progressively lower altitudes, first 200 ft, then 100 ft, then 50 ft, and finally as low as 10 ft AGL. PCA go-arounds were also made from altitudes of 200 ft and 100 ft AGL.

PCA Logic Block Diagram

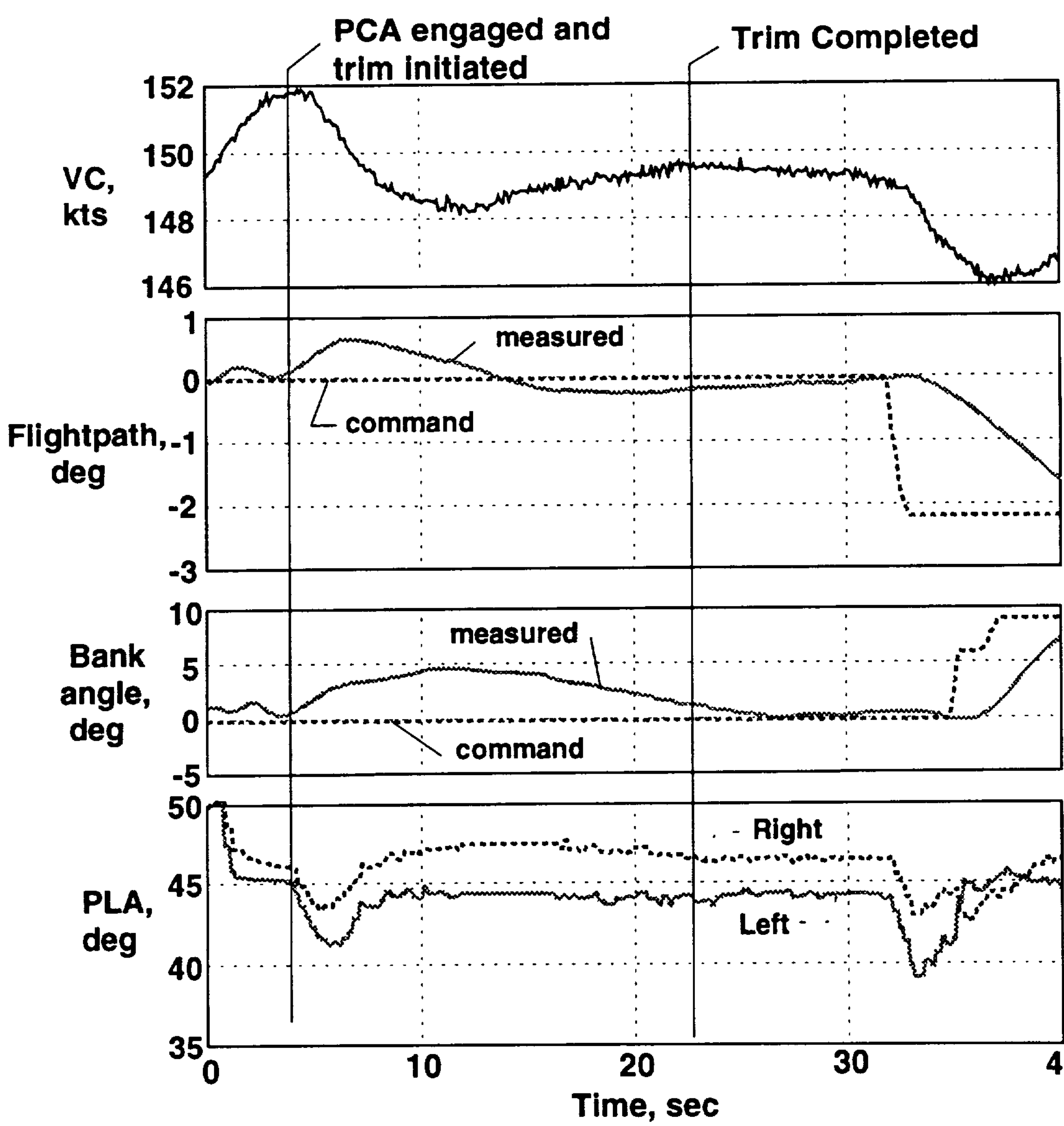
Shade indicate parameters changed during the initial PCA flights



PCA Trim Tests

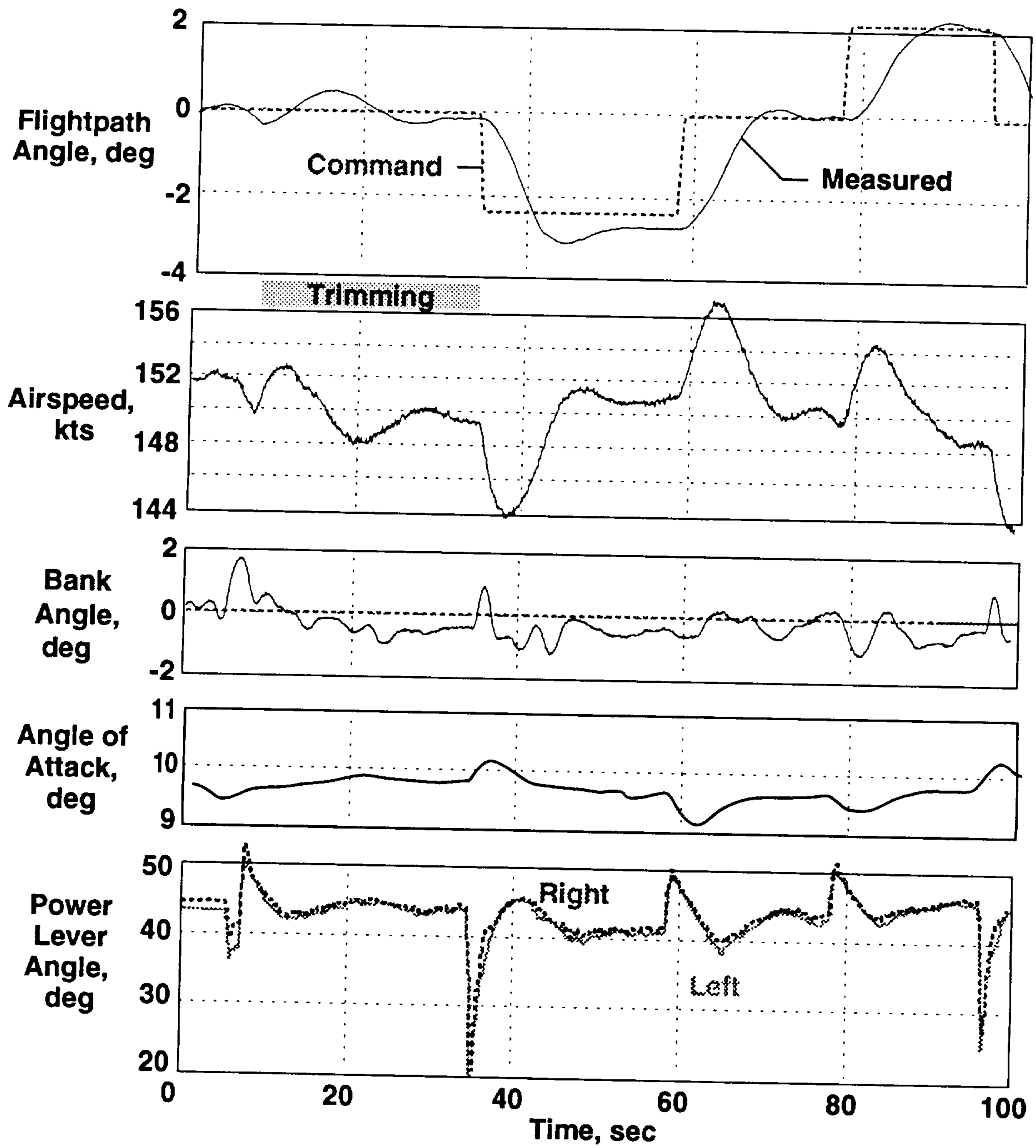
When PCA was first engaged, with pitch and roll thumbwheels in the detent position, the trimming function, described in the previous paper, slowly adjusted the thrust of the engines to achieve level flight. A PCA trimming operation is shown below, with about 20 sec required to satisfy the trim requirements. The trim performed well, much as it did in the simulation, although 30 seconds or more was normally required for trimming to be completed.

If the air was turbulent, the trim criteria might never be satisfied; if this occurred, the pilot would select trim off to improve the flightpath stability. After long periods of PCA operation (several minutes), biases would sometimes develop which would require the pilot to select other than the detent position on the thumbwheels to achieve level flight. When this occurred, the pilot would select trim on and then trim auto to trim out the biases. There were a few instances when the trim requirements were met immediately after PCA engagement, even though an adequate trim had not really been achieved. In these cases, when biases developed, the pilot would cycle trim to off and back to auto.



PCA Flightpath Step Response

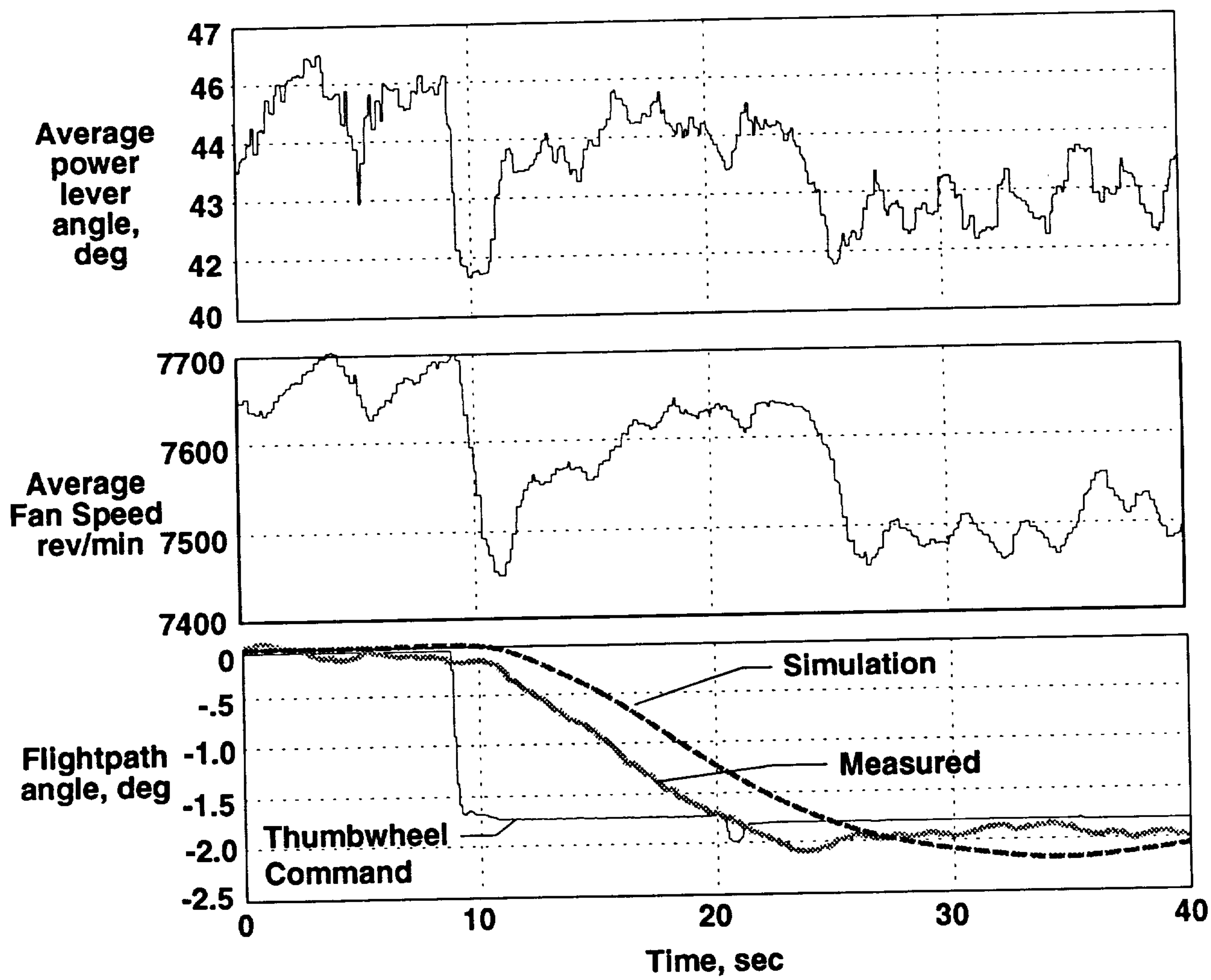
Shown below is a series of PCA flightpath angle step input responses. The pilot carefully matched the throttles before trimming the airplane, so that the engines were well-matched. The air was very smooth, as indicated by the minimal noise on the airspeed trace. After the trim cycle was completed, at 150 kts and 44 deg PLA, the pilot made a -2.4 deg step down. The PCA system reduced the throttles almost to idle, then back up and stabilized at about 42 deg; airspeed dropped 6 kts as the nose started down, then stabilized 1 kt above the initial speed in the descent. The response shows about 10 sec to reach the minimum flightpath with a slight overshoot. At the reduced PLA, the inlet effect resulted in a slight increase in angle-of-attack. The bank angle command remained zero, and only a 1 deg bank angle change occurred during the flightpath step. The step back to zero, the step to +2 deg flightpath, and the step back to zero all show similar trends. The throttle increases were similar in thrust, but less in PLA due to the non-linear thrust characteristics shown previously.



PCA Step Response

Numerous step thumbwheel command inputs were made to both flightpath and bank angle axes at varying weights, airspeeds, and gain combinations. These step inputs were designed to allow detailed post-flight comparisons of actual flight performance with simulation predictions, and between differing flight control configurations tested. A response to a small negative flightpath angle command is shown below at 150 knots with the flaps down. The initial throttle decrease is followed by throttle modulation to achieve the desired flight path with minimum overshoot. The average fan speed, a good indicator of thrust, is also shown. Approximately 11 sec is required to achieve the 1.8 deg decrease in flight path angle. A comparison of the non-linear simulation at this condition shows a slightly slower response, but reasonably good agreement with the flight data.

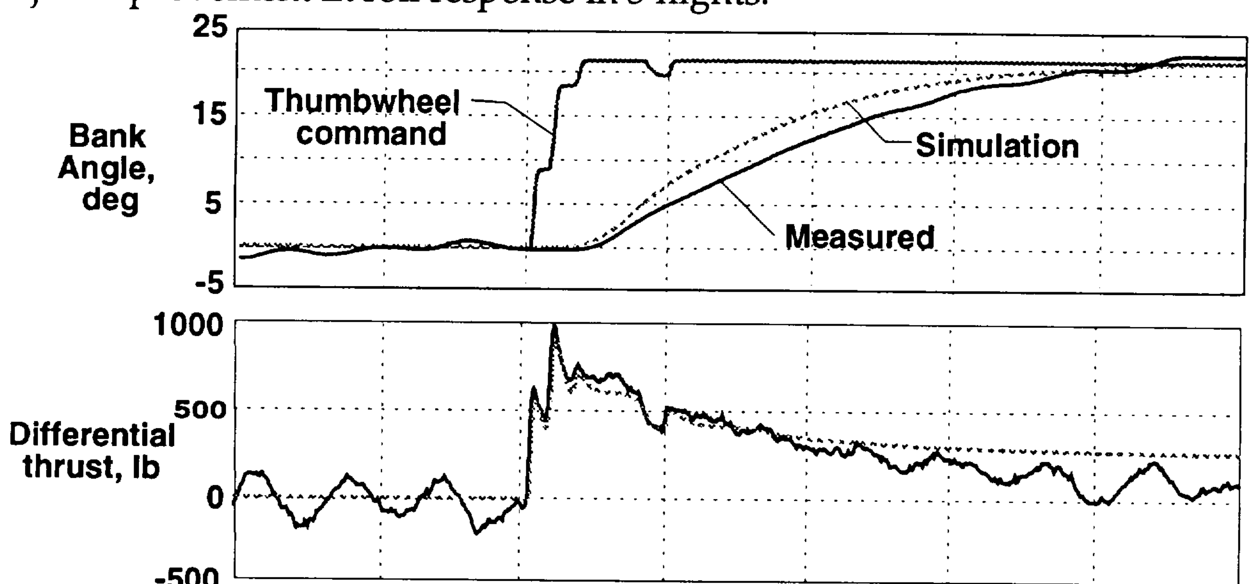
Pitch response at higher speeds was degraded due to the adverse inlet effect.



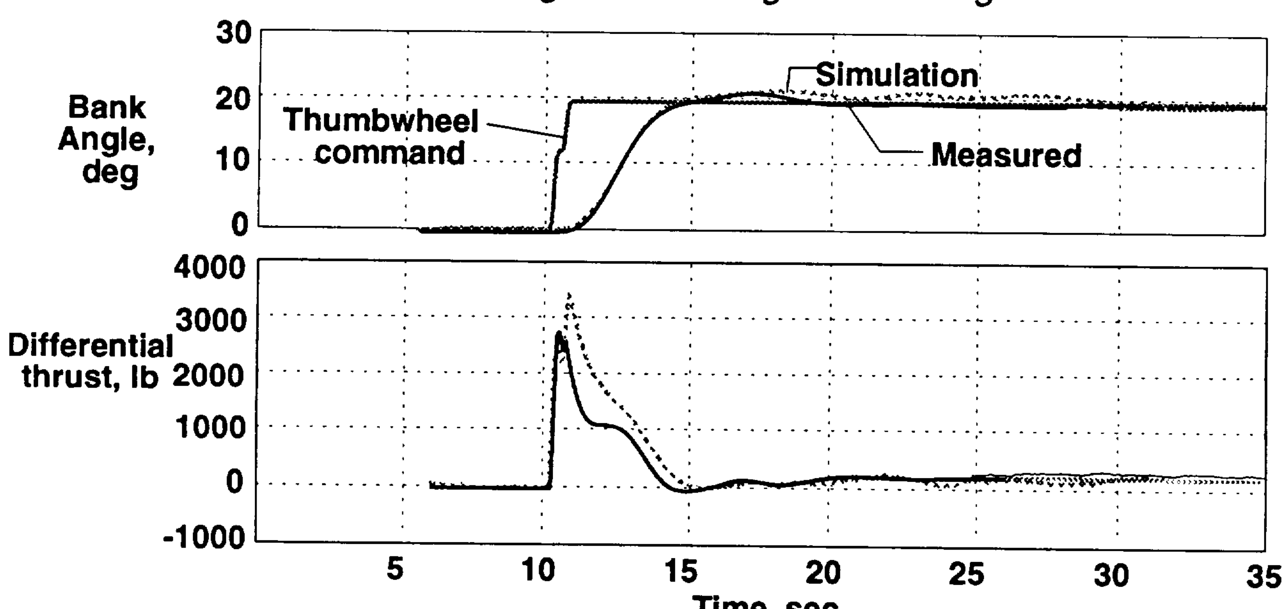
Bank Angle Step Response

Roll response to a full roll step command at 150 kts is shown below. Roll control was initially quite poor due to low roll rate, as shown, with 28 seconds required to achieve the commanded bank angle. Only a very small differential throttle command was generated by the control laws. This low roll rate was dictated by results from the MDA hardware-in-the-loop simulation, in which higher gains caused a limit cycle oscillation.

Extensive flight evaluations were conducted to improve roll performance. After several iterations over 5 flights, changes in gains, in yaw rate filtering, and addition of bank angle feedback greatly improved the roll response, as shown in the lower part of the figure, with the commanded bank angle being reached within 6 sec. A significant degree of differential thrust was commanded in this test. No evidence of the limit cycle oscillation was seen in the flight tests. Again, comparison to the non-linear simulation prediction for this condition is reasonably good. The flexibility of the flight software was absolutely critical in making the major improvement in roll response in 5 flights.



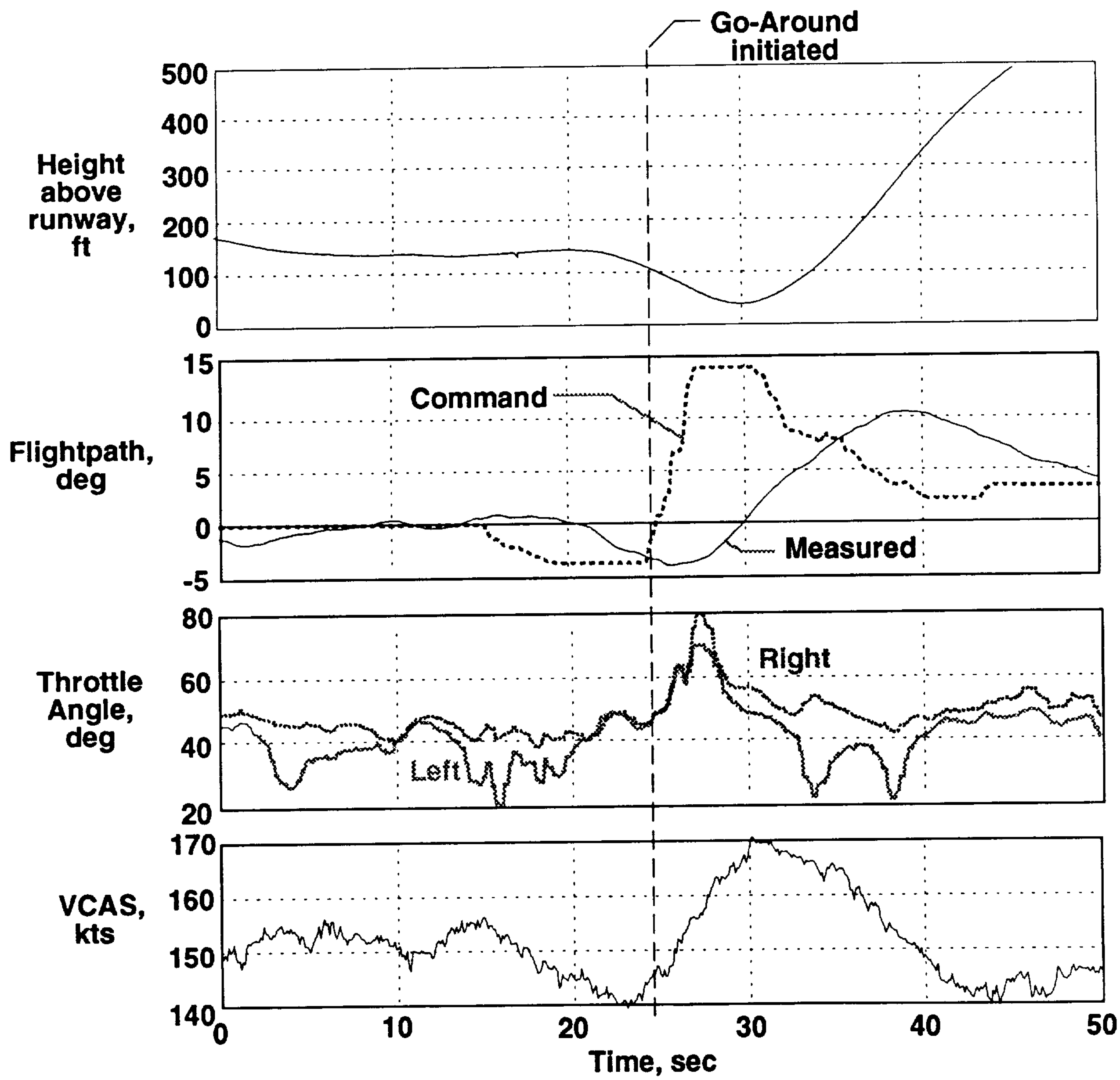
Original bank angle control logic



Improved bank angle control logic

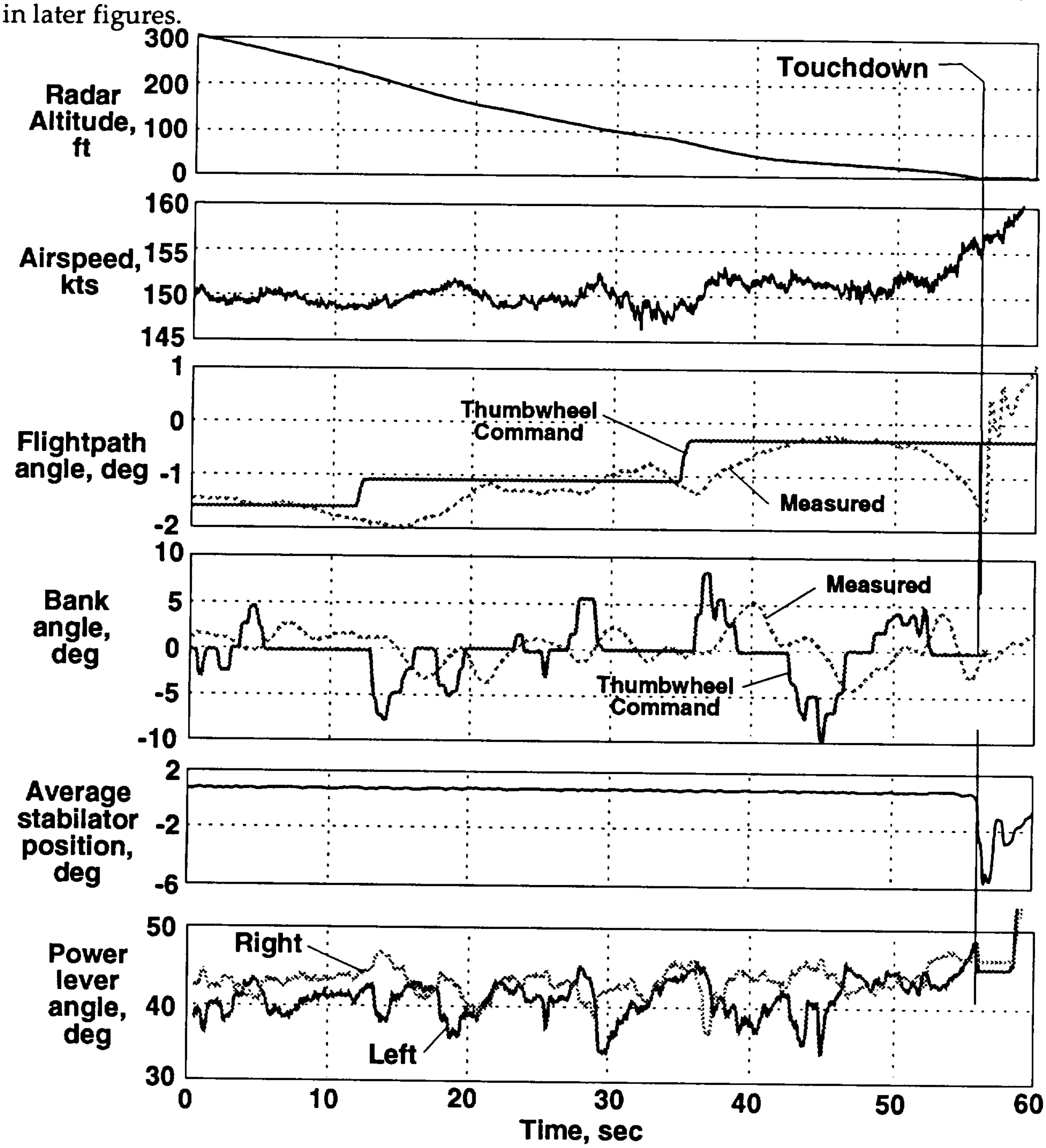
PCA Approach and Go-Around

Once the PCA step response and up-and-away control were satisfactory, PCA approaches were made. Shown below is approach with a PCA go-around. In this case, the pilot had leveled off about 140 ft AGL, with a trim speed of 151 kts in light turbulence. At t = 15 sec, he reduced the flightpath command to -3 deg. Speed dropped to 140 kts, and at 110 ft AGL, he moved the flightpath command from -3 to +14 degrees to initiate the go-around. About 70 ft was lost, and it was 5 seconds from the go-around command until the flightpath became positive, as the speed increased to 170 kts. The PCA system command reached almost full throttle due to the large error between actual and commanded flightpath at t = 27 sec during the go-around. Throttle command then was reduced as flightpath angle rate (gammadot) became positive. This performance was considered good.



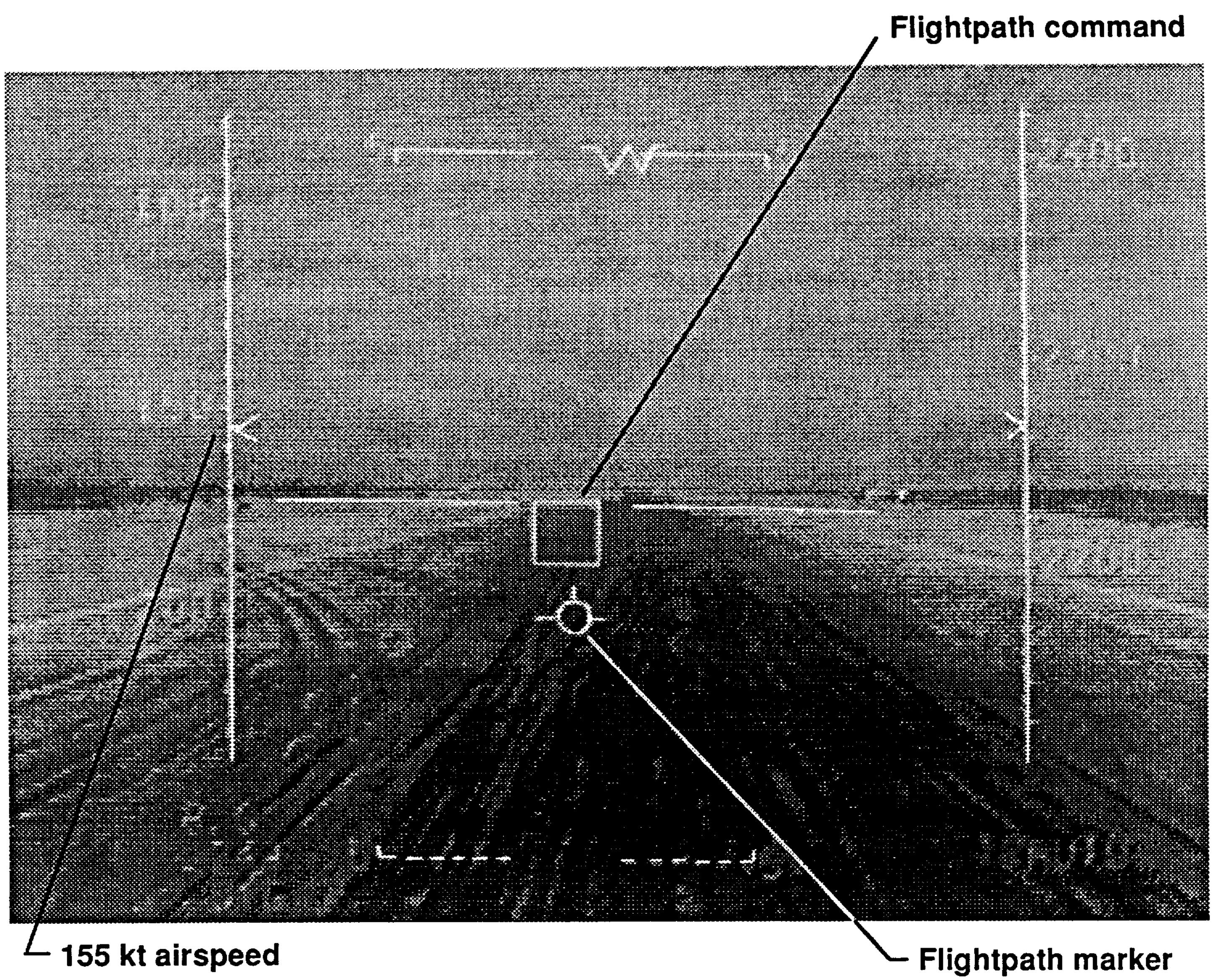
PCA Approach and Landing:

Following PCA low approaches, and PCA go-arounds, actual PCA landings were made. A time history of the last 56 sec of the first PCA landing is shown below. The conditions for this landing included an 8 kt headwind approximately down the runway, and only very light turbulence, except for a short period of light turbulence at t = 30 sec. Based on simulations with the revised ground effect model, the pilot reduced the flightpath command from -1.6 deg to -1.1 deg at an altitude of 200 ft AGL, and to -0.4 deg at 80 ft, resulting in a very shallow final approach. Pitch commands were few, and almost full time was spent making small bank angle commands to maintain runway alignment. At an altitude of 20 ft, 6 sec before touchdown the ground effect begins to affect the flightpath, primarily with a nose-down pitching moment. The PCA system increased throttle setting, and speed to try to counter the ground effect, but with no flight control input, the nose pitched down to -1.8 deg at touchdown, at which point the pilot made an aft stick input to cushion the impact on the main gear and to assure that the nosegear did not touch first. Bank angle control and lineup was good throughout the final approach. A small correction to the right was made just before touchdown. The HUD video at touchdown and the last 6 sec of this landing are shown in later figures.



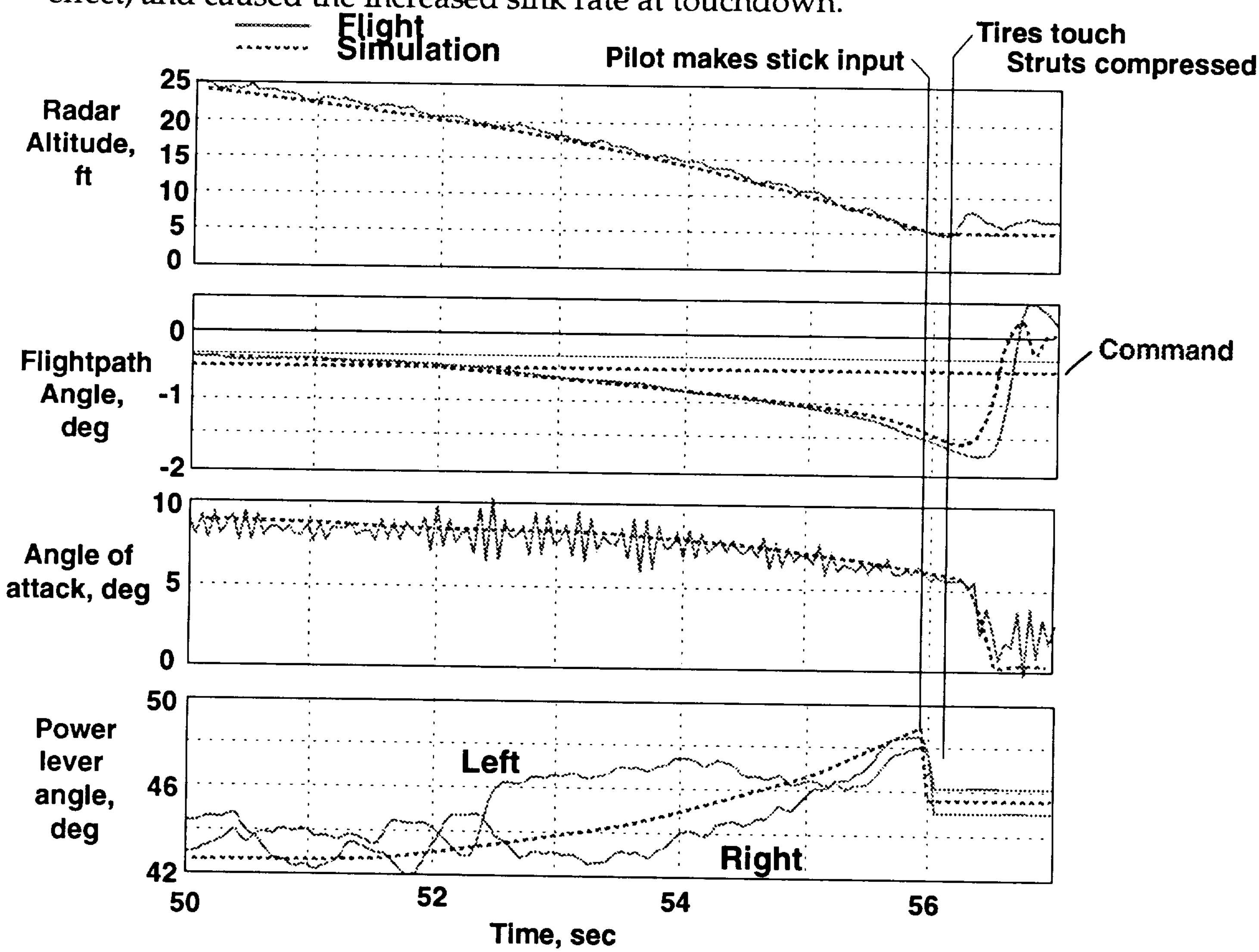
F-15 HUD Video at first PCA landing

Shown below is the last HUD video frame prior to touchdown. It shows the flightpath command box at -0.4 deg, and the flightpath marker at -1.8 deg, well below the command due to the ground effect. The radar altimeter is off; it does not show an output below 10 ft. The bank angle at touchdown was -1 deg and the touchdown was approximately 6 ft of the left of the runway centerline. The pilot rated the pitch control as very good except for the ground effect, and roll control adequate for this first landing.



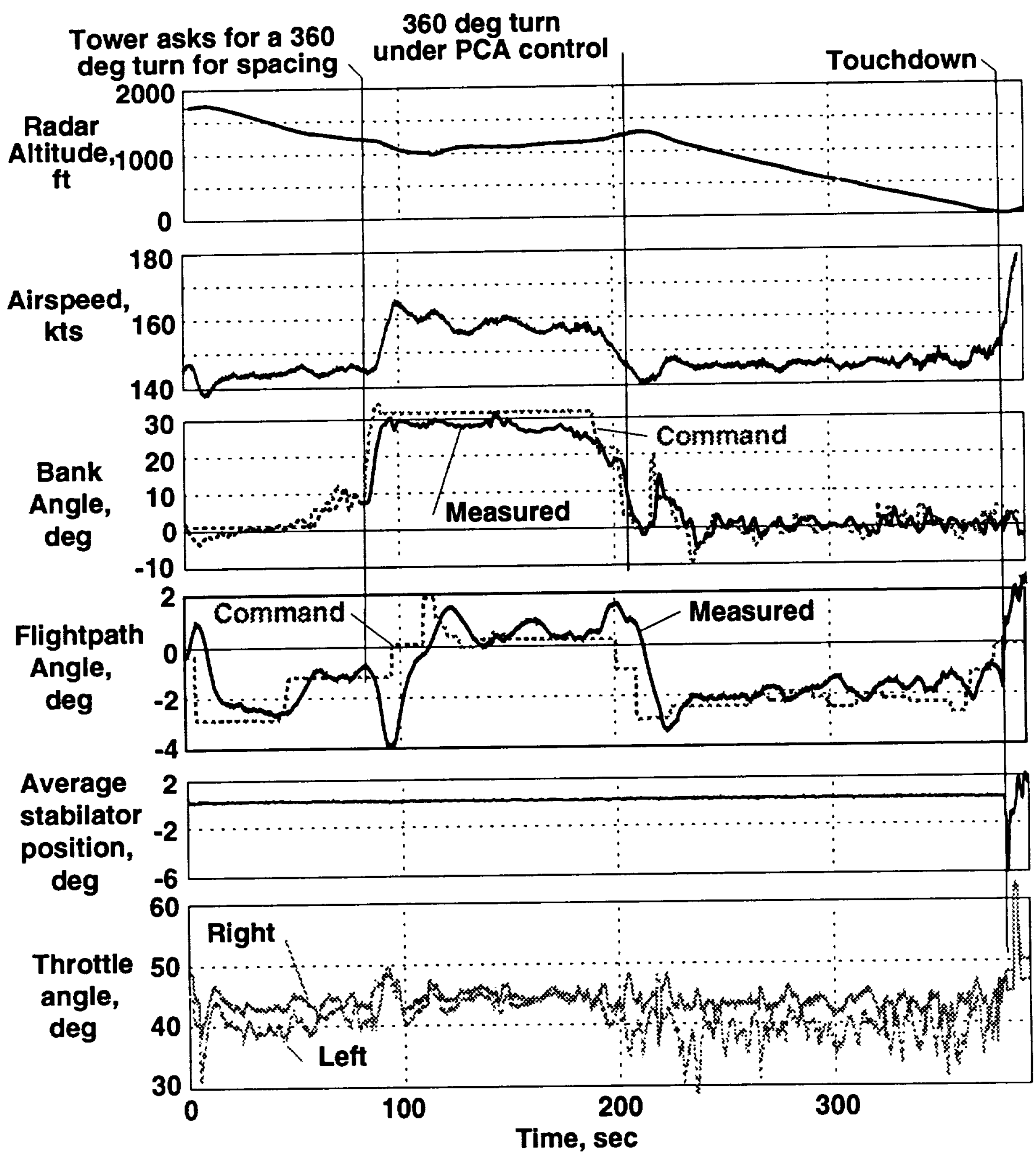
Ground Effect on PCA Landings

With the inlet effect modeled, and the ground effect model revised as discussed in paper 13, the observed large ground effect on landing could also be studied in the simulation. The data below from the first PCA landing, shown earlier, shows a comparison of the simulation to the flight data. Excellent agreement is seen. The ground effect, beginning about 20 ft AGL, caused the angle of attack to be reduced from 9 to about 7.5 deg. This angle of attack change caused the inlet effect to generate an additional nose-down pitching moment that reduced the angle of attack further to 6.5 deg. At this low angle of attack, the PCA action of increasing thrust to counter the pitchdown caused additional nose-down pitching moment that made the angle of attack at touchdown equal to 6 deg, (a 33% reduction in angle of attack) which more than compensated for the increased lift due to ground effect, and caused the increased sink rate at touchdown.



Second PCA Approach and Landing

Following the first PCA landing, another approach was made. In this case, shown below, the control tower requested a 360 deg turn for spacing 6 miles from the runway at 90 sec. The pilot made this turn under PCA control, selecting an immediate 32 deg bank. The nose dropped to -4 deg but was recovering when the pilot commanded a slight climb. At 200 sec, he rolled out and then continued the approach. Air was smooth until 200 ft AGL when very light turbulence began. On final approach, a steeper glideslope of -2.5 deg, then decreasing to -1 degree was flown until 20 ft when the command was raised to 0. In spite of this different technique, the ground effect caused a significant pitchdown, and touchdown was again at 8 ft/sec. Lineup was again good, with touchdown 6 ft from the centerline.

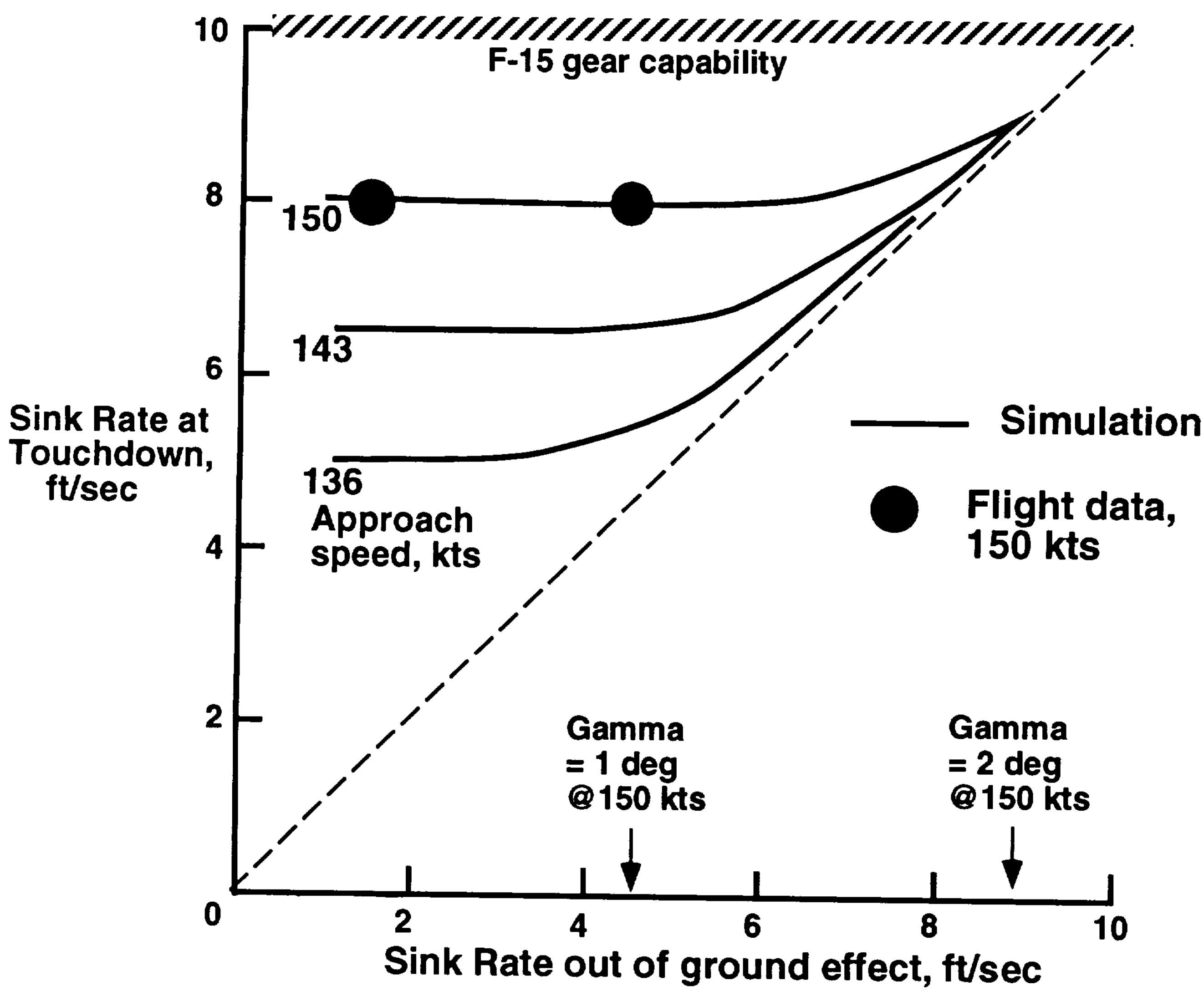


Effect of approach flightpath on touchdown sink rate

With the excellent agreement between the updated simulation and the PCA flight data, the ground effects could be further studied. The Dryden simulation with the dynamic ground effect and the inlet effect modelled was used to evaluate the touchdown sink rate as a function of the approach flightpath angle. The simulation results are shown below for a range of approach flightpath angles (sink rates out of ground effect) ; the overall result at 150 kts. is that the touchdown sink rate is 8 ft/sec for a range of lower sink rates out of ground effect from 7 to 1 ft/sec. The 2 flight landings, one at a very low flightpath angle and the second at a 1 deg flightpath angle agree very well with the simulation.

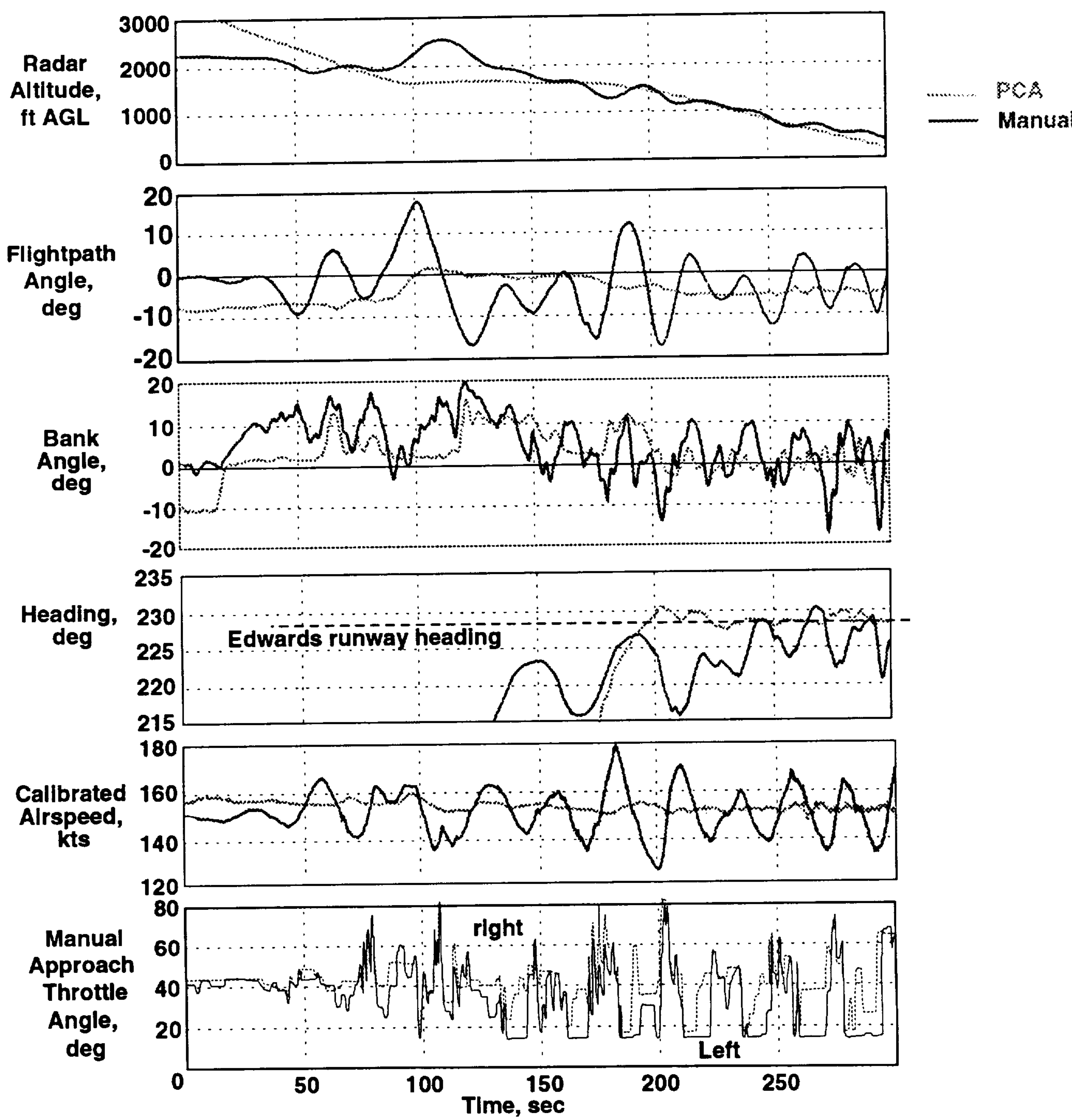
In the simulation, the effects of lower speeds were also evaluated. As expected, it was found that PCA landings could be made at lower touchdown sink rates if the speed was lowered. Lateral control deteriorated (due to lower natural dutch roll damping) at lower speeds, but remained acceptable in the simulation down to 136 kts, and pitch control continued to improve at lower speeds and the higher angles of attack.

Although ground effect will be a concern for any type of airplane using a PCA system, the added adverse ground effects due to the F-15 inlets should not in general, be a factor, particularly for transports with podded engines.



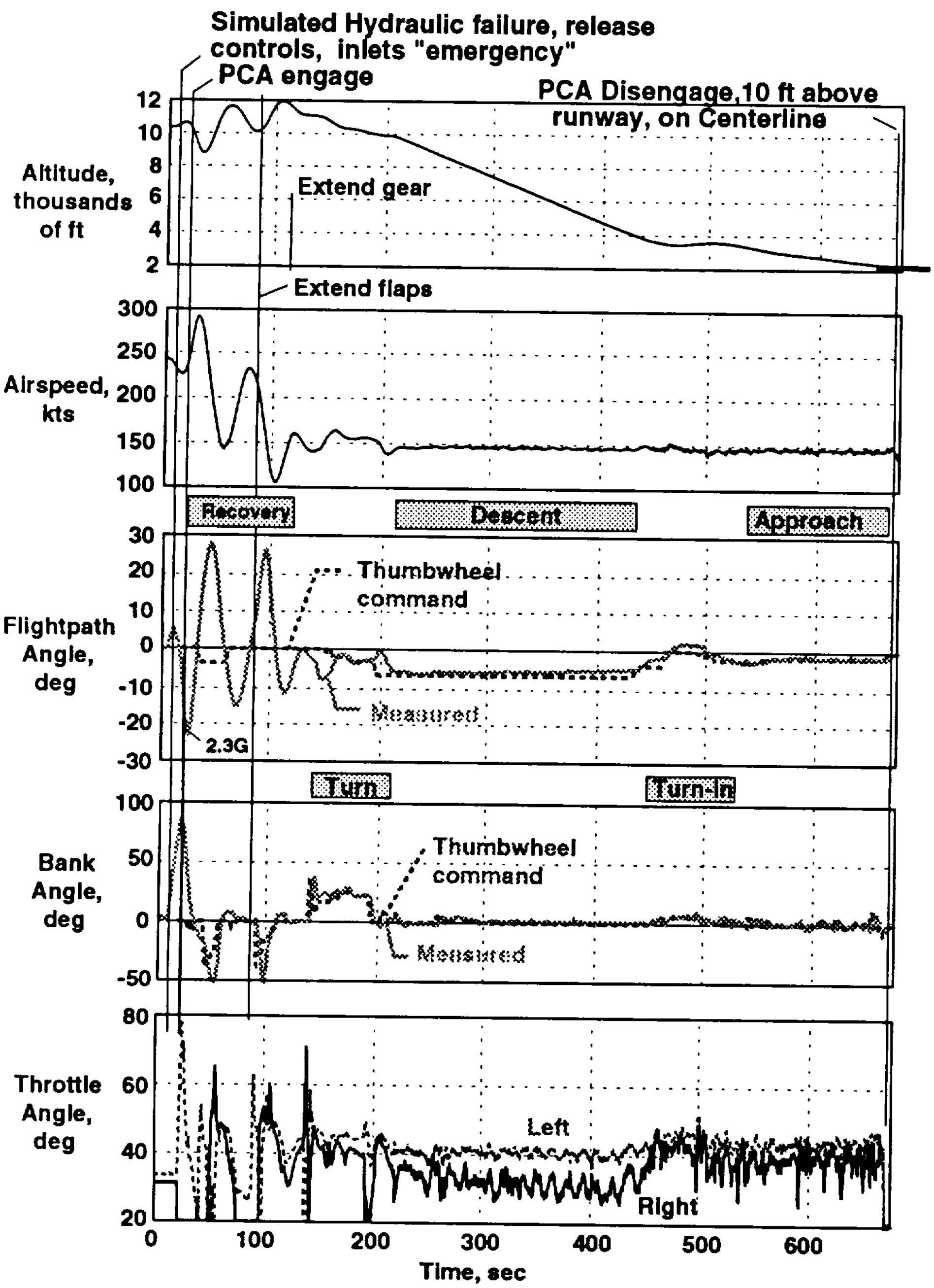
Manual Throttles-only and PCA Approach Comparison

Manual throttles-only approaches were flown for comparison with the PCA approaches. A manual approach was flown by a guest pilot on the same flight in which he had flown the upset, PCA recovery and approach to 10 ft AGL. A 5 minute interval of the two approaches is shown below. The manual approach shows poor heading control and flightpath oscillations of at least ±5 deg at a time when PCA was controlling to ±0.5 deg. Large airspeed excursions are evident along with much throttle activity. The right throttle was on the idle stop for about half of the approach. The pilot concluded that he might be able to hit the runway, but it would have been a crash. All guest pilots tried manual throttles-only approaches, none were successful, and all agreed that a safe landing was very unlikely. The PCA project pilot, even after extensive practice, also concluded that a safe landing was most unlikely.



Simulated Upset and PCA Recovery

A PCA guest pilot performed a test which simulated a loss of hydraulics upset followed by a PCA system engagement and recovery, shown below. In this test, the pilot trimmed the airplane at 250 kts at 10,000 ft, used the stick to roll to a 90 deg bank, released the controls, and moved the inlets to the "emergency" setting where they would go if hydraulics were lost. PCA was engaged, with trim auto at an 85 deg bank and -18 flightpath. The PCA system commanded full differential thrust, rolled the wings level, then reduced thrust to begin the phugoid damping. The pilot put in a bank command to convert some of the excess pitch energy into a turn to reduce the pitchup, airspeed decayed to 150 kts over the top. After one full pitch cycle, he lowered the flaps, which caused another pitchup and speed reduction, with speed falling to a minimum of 105 kts. The landing gear was extended, and the pitch oscillation was damped quickly. PCA trim was satisfied. Trim speed was 150 kts. He then turned back towards the Edwards runway and began a descent, with a -6 deg flightpath command. At 450 sec, he leveled and made a turn to start a long straight-in approach to runway 22. The approach was continued with minimal deviation until 10 ft over the runway and on centerline in perfect position to land, 11 minutes after the upset. At that point, he used the stick to disengage PCA and then flared slightly for touchdown.

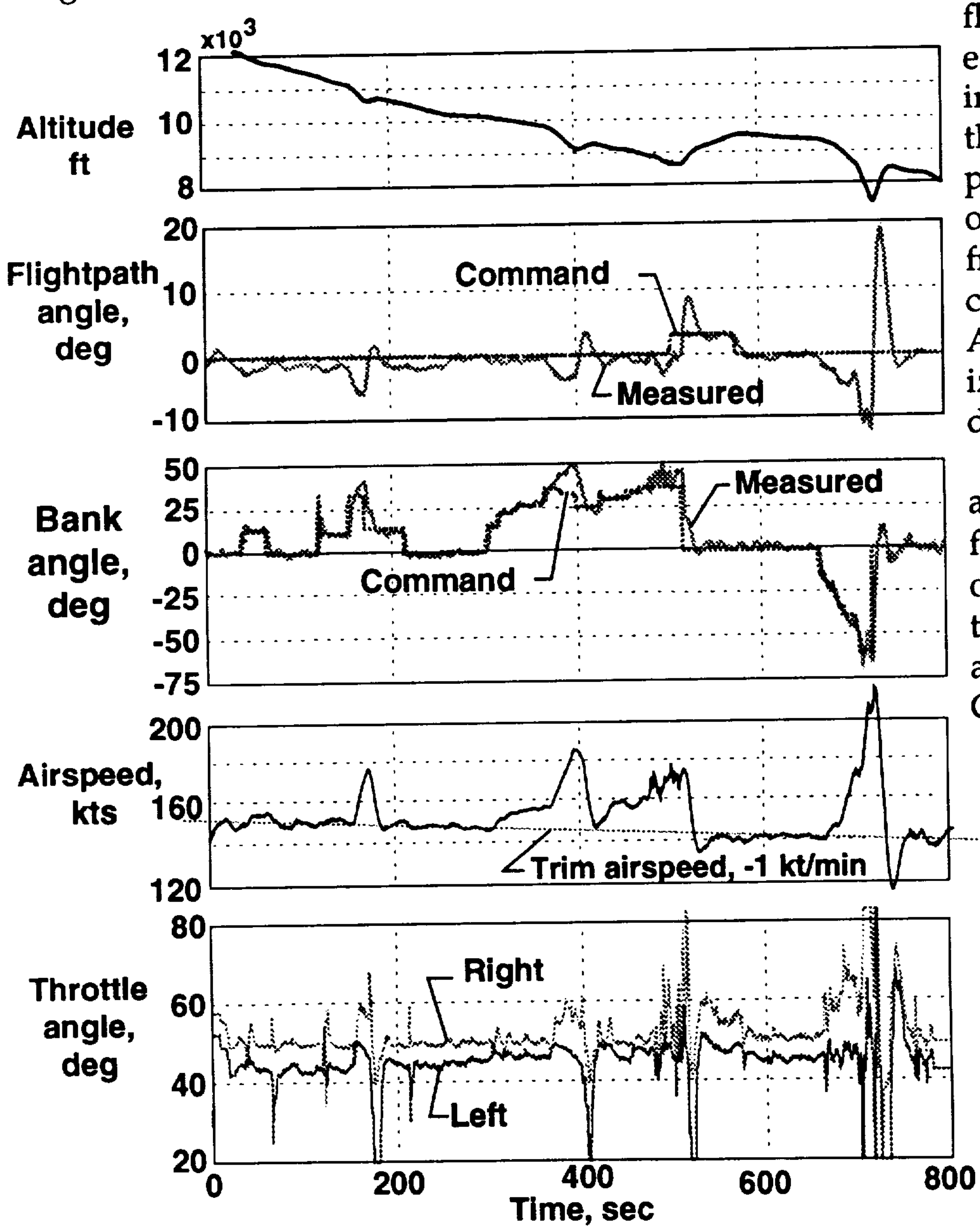


All PCA guest pilots flew this simulated upset as part of their PCA demonstration.

PCA Maximum Bank Angle Test

Tests were performed to determine the maximum bank angle capability of the PCA system in the F-15. The software limits and thumbwheel scaling were modified to permit bank angle commands up to 60 deg. Results are shown below with flaps and gear down. Initial trim speed was 151 kts at an altitude at 12,000 ft. Commands to 15 deg were flown for reference, and were held accurately. A command of 35 deg resulted in an overshoot to 40 deg and a drop in pitch attitude to -5 deg. Speed increased to about 180 kts to sustain the bank and keep the nose from dropping more. The higher throttle setting makes the inlet effect more destabilizing. Repeating the test, bank commands to 25 deg were accurately held, and again the 35 deg command resulted in an overshoot to nearly 50 deg. After 400 sec, altitude was down to 9000 ft and a 35 deg command was held at approximately 40 deg in light-to-moderate turbulence (note dynamics on airspeed) Trim speed was down to 145 kts. At this point, the pilot, still with PCA control, rolled to wings level and commanded a climb to get above the turbulence. At 650 sec, a right turn was commanded, 40 deg was held, and then bank angle was increased to the full 60 deg command. Bank angle oscillated ±10 deg, and the flightpath fell to -10 deg, even though speed increased to 210 kts. On the rollout command, a pitch overshoot to +20 deg occurred as the energy from the higher speed was converted into pitch. After the flightpath stabilized, the trim speed was down to 140 kts.

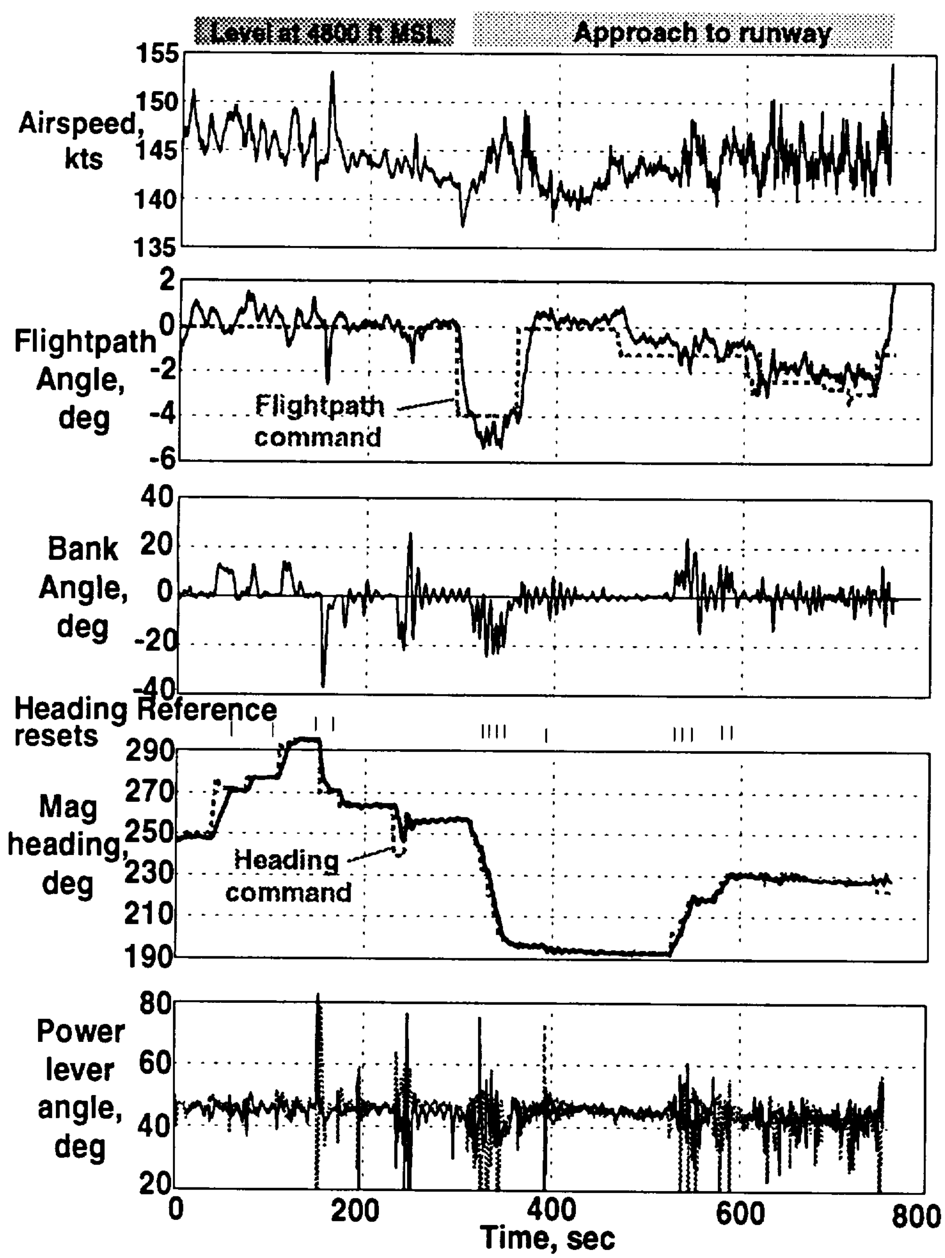
The speed reduction of about 1 kt/min in level flight was also observed at other times, and was due to the weight reduction and aft movement of the CG as fuel was burned.



PCA Heading Mode

A heading mode was developed for the F-15 PCA system. This mode was designed to maintain a commanded heading mode when the bank angle thumbwheel was in or near the detent, and to allow a heading to be selected with the bank angle thumbwheel. This mode was developed late in the PCA project, and did not get extensive simulation nor flight test. The heading mode control law is shown on the next page. Since there was no convenient input device, (such as a heading command knob) in the F-15 for making heading commands, the bank thumbwheel was used, but could only be reasonably scaled for about ±10 deg of heading change. When in the heading mode, the pilot would depress the PCA "engage" button on the throttle to establish a new heading reference (the heading at that time), and the thumbwheel would then be used for heading command. If more than a 10 deg heading change was needed, the engage button would be depressed again.

The gain for large heading commands was initially too high, resulting in a very large initial bank angle, and lightly damped bank angle oscillations. With the flexibility of the PCA software, a 60 percent reduction in gain was made and performance was much improved. Flight test of the heading mode is shown in the figure. The pilot first made heading changes in level flight, then turned toward the runway and made an approach. Despite the cumbersome mechanization, the heading mode worked acceptably well. Note that the gain was still somewhat too high, with some bank angle oscillations. Heading was held to within ±0.5 deg, and pitch control was good. Bank angle limiting would need to be incorporated in this mode.

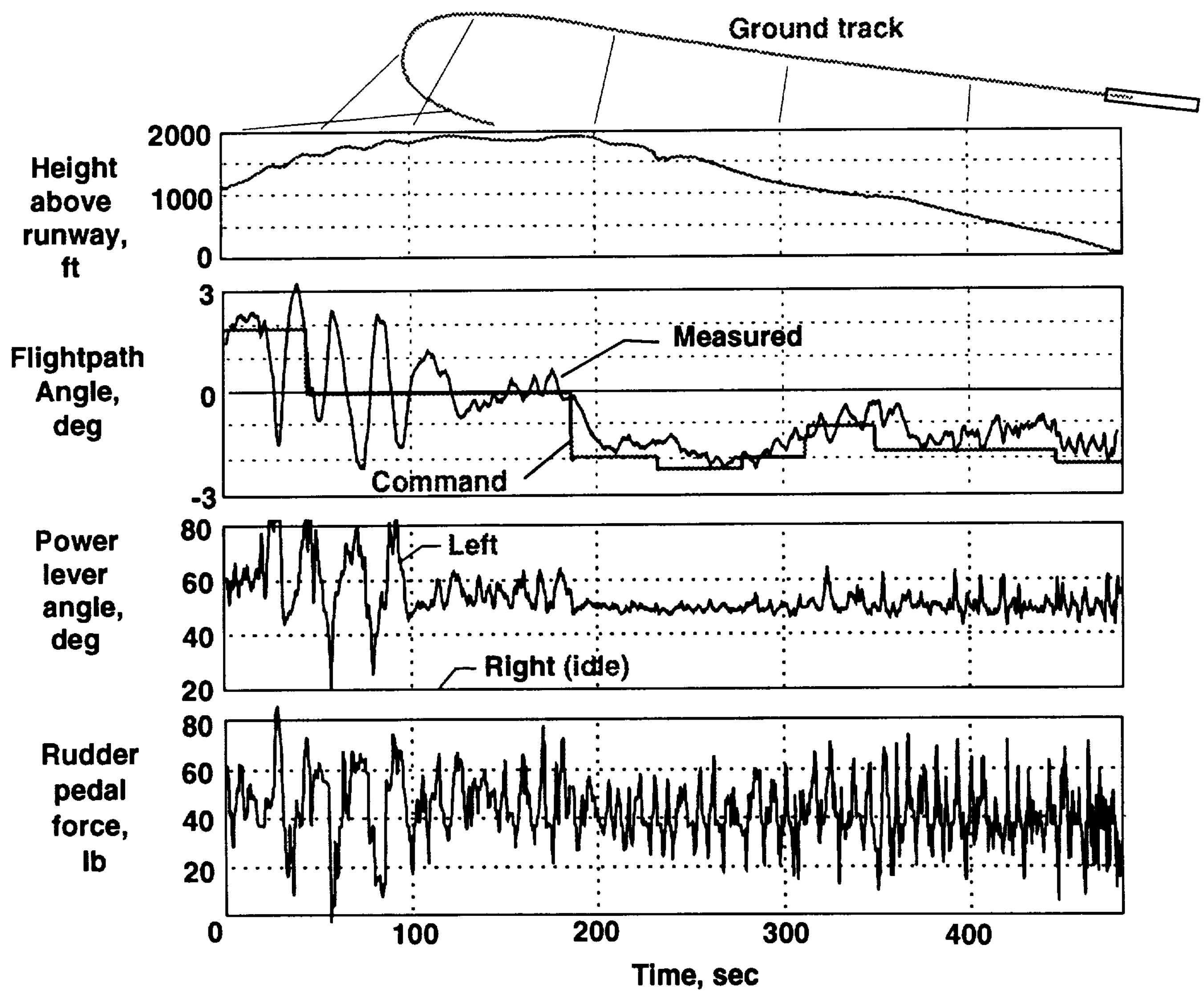


Single engine Plus Rudder

Analysis of flight control system failures has shown several cases in which pitch control was lost but roll control through rudder or ailerons was still possible. In this case, PCA could be used for flightpath control, and, in fact, one engine under PCA control could be sufficient to control pitch.

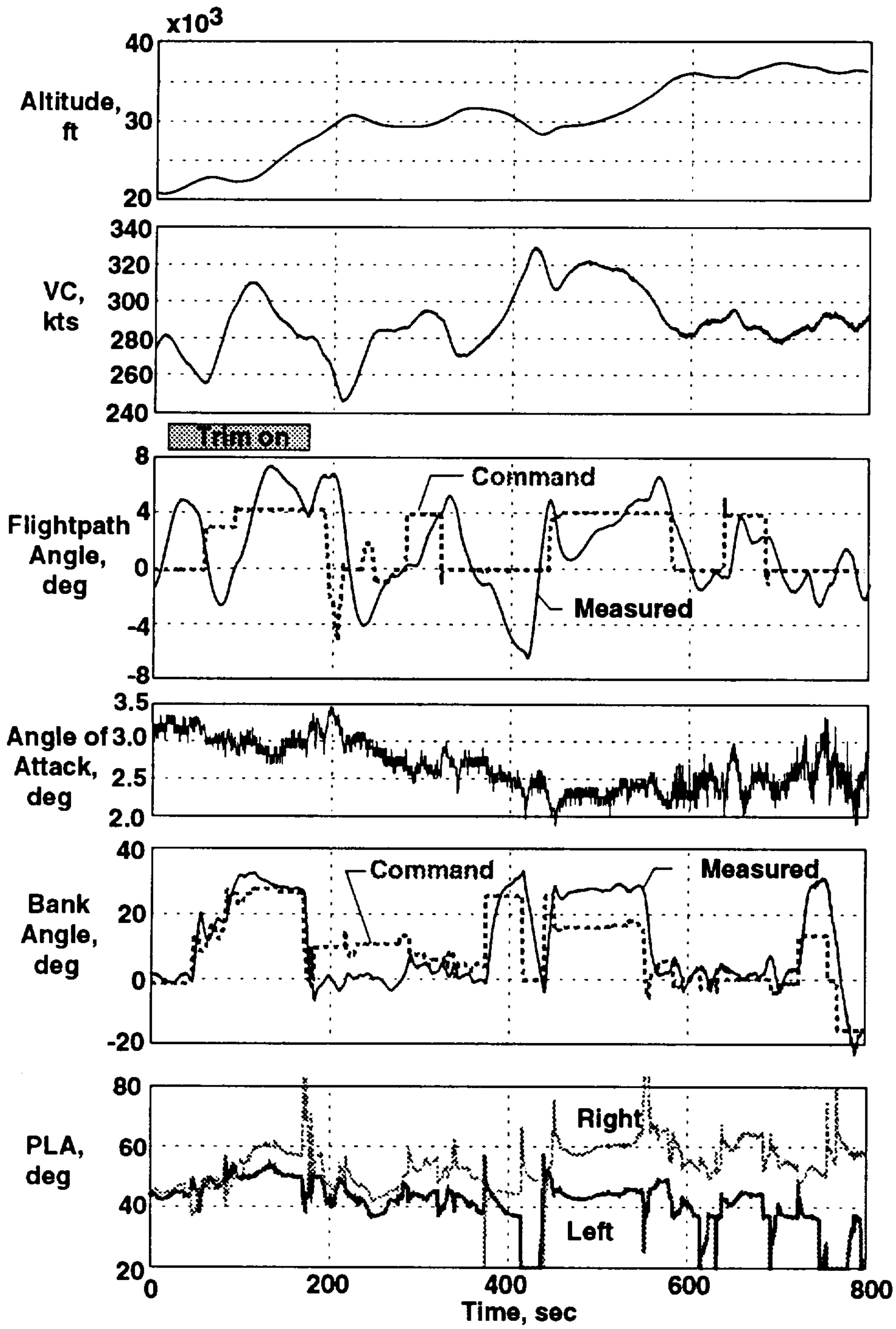
To investigate this mode, an option to fly a "single engine plus rudder" mode was provided. The pilot controlled bank angle and heading with rudder, while the PCA flightpath command controlled flightpath with one engine. The other engine throttle was moved to idle for the test. The only control law change needed was to eliminate the differential thrust command, and increase the gain on the flightpath angle command. Shown below is an approach flown in this mode at 170 kts with the flaps up. The pilot had to get used to this method for controlling bank angle, and found strong interactions between his rudder control and the yaw due to the engine serving as a pitch controller. During the turn, the PCA trim had not been completed, and phugoid damping was poor. Once the turn was completed, PCA trim was completed, and as experience was gained, control improved. The oscillations in pitch were reduced, and the rudder inputs became smaller. Over the latter part of the approach, flightpath was held within a degree of command, about half of that due to an apparent bias of 1/2 deg. Pitch control at 170 kts was improved because the one engine used was at higher than normal power, and the inlet effect was minimal at the higher mass flow ratio.

The pilot was uncomfortable with this mode due to lack of experience, and the fact that every pitch input caused a roll disturbance. In spite of these problems, he was able to maintain runway lineup down to 100 ft AGL, and thought he could make a safe landing on the lakebed where precise lineup would not be critical.



PCA Flight Envelope Expansion

The PCA system was designed for operation between 170 and 190 kts and altitudes up to 10,000 ft. After the PCA landings, when PCA operation was better than expected, it was decided to expand the PCA system operation outside of the design envelope to see how robust the control algorithm was. Shown below is a 280 kt climb with flaps up, gear up, inlets emergency, and velocity feedback active. After engaging and initiating PCA trim, the pilot started a turn. The PCA trim process took over 150 sec due to poor phugoid damping and pilot inputs. Once trim was completed, PCA performance was better. At 30,000 ft, pitch and roll steps were made. Note at 410 sec, when the right roll command was removed, that the left throttle went to idle, which contributed to allowing the nose to drop 5 deg. The climb was then continued. At 35,000 ft, another set of flightpath and roll steps were made. Flightpath was generally maintained within ±2 deg. Roll was better than pitch. Maximum altitude was 37,000 ft and maximum Mach was 0.88. The climb was discontinued at this point not because of PCA limitations, but because CAS off flight is not recommended in the transonic region.

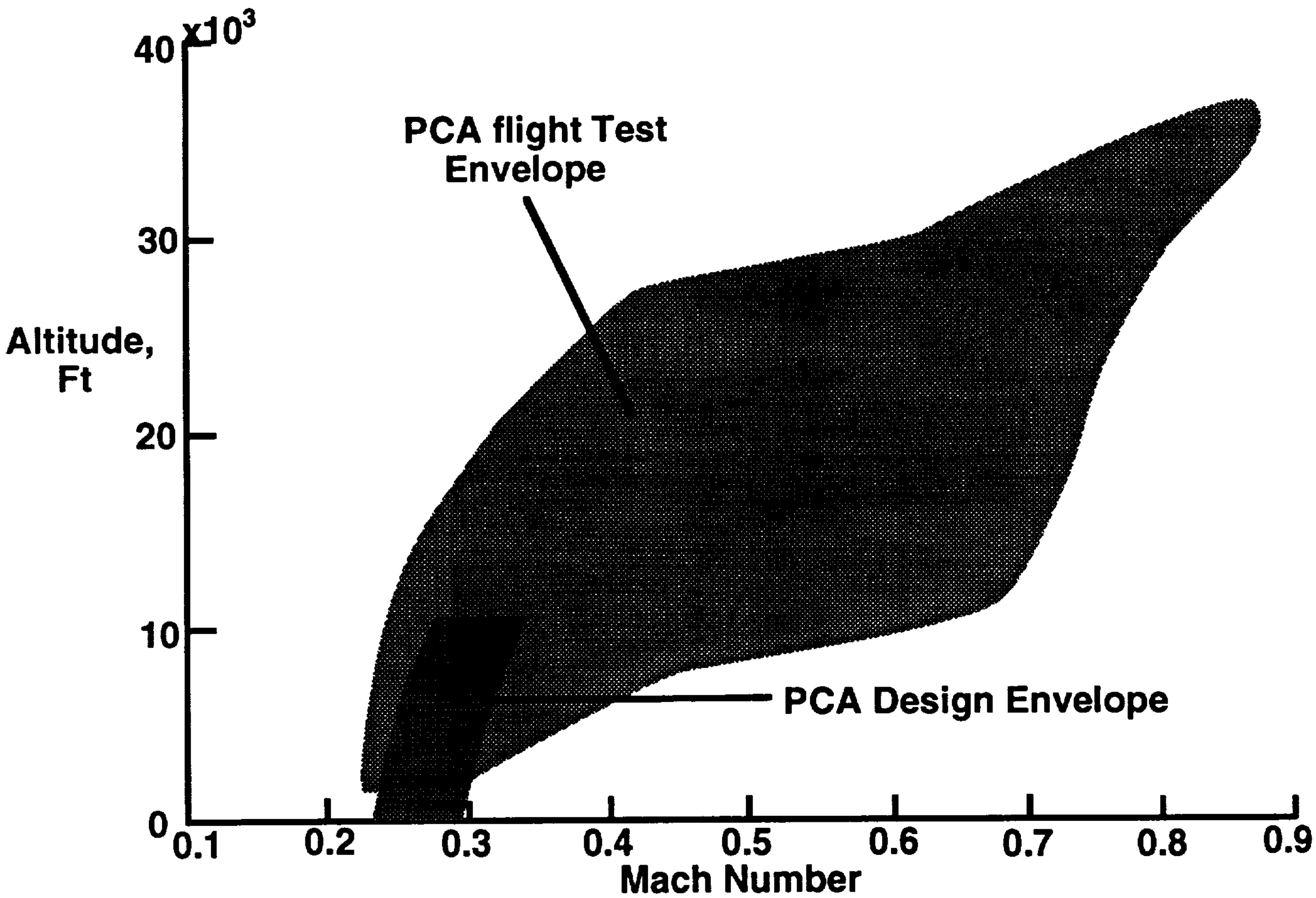


Note that the throttles, which were well matched at the beginning of the test, developed an increasing bias, with more right throttle required to hold wings level. This may be the result of wing fuel migration during the extended uncoordinated turn from 90 to 180 sec. Once the fuel had shifted to the right, increased right throttle would be required. Without a left turn to return the fuel the bias continued. Wing fuel quantity measurements also showed a bias consistent with fuel migration. Similar throttle splits had been seen at other flight conditions when extended periods of turning flight were flown.

PCA Design and Flight Test Envelope

The PCA system for the F-15 was designed for an airspeed range from 170 to 190 kts at altitudes below 10,000 ft. Later, the PCA system was tested over a wider range to determine it's robustness. The tested PCA envelope is shown below. Data from the 250 kt upsets, which reached 320 kts during the recovery, and the PCA climb at 280 kts showed that performance continued to provide postive control over a much larger envelope than considered in the design. The engine model in particular used 10,000 ft data for all higher altitudes. The fact that the PCA system remained usable well beyond it's design envelope is encouraging for future applications.

F-15 PCA Design and Test Envelope



PCA Guest Pilots

Several guest pilots were invited to fly the F-15 with the PCA system installed. The following is a list of all PCA pilots and their affiliations, along with a sample of comments.

Pilot	Affiliation	Assignment
Gordon Fullerton	NASA	Dryden F-15 PCA Project Pilot
Jim Smolka	NASA	Dryden F-15 project pilot
Capt. Dave Cooley*	USAF	Experimental Test Pilot, 445th Test Squadron, Edwards AFB, CA
Steve Herlt*	MDA	Contractor Test Pilot, F-15 Combined Test Force, Edwards AFB CA
Ed Schneider*	NASA	Dryden F-18 project pilot
Tom McMurtry*	NASA	Dryden Chief, Flight Operations
Lt. Rick Gertz*	USAF	USAF Test Pilot School, Edwards AFB
Lt. Len Hamilton*	NAVY	F-14 test pilot, Naval Air Warfare Center, Patuxent River MD

* indicate guest pilot

Excerpts from Lt. Len Hamilton, USN

The PCA system flown in the HIDEC F-15 was evaluated as highly effective as a backup recovery system should an aircraft lose total conventional flight controls. The system was simple and intuitive to use and would require only minimal training for pilots to learn to use effectively. Of course landing using PCA would require higher workloads than normal but this pilot believes landings could be done safely. The fact that the system provides a simple straight forward go-around capability allowing multiple approaches further supports the safe landing capability of the system. The dutch roll suppression characteristics of the system were extremely impressive to the pilot and would allow landings to be done even in non-ideal wind conditions. The PCA system exhibited great promise and if incorporated into future transport aircraft could further improve the safety of the passenger airlines.

Excerpts from Comments of Capt. Dave Cooley, USAF

General Handling Comments The aircraft responded adequately to all inputs commanded by the pilot. Pitch and roll response were both very sluggish yet always consistent and therefore predictable. The phugoid was surpressed by the system and was not noticeable except when making large changes in pitch. The dutch roll was very well controlled by the system. Generally, the system provided excellent flight path stability and good control of the aircraft without being overly sensitive to gusts.

Excerpts from comments of Steve Herlt, MDA

This Propulsion Controlled Aircraft demonstration, from the ground training and the demonstration profile to the actual PCA control law implementation, was very well done. More than simply a proof of concept demonstrator, today's flight exhibited capabilities that would enhance the survivability of aircraft. As long as aircraft have failure modes where you may lose the ability to fly the airplane with the control stick or yoke, I would like to have the backup capability demonstrated today by the Propulsion Controlled Aircraft.

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NASA Dryden Flight Research Center

"Dynamic Ground Effects Flight Test of the NASA F-15 Airp

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Author: Stephen Corda
Affiliation: PRC, Inc.
Phone: 805-258-2103
Fax: 805-258-3744
Address: Bldg. 4839, P. O. Box 273, Edwards, CA 93523-0273
e-mail: Stephen_Corda@QMGATE.DFRF.NASA.GOV

Author: Mark T. Stephenson

Affiliation: NASA Dryden Flight Research Center
Address: M. S. D2033, P. O. Box 273, Edwards, CA 93523–0273

Author: Frank W. Burcham Jr.
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3126
Fax: 805–258–3744
Address: M. S. D2033, P. O. Box 273, Edwards, CA 93523–0273
e–mail: Bill_Burcham@QMGATE.DFRF.NASA.GOV

Dynamic Ground Effects Flight Test of an F-15 Aircraft

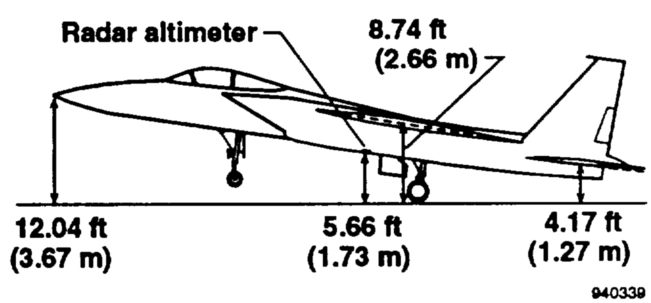
Stephen Corda
PRC, Inc.
Edwards, California

Mark T. Stephenson and
Frank W. Burcham
NASA Dryden Flight Research Center
Edwards, California

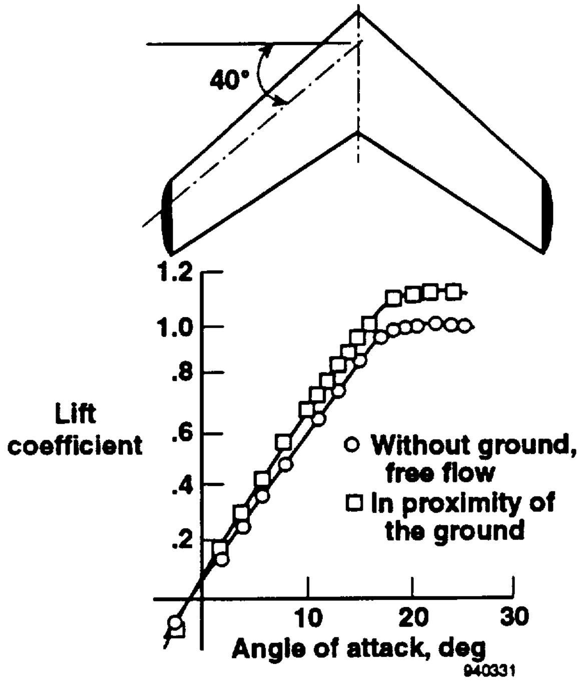
Abstract

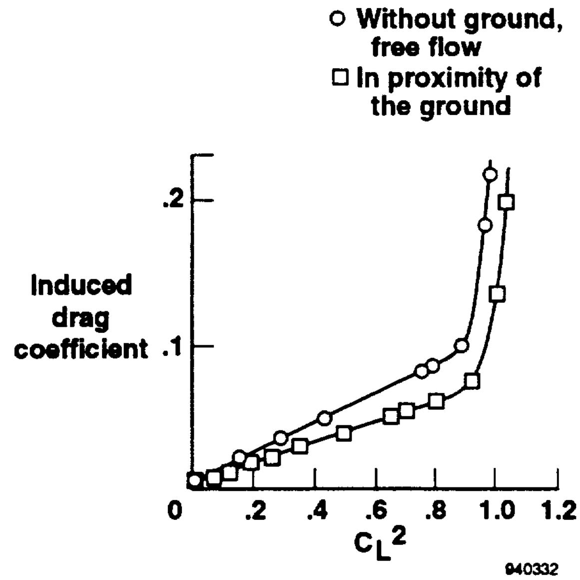
Aerodynamic characteristics of an aircraft may significantly differ when flying close to the ground rather than when flying up and away. Recent research has also determined that dynamic effects (i.e., sink rate) influence ground effects (GE). A ground effects flight test program of the F-15 aircraft was conducted to support the propulsion controlled aircraft (PCA) program at the NASA Dryden Flight Research Center.

Flight data was collected for 24 landings on 7 test flights. Dynamic ground effects data were obtained for low- and high-sink rates, between 0.8 and 6.5 ft/sec at two approach speed and flap combinations. These combinations consisted of 150 kt with the flaps down (30° deflection) and 170 kt with the flaps up (0° deflection), both with the inlet ramps in the full-up position. The aerodynamic coefficients caused by ground effects were estimated from the flight data. These ground effects data were correlated with the aircraft speed, flap setting, and sink rate. Results are compared to previous flight test and wind-tunnel ground effects data for various wings and for complete aircraft.



F-15 at touchdown attitude





Ground Effects Background

Ground effects may be explained by the interaction of the aircraft wingtip vortices with the ground. This interaction reduces the strength of these vortices. The weakened wingtip vortices reduce the downwash which increases the lift and decreases the induced drag or the drag due to lift. These figures show this change for a 40° sweptback wing. In addition, the reduced downwash at the wing trailing edge increases the angle-of-attack of the relative wind at the elevator, resulting in a nose-down pitching moment.

Ground effects data can be obtained in the wind tunnel or in flight. In conventional wind-tunnel ground effects testing, measurements are taken for a stationary aircraft model at various fixed ground heights. The results are called static ground effects data. Unfortunately, this static data simulates the aircraft flying near the ground at a constant altitude rather than simulating the transient or dynamic effects of the aircraft descending through a given altitude, termed "dynamic" ground effects data. Note that static conditions, whether in the wind tunnel or in flight, produce significantly different ground effects on an aircraft than those produced by dynamic conditions.

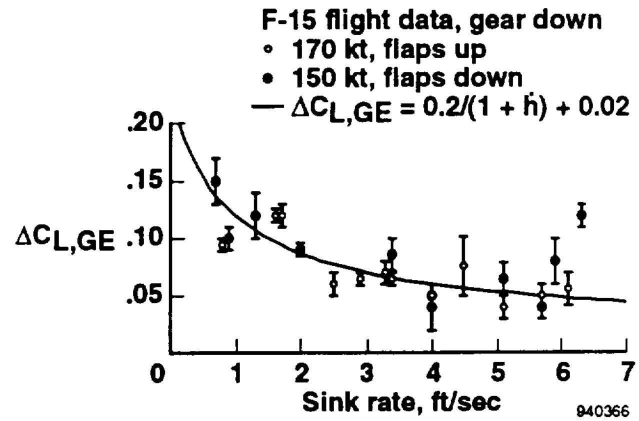
Approach Speed, Flap Setting, and Sink Rate Effects

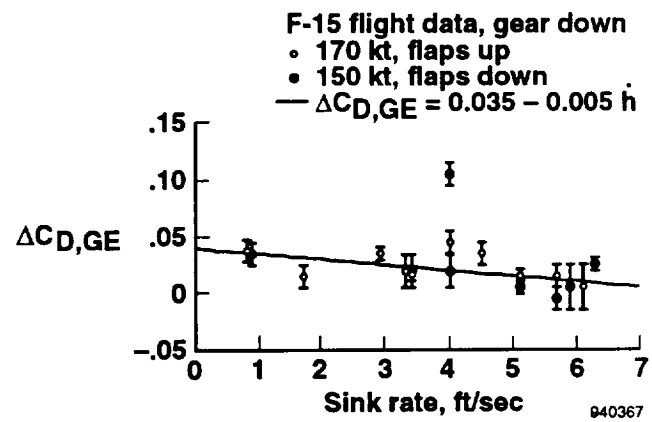
These figures show the F-15 ground effects flight data plotted versus as a function approach speed, flap setting, and sink rate. These figures show the changes due to ground effect of the lift, drag, and pitching moment coefficients as a function of sink rate. Changes in the aerodynamic coefficients were calculated at touchdown. Sink rates ranged from a low of 0.7 ft/sec (42 ft/min) to a high of 6.5 ft/sec (390 ft/min). For reference, the F-15 landing gear has a maximum sink rate capability of about 10 ft/sec (600 ft/min).

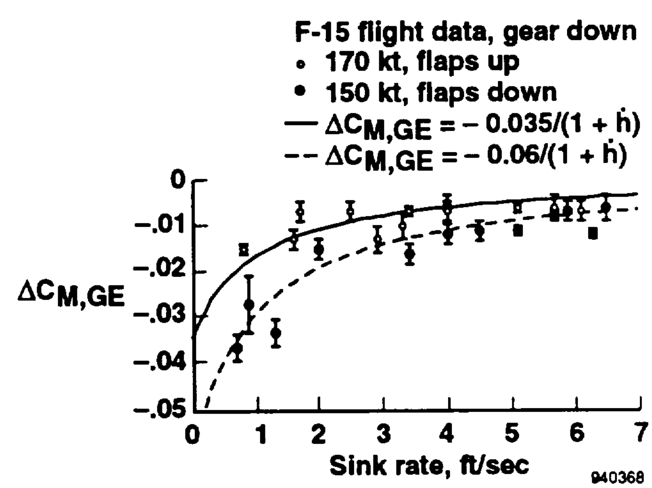
In general, these figures show that ground effect becomes more significant as sink rate decreases. The changes in the lift coefficient and the nose-down pitching moment increase with decreasing sink rate. The changes because of ground effect decrease and approach zero as the sink rate increases. These trends are not as clear for the drag coefficient.

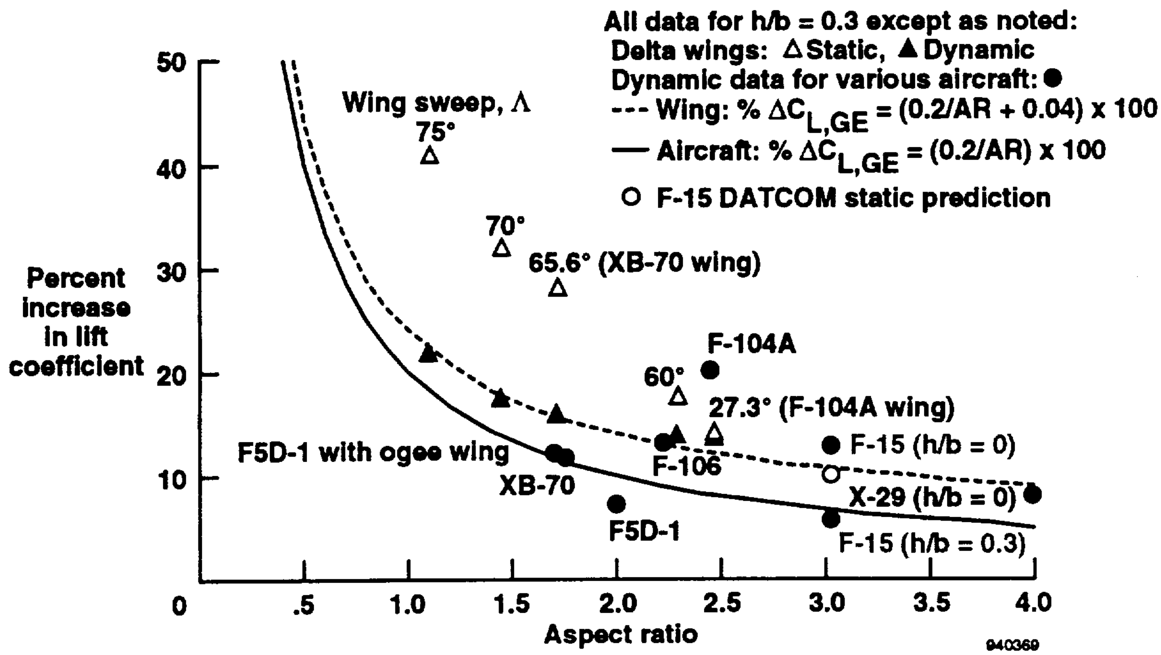
The approaches at 150 kts with the flaps down show more significant ground effects. This difference is most apparent for the pitching moment. This increase may be caused by a camber effect due to the flaps being down.

These figures show simple correlation curves that have been fit through the ground effects data. These curves give the change in lift, drag, and pitching moment coefficients because of ground effect as a function of sink rate.





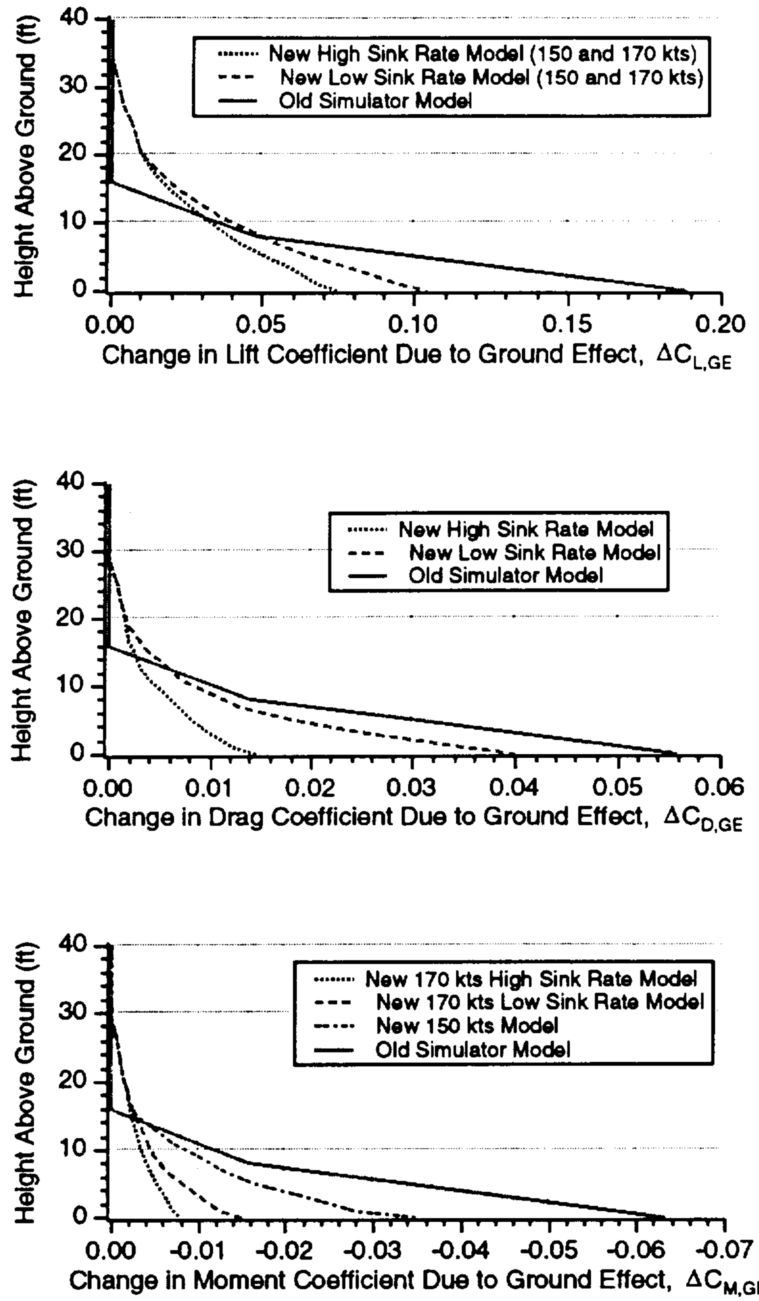




Previous Ground Effect Data Comparison

The F-15 ground effects lift data resulting from this investigation were compared to other wind tunnel and flight data for various wings and for complete aircraft. This figure shows the percent increase in the lift coefficient caused by ground effect as a function of the aspect ratio for the various wings and aircraft. The percent increase in the lift coefficient is defined as the difference between the lift coefficients in and out of ground effect divided by the out of ground effect lift coefficient. Static and dynamic data are shown. These data are for a height above the ground divided by wing span, h/b, of 0.3. The F-15 data are for the 170 kts with the flaps up configuration.

Correlation curves for the wing and for the aircraft are shown. In general, the F-15 flight data correlate well with the available aircraft dynamic ground effect data. These data show a decrease in the percent change in the lift coefficient as the aspect ratio increases. The changes in lift appear to approach nearly constant values for aspect ratios greater than about 3.



Improvement in F-15 Ground Effects Flight Simulator Model

This figure shows the improvements made to the NASA Dryden F-15 flight simulator modeling of ground effects based on the ground effects flight test data. The changes in the aerodynamic coefficients are shown as a function of height above the ground. The new ground effects model is a function of approach velocity and sink rate. The new model more closely duplicates actual flight data as seen in the results presented in the flight test paper by Burcham and Maine ("Flight Test of a Propulsion Controlled Aircraft System on the NASA F-15 Airplane").

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NASA Dryden Flight Research Center

"Design Challenges Encountered in the F-15 PCA Flight Test Program"

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Author: Trindel A. Maine
Affiliation: NASA Dryden Flight Research Center
Phone: 805-258-3794
Fax: 805-258-3744
Address: M.S. D2033, P. O. Box 273, Edwards, CA 93523-0273
e-mail: tam@alien.dfrf.nasa.gov

Author: Frank W. Burcham Jr.
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3126
Fax: 805–258–3744
Address: M.S. D2033, P. O. Box 273, Edwards, CA 93523–0273
e–mail: Bill_Burcham@QMGATE.DFRF.NASA.GOV

Author: Peter Schaefer
Affiliation: University of Southern California
Phone: 805–258–2907
Fax: 805–258–3744
Address: M.S. D2033, P. O. Box 273, Edwards, CA 93523–0273
e–mail: schaefer@alien.dfrf.nasa.gov

Author: John Burken
Affiliation: NASA Dryden Flight Research Center
Phone: 805–258–3726
Fax: 805–258–3744
Address: M.S. D2033, P. O. Box 273, Edwards, CA 93523–0273
e–mail: burken@halon.dfrf.nasa.gov

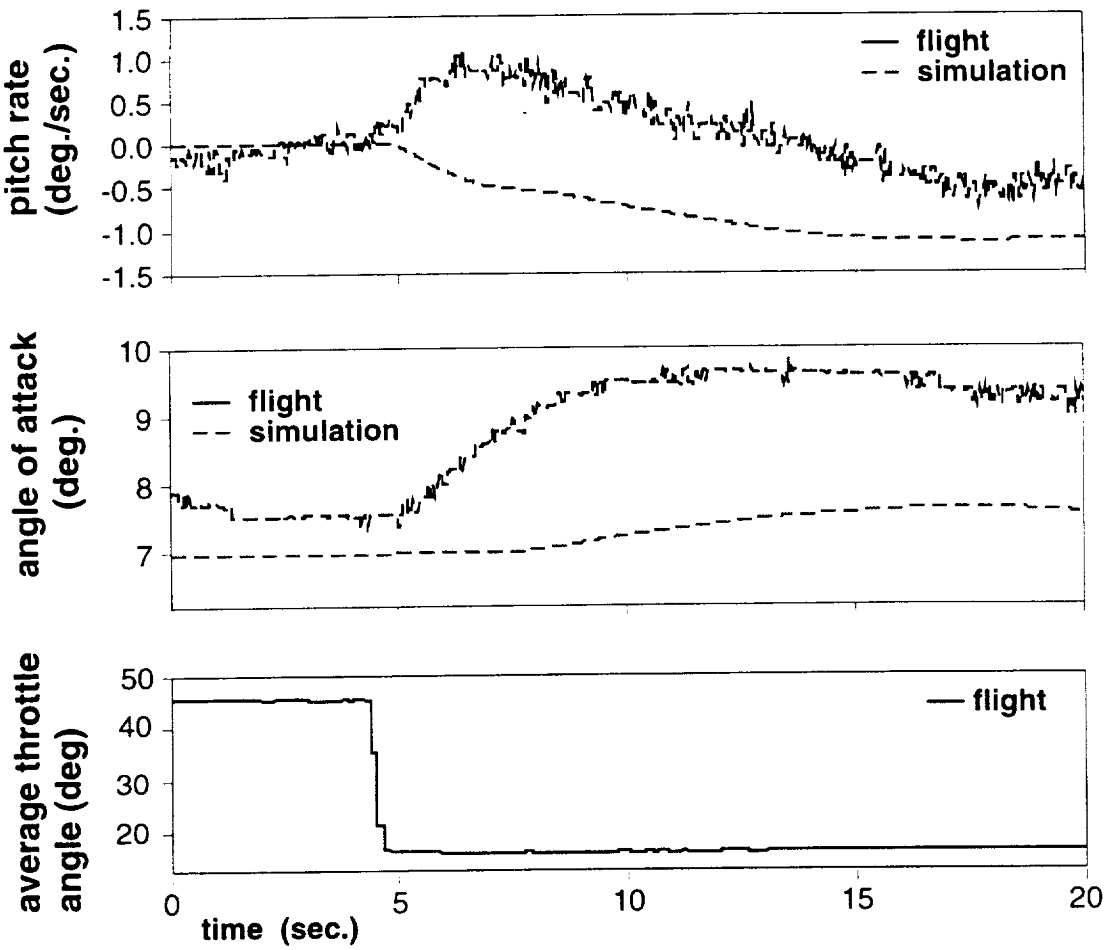
Design Challenges Encountered in the F-15 PCA Flight Test Program

Trindel A. Maine
Frank W. Burcham
Peter Schaefer
John Burken

Abstract

The NASA Dryden Flight Research Center conducted flight tests of a propulsion-controlled aircraft system on an F-15 airplane. This system was designed to explore the feasibility of providing safe emergency landing capability using only the engines to provide flight control in the event of a catastrophic loss of conventional flight controls. Control laws were designed to control the flightpath and bank angle using only commands to the throttles.

While the program was highly successful, this paper concentrates on the challenges encountered using engine thrust as the only control effector. Compared to conventional flight control surfaces, the engines are slow, non-linear, and have limited control effectiveness. This increases the vulnerability of the system to outside disturbances and changes in aerodynamic conditions. As a result, the PCA system had problems with gust rejection. Cross coupling of the longitudinal and lateral axis also occurred, primarily as a result of control saturation. The normally negligible effects of inlet airframe interactions became significant with the engines as the control effector. Flight and simulation data are used to illustrate these difficulties.



Inlet-Airframe Interactions

During the control law design process, a few flights were flown where the pilot flew the airplane manually using the throttles. This task was significantly harder than simulation had predicted. An examination of the flight and simulation data showed that the flight data had a transient adverse pitch response that was not modeled in the simulation as is shown in this figure. The study of this problem is discussed in detail in the *Flight Test of a Propulsion Controlled Aircraft System on a NASA F-15 Airplane.* It was found that a decrease in the velocity of the inlet airflow and a corresponding increase in the pressure on the overhanging inlet ramps caused a small upward-pitching moment. This was found to be significant when the inlet mass flow ratio was less than one and the trim angle of attack was less than 9°. The decision was made to change the intended PCA landing speed from 170 knots to 150 knots in order to move both the trim angle of attack and the inlet mass flow ratio out of the problem range. Changes made in the PCA control laws are discussed in *PCA Design and Development.*

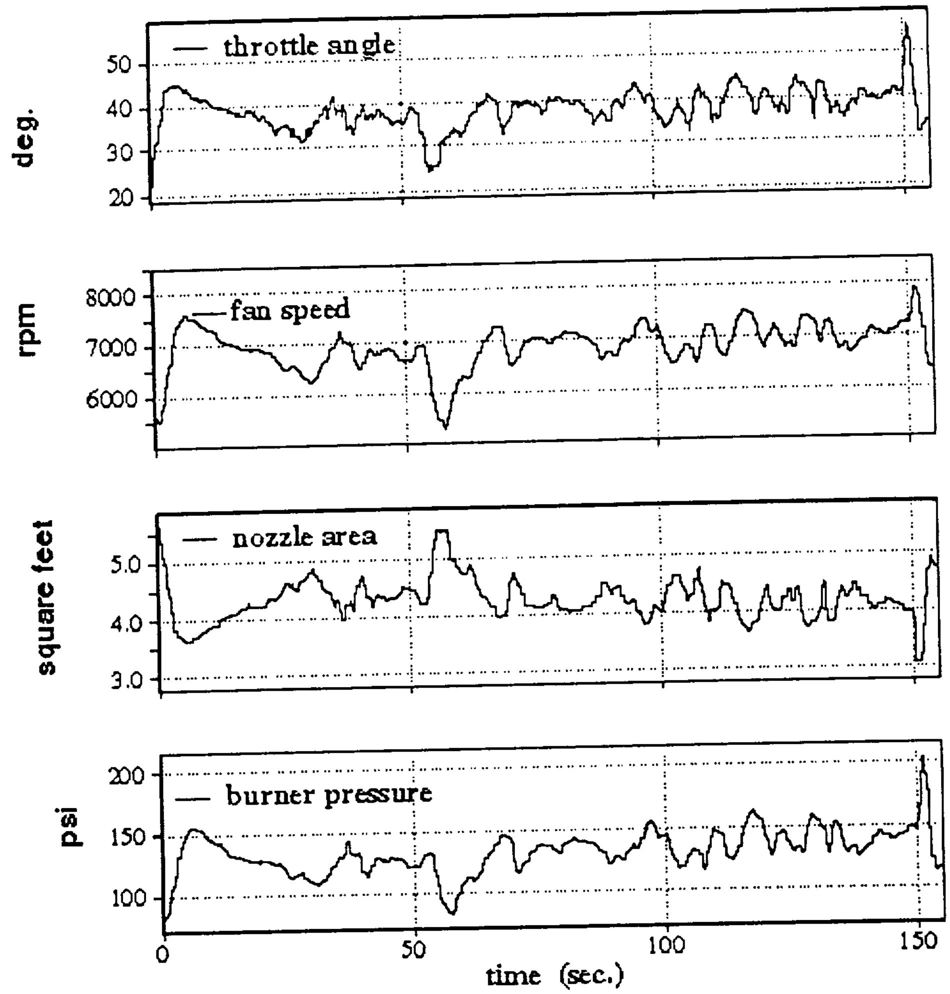
The inlet airflow effect is easily accommodated by the normal flight controls and would often be neglected in an airplane simulation . Because of the limited control power available when using the engines as the sole control effectors, normally neglected effects are likely to be significant. Moreover, the direct coupling of inlet airflow changes to control system commands made the airflow effect a significant problem.

The Gas Turbine Engine as a Control Effector

It is a challenge to use a gas turbine engine as a control effector for PCA. In the PCA application each engine of the F-15 is commanded to produce a specified incremental thrust change. This is done by converting the thrust command generated by the PCA control laws into a throttle comand using non-linear lookup tables. Given a throttle command the engine should automatically adjust to provide the desired amount of thrust.

Proper use of a control effector in a design requires a reasonably accurate model of the effector's response to command inputs and disturbances. This means that a model is needed which accurately reflects the dynamic thrust response of the engine to changes in the commanded throttle angle. Models used in the development of the PCA system were simplified first-order linear models with rate limits. These models were derived by matching the step responses of a high-fidelity engine simulation developed by Pratt and Whitney for the 1128 engine.

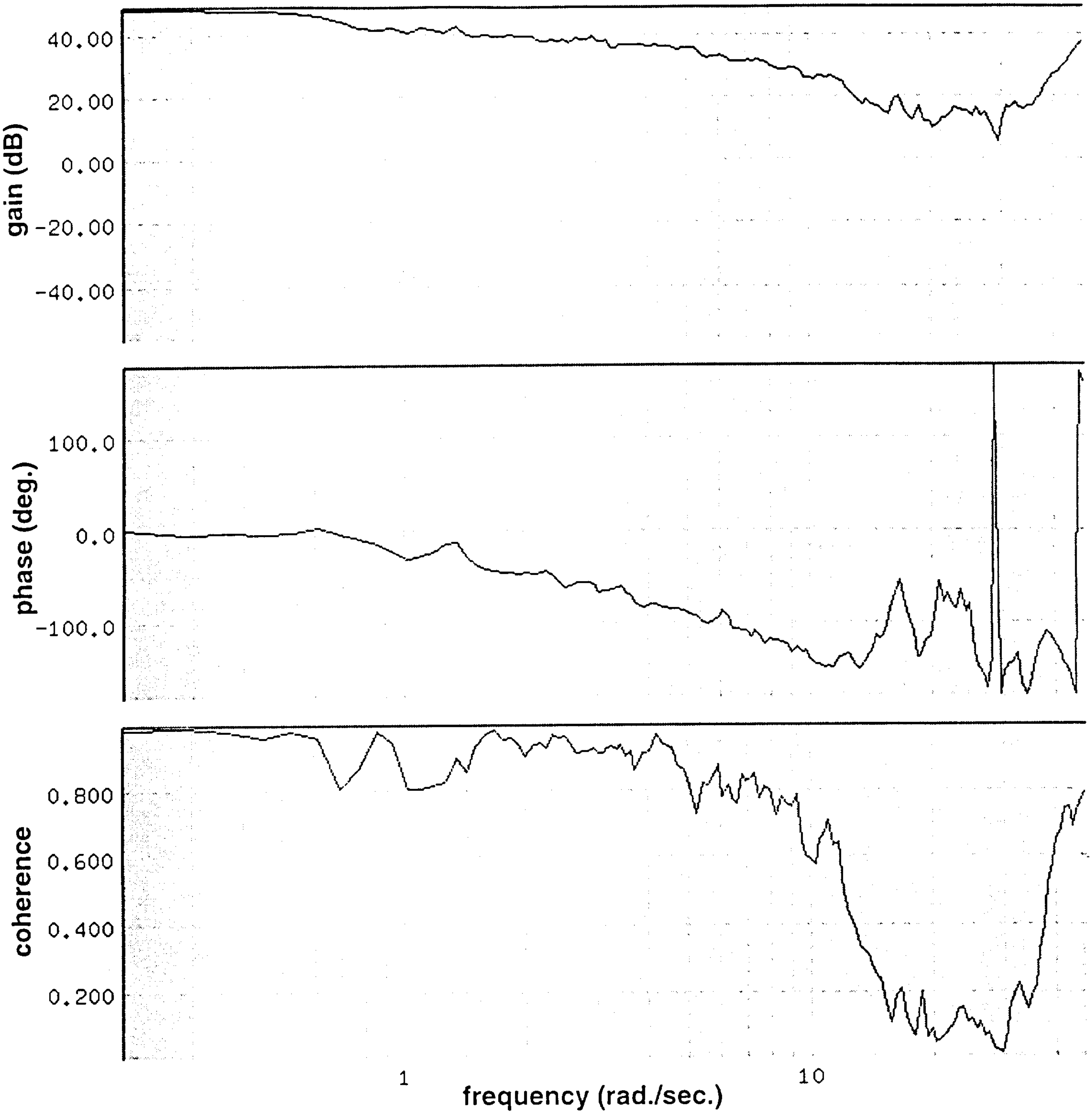
In an effort to refine the system analysis process, an effort was made to verify the match of the simplified engine model to in-flight engine performance. Ideally, flight data could be used to produce a transfer function model of throttle angle to net thrust. This was not possible because of high noise levels, unknown system time delays, a lack of adequate synchronization between signals and no direct measure of thrust. However, it was possible to determine the response of some key engine parameters to throttle commands. These paramenters are the low compressor fan speed, the total burner pressure, and the nozzle area. While these parameters cannot be used alone to determine the thrust response of the engine, they do give insight into some of the bandwidth limiting factors.



Flight Data: Landing Approach Workload

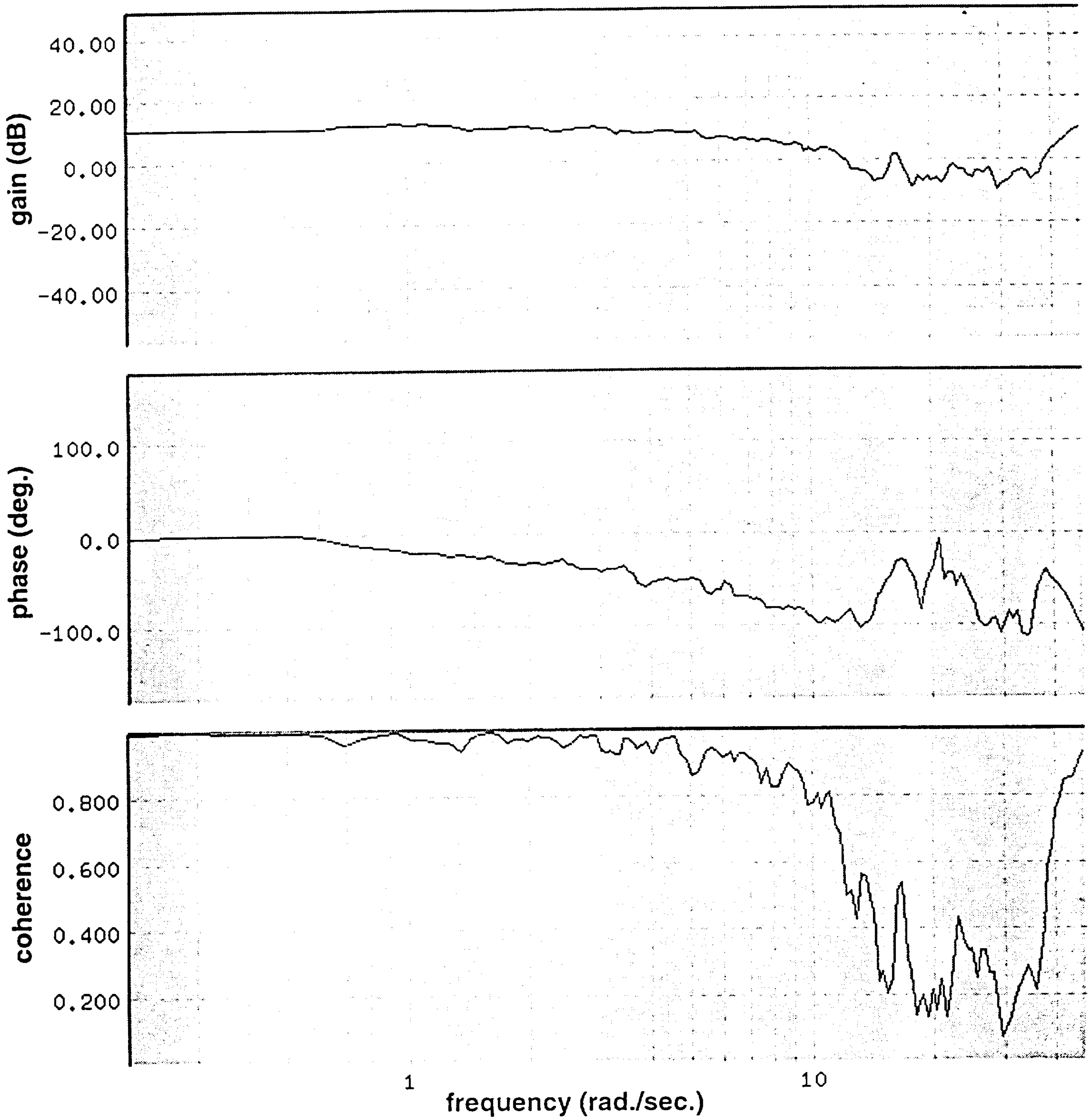
The data shown in this set of plots is from the left engine of the F-15 on a landing approach during a guest pilot evaluation flight. The engine activity is representative of typical engine workloads while the airplane is under PCA control. This particular segment of data is free of command saturation which could corrupt the data required to obtain good transfer functions.

Note that the the activity of the low compressor fan speed closely follows that of burner pressure and that nozzle area moves in the opposite direction from burner pressure and fan speed.



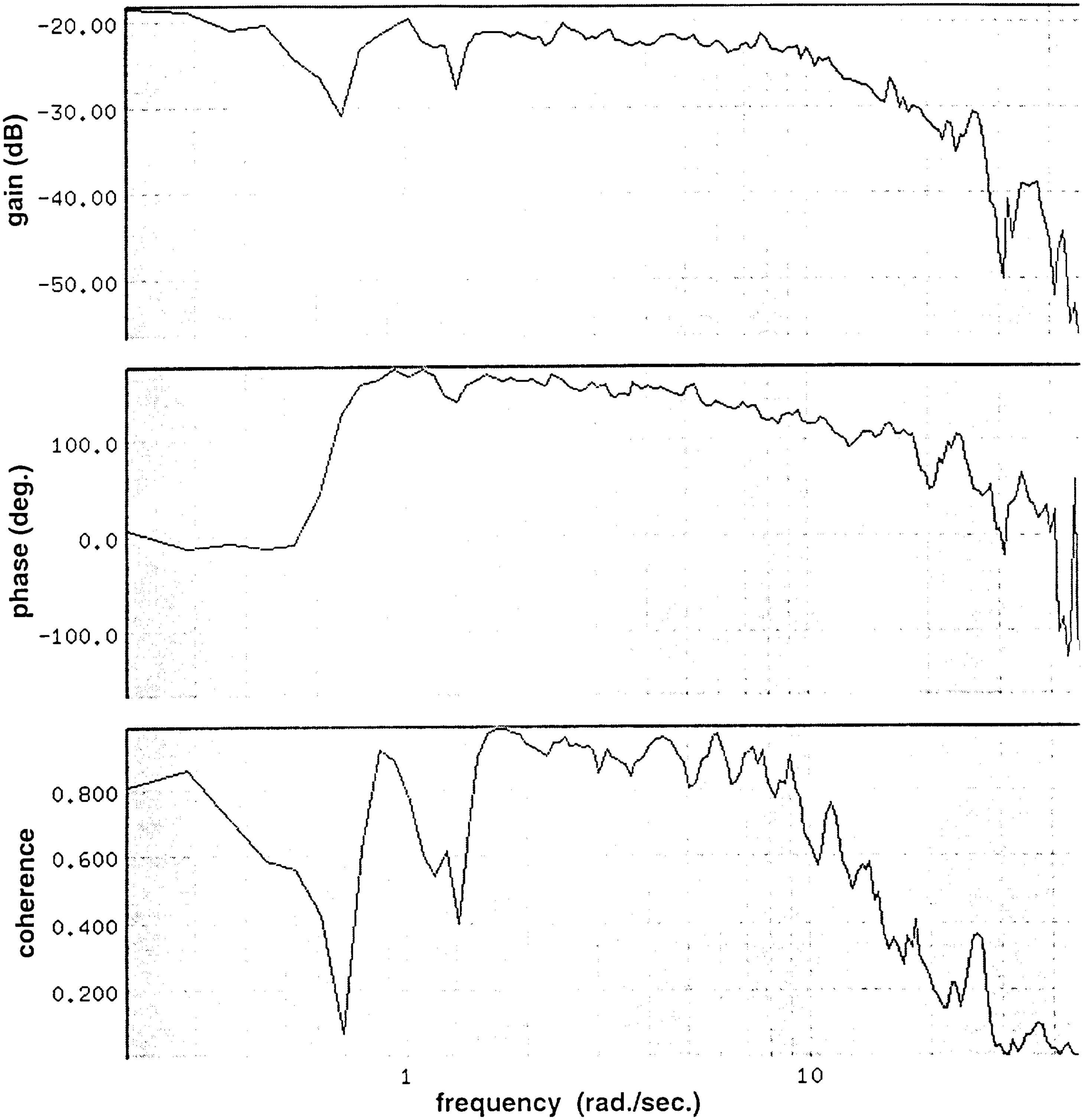
Fan Speed Frequency Response to Throttles

This set of plots shows the frequency response of the low compressor fan speed to throttle commands. These gain and phase plots were produced using fast-fourier transforms. The coherence plot indicates that the results are reliable out to about 5 rad./sec. The phase plot crosses the -45° line near 2 rad./sec. the fan speed response appears to be first order with a 2 rad/sec cuttof frequency.



Burner Pressure Frequency Response to Throttles

The coherence on the burner pressure response indicates that the gain and phase information is reliable out to 10 rad./sec. This response can easily be modeled as first order with a cutoff of about 5 rad./sec. This cutoff is indicated by both a 3 dB magnitude drop in the gain plot and the 45° crossover on the phase plot.



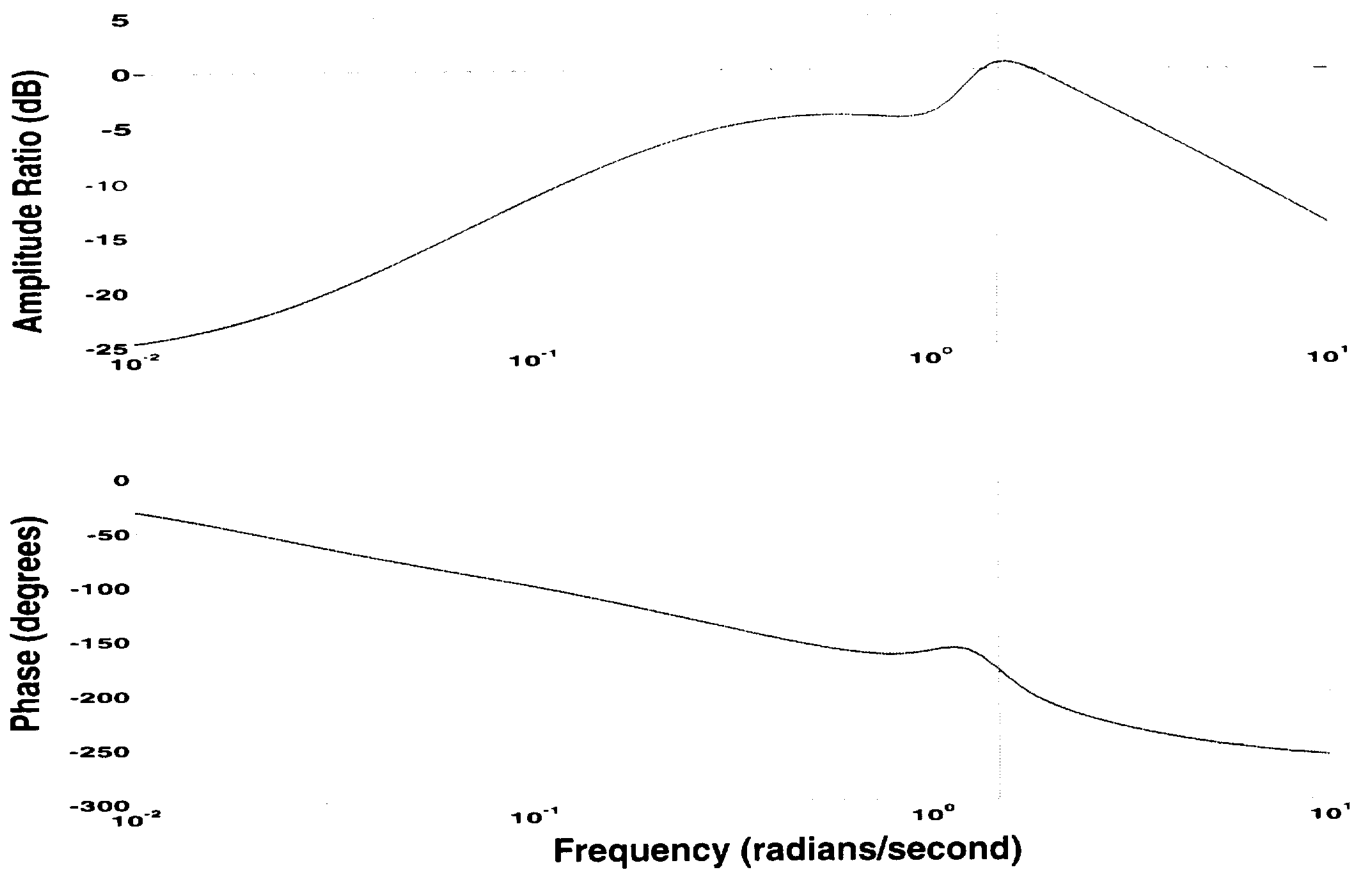
Nozzle Area Frequency Response to Throttles

The coherence plot indicates the frequency response data is reliable from 2 rad./sec. to about 9 rad./sec. Low frequency coherence is poor because the nozzle actuators operate within a very narrow range of rates. Although bandwidth cannot be accurately estimated from these plots, it is apparent that the bandwidth is high, with a cutoff near 10 rad./sec. The slow phase rolloff indicates that the nozzle actuation can safely be modelled as first order.

Engine Response Summary

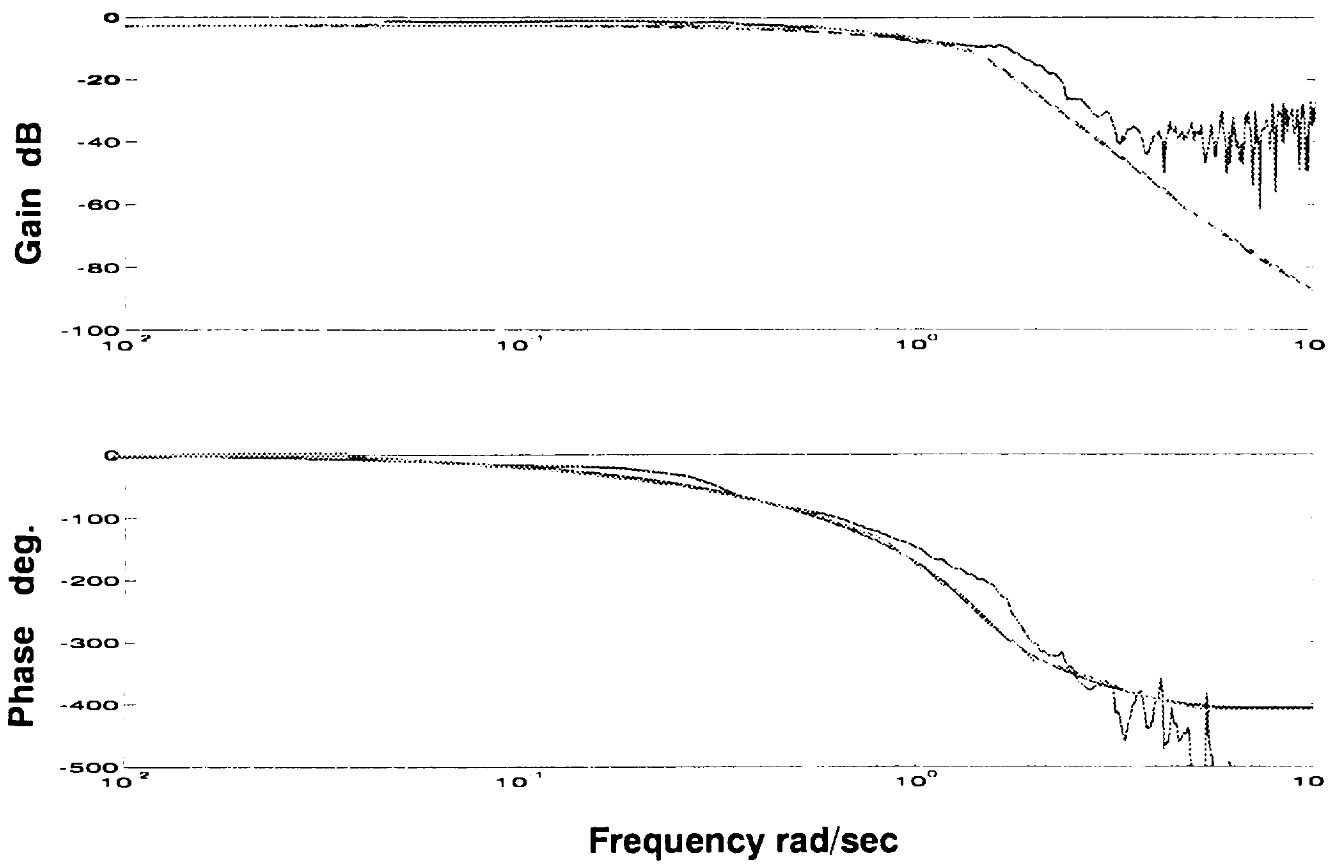
All three of these parameters support the use of a first order model of the engine response. The flight data indicate the bandwidth of the engine is higher than the linear model that was used in the design process which had a cutoff frequency of .9 rad./sec.. Using the fan speed as the most conservative of the three parameters , gives a bandwidth of about 2 rad./sec. Fast reductions in thrust can be achieved by opening the nozzles. However, since the nozzle area is driven by the schedules in the engine control laws, the PCA system often could not take advantage of this.

It is important to note that this analysis was done using flight data collected on an approach with only light turbulence. Because of this, command saturation was not a problem. In rougher air, with the limited control authority available from the engines, control effector bandwidth was effectively further diminished by command saturation.



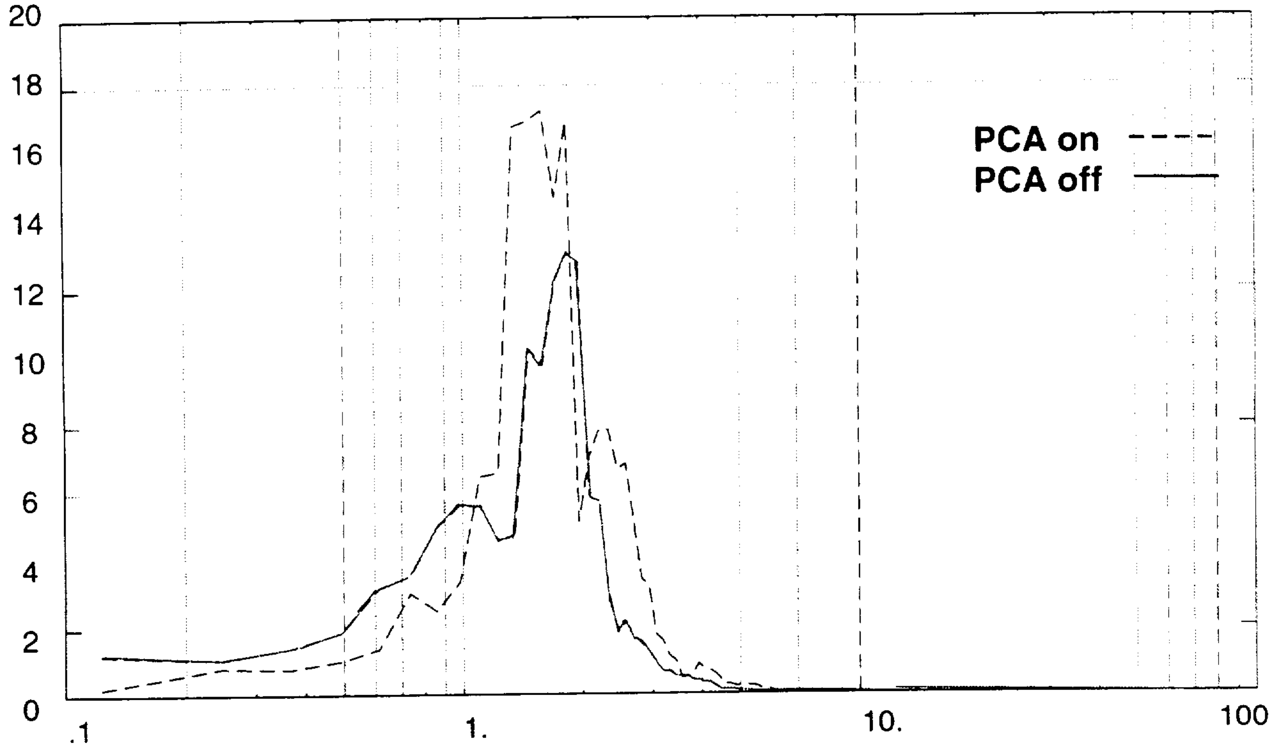
Linear Open-Loop Roll Rate Response to Roll Gust Disturbance

A linear analysis of the F-15 airplane's lateral-directional dynamics driven by the Dryden gust model produced the open loop Bode plot shown above. This figure shows the roll rate sensitivity of the F-15 airplane with the surfaces disabled to roll rate gust disturbances. A peak in the response occurs at approximately 1.5 rad./sec. with a magnitude slightly above the 0 dB line (green). This peak indicates that the F-15 airframe actually amplifies the effects of gust disturbances at this frequency. This characteristic is seen in the flight data as a tendency toward bank angle oscillation of approximately 1.5 rad./sec. This frequency is sufficiently close to the cutoff frequency of the engines for engine response lag to be significant.



PCA Closed-Loop Bank Angle Frequency Response from Flight and Linear Analysis

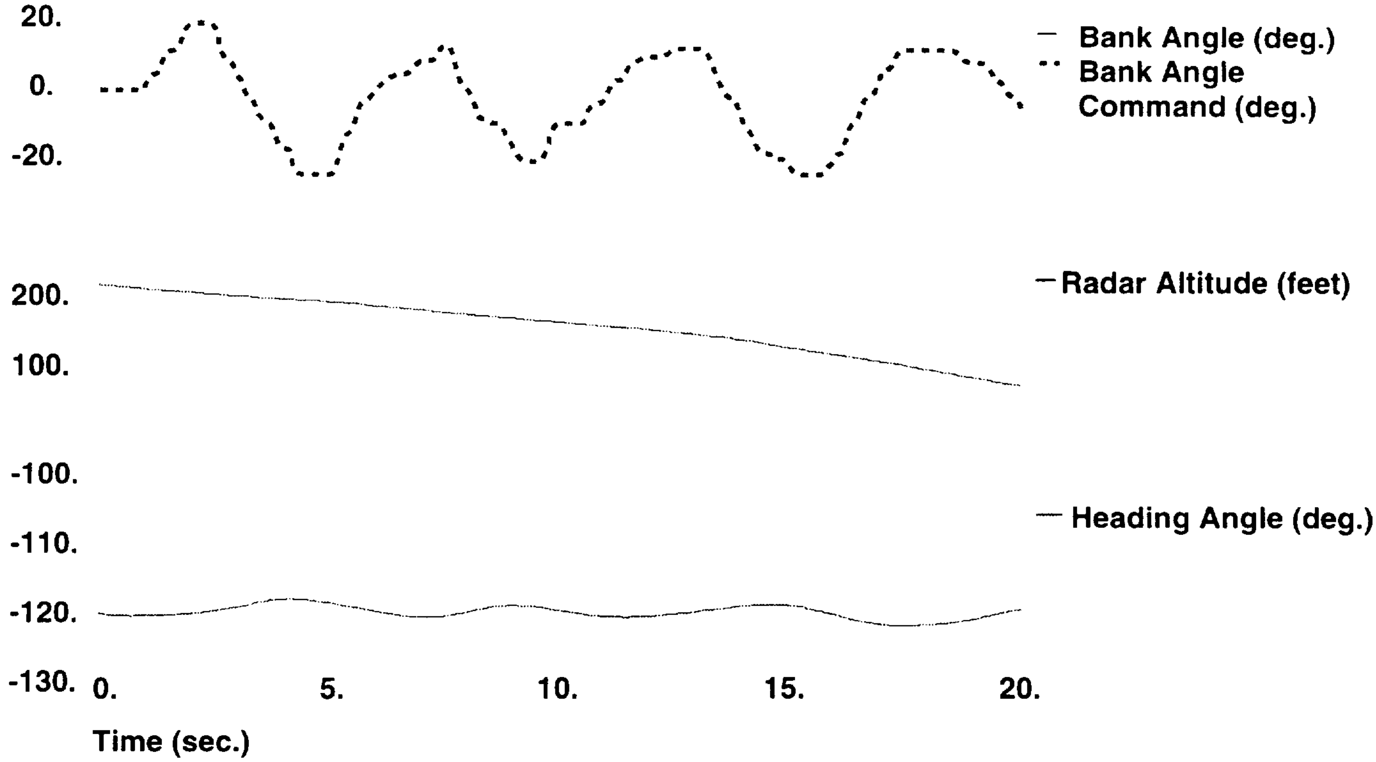
This figure shows the both the analytical (red) and a flight-derived (blue) frequency response of the closed-loop lateral response of bank angle to pilot command. The flight-derived response was determined through a pilot-conducted frequency sweep using the lateral thumbwheel. From this figure, it is clear that the combined phase lag from the control system delays and the engine dynamics at the bank-angle oscillation frequency of 1.5 rad./sec. is approximately 200 deg. This large phase lag in the closed-loop response results in the PCA commands being significantly out of phase with the aircrafts motion.



Roll Rate Power Spectral Density From Flight Data With and Without the PCA System

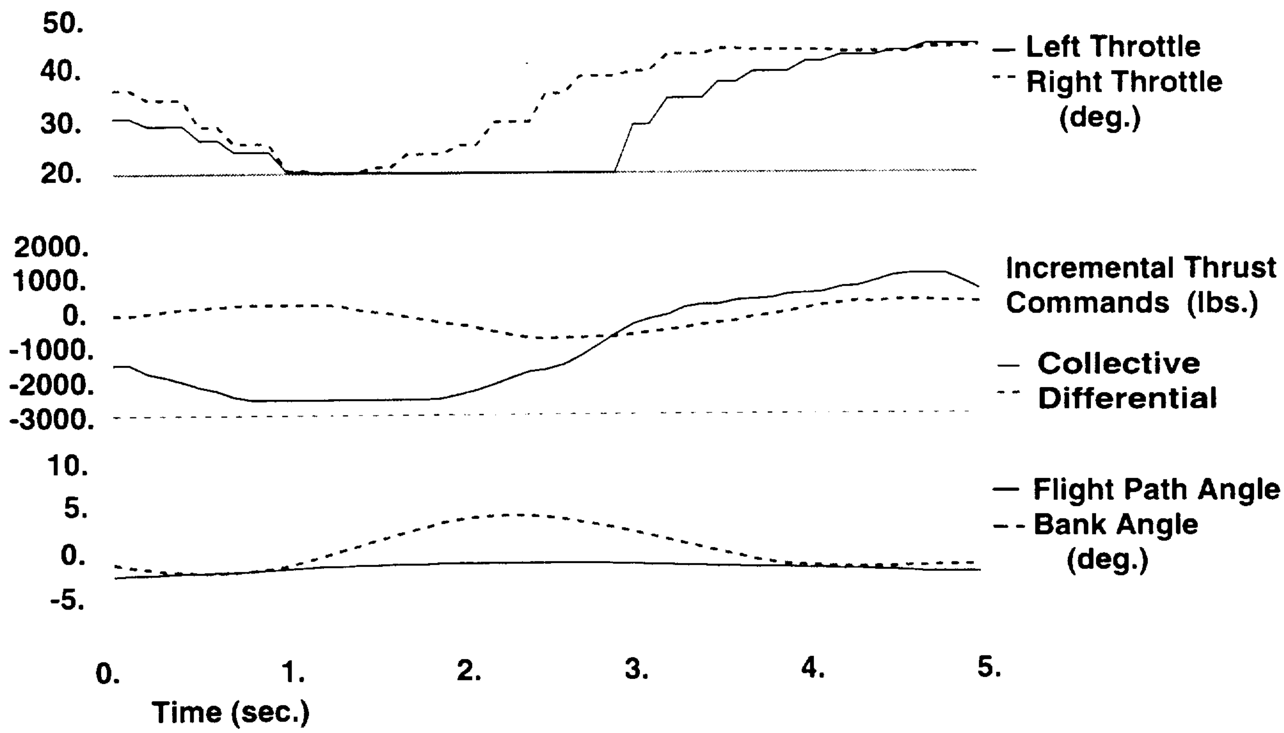
To further investigate the PCA systems difficulties with lateral gust disturbances, the F-15 airplane was flown through turbulent air with the PCA system on and then was flown again through the same air mass with all control augmentation off. Comparisons of the power spectrum of roll rate activity show the control system amplifying roll rate disturbances by approximately 30%.

This program was a first demonstration of the feasibility of throttles-only flight control and did not seriously address the anticipated gust rejection problem. Relatively little effort was directed at designing control laws that would handle even light turbulence well. As the program progressed, the impossibility of ordering the weather to match the flight test schedule and the high level of success achieved in still air led to attempts to fly in increasingly turbulent air. In retrospect, a greater effort cold have been made to design the control laws to reject gust disturbances.



Lateral Pilot Induced Oscillation on PCA Approach

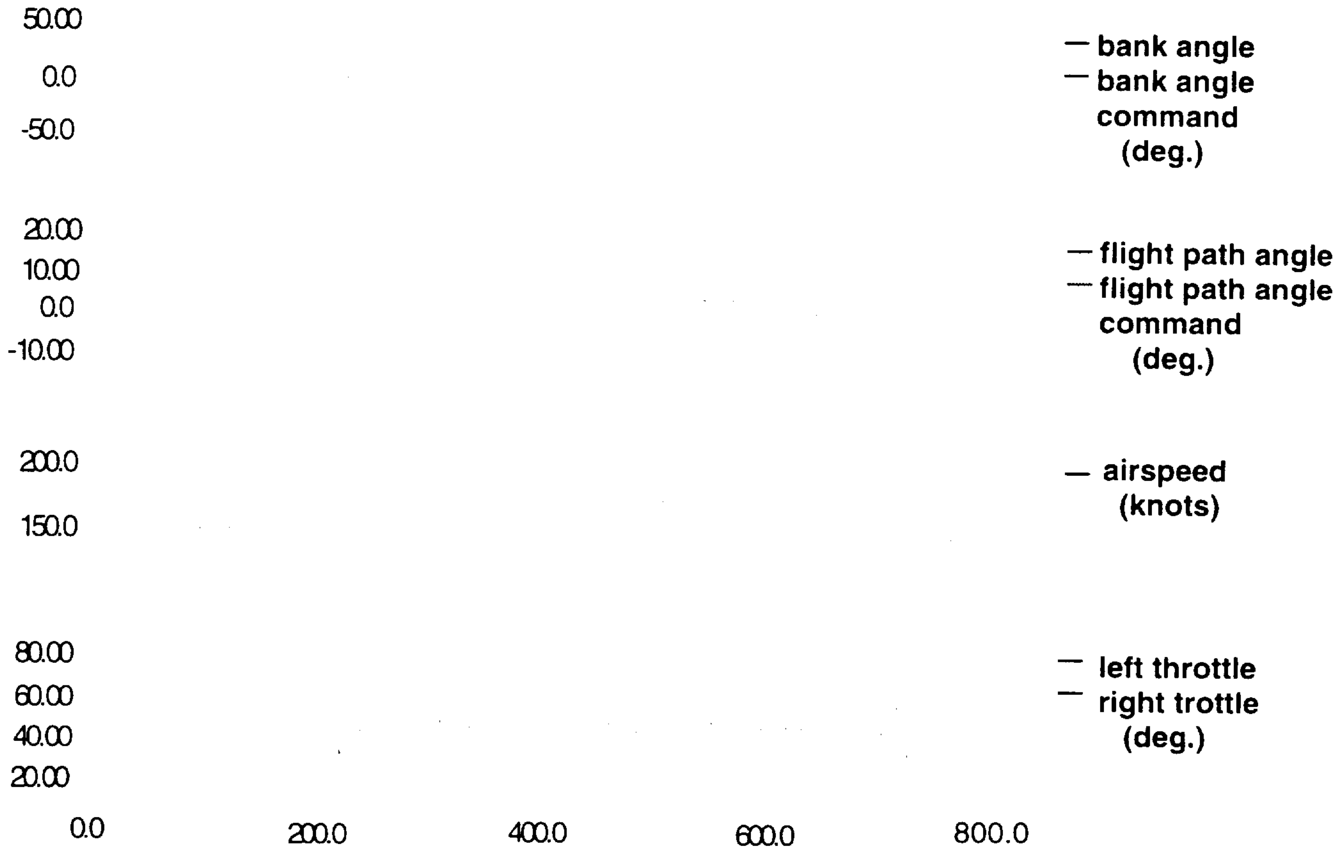
Both the disturbance amplification and the command-to-bank-angle phase lag at 1.5 radians shown in the previous 3 figures, result in a condition in which a pilot-induced oscillation can easily occur. This figure shows the pilot attempting to damp the gust-excited bank oscillation (blue) by applying a counter command (red). Instead of damping the bank-angle oscillation, the pilot is actually providing further excitation. This typically occurred in gusty weather when the pilot was aggressively working to maintain the runway heading just prior to landing. This oscillation substantially complicated the landing task and limited the flight regime of this inital PCA demonstration program to relatively light levels of turbulence.



Cross Coupling Response Caused By PCA Command Saturation

Cross-coupling between the longitudinal and lateral-directional axes was observed during the flight program. Cross-coupling caused by throttle command saturation typically occured on landing approaches in gusty conditions. On low-speed approaches, the commanded collective thrust was close to idle. If the PCA system was required to correct for a significant bank-angle disturbance, then the low collective thrust command combined with the differential command occasionally resulted in a throttle command which was below idle. This command saturation results in transient degradation of both longitudinal and lateral control power.

This figure shows an example of this loss of commanded control power occuring between 1 and 3 seconds. Both throttles were saturated at idle (green) when a lateral disturbance occurred. The system commanded an increasing differential thrust command, but since both throttles were already at the idle limit, the portion of the differential command that would normally be achieved by lowering the right throttle was lost. As a result the system was unable to prevent a 5° bank angle excursion and a smaller increase in flightpath angle. This contributes to difficulties in maintaining wings level in turbulent conditions.



Dynamic Cross-Coupling at Large Bank Angles

Dynamic cross-coupling effects are also evident at large bank angles. As the bank angle increases, the vertical component of lift is reduced and an increase in speed is required to maintain flight path angle. Using the F-15 PCA system the bank angle response is significantly faster than the flightpath angle response. The required changes in air-speed lag behind the bank-angle response to bank-angle command, thus creating a disturbance in the flightpath angle.

This figure shows the results of a bank angle response test with a series of increasing bank angle commands. As can be seen large bank angle commands result in significant changes in both velocity and flightpath angle as well as poor command tracking in bank angle. Commands below about 25° did not produce significant flight path angle disturbances, but above 25° the disturbances became increasingly severe. At the extremes, bank angle commands of 60° produced as much as -10° of flightpath angle disturbance and 20° of flightpath angle upset on the rollout. Note that command saturation is also contributing to the problem, with the left and right throttles regularly hitting the idle and military thrust limits (green). Limiting bank angles commands to below 25° is probably reasonable for an emergency landing system and possibly could be opened up with a bank angle cross feed to the longitudinal control laws.

NASA Dryden Flight Research Center

"F-15 PCA Conclusions and Lessons Learned"

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Author: Frank W. Burcham Jr.
Affiliation: NASA Dryden Flight Research Center
Phone: 805-258-3126
Fax: 805-258-3744
Address: M.S. D2033, P. O. Box 273, Edwards, CA 93523-0273
e-mail: Bill_Burcham@QMGATE.DFRF.NASA.GOV

F-15 PCA Conclusions

A propulsion controlled aircraft (PCA) system on an F-15 airplane has been developed and flown, as part of a study of throttles-only flight control capability. For comparison, manual throttles-only approaches have also been flown. The following conclusions have been made:

1. The augmented PCA system, using computer-controlled engine thrust, provided a suitable method for emergency flight control of an airplane without any flight controls. PCA pitch and roll control provided good up-and away flight control, which was adequate for safe runway landings in good weather. Overall, the PCA system performance was considerably better than expected.

2. The PCA pitch control was sluggish but very stable and predictable. About 10 sec was required to achieve a commanded flightpath change. On approaches, the pilots tended to set the flightpath command and make very few changes.

3. PCA bank angle control was positive and predictable, but lagged inputs by about 3 sec. On approaches, the pilots spent most of their time making bank angle corrections. A heading mode was implemented, and reduced the pilot workload, but was not adequately evaluated to make any firm conclusions.

4. The PCA pilot input pitch and bank angle thumbwheels were liked by all pilots. The guest pilots were able to use the PCA system effectively on their first flight. They liked the stable pitch control, and could adapt to the roll control. All were able to complete approaches to the runway that they felt could have been carried on to safe landings.

5. The simulations used to develop the PCA system required extensive updates, many based on flight data, to incorporate models of many small effects that are normally ignored. Initial simulation results were overly optimistic. Fully adequate simulation-to-flight comparisons were not obtained until after the flight program was completed.

Conclusions - continued

6. The most significant addition to the simulation was an inlet airflow effect that resulted in an initial pitching motion opposite to that expected, and required extensive data analysis and control law development. This inlet airflow effect, a direct function of controller input, was a result of the highly integrated nature of the F-15 propulsion system, and would not be expected for an airplane with podded engines. Ground effect was also not properly predicted until updated dynamic ground effect data and the inlet effect were properly modeled.

7. The PCA system operated successfully well beyond the original design goals. PCA engagements in upset conditions up to 90 deg bank and 20 deg dive were successful, showing that PCA has a good chance for recovering airplanes from actual flight control system failures, provided that the flight controls fail in a condition in which throttle forces and moments have adequate authority to achieve controlled flight. PCA operated successfully at altitudes above 35,000 ft and Mach numbers to 0.88.

8. Manual throttles-only control is possible for up and away flying but is not capable of making a safe landing for an airplane with the low natural stability and the adverse inlet airflow effect of the F-15.

9. The F-15 airplane flown with the control augmentation off has sufficiently poor stability and flying qualities to make it a very challenging application for PCA. The success of the F-15 PCA system in stabilizing a difficult airplane indicates that more stable airplanes such as large transports should have better or at least equal success with PCA systems.

10. The flexible flight software that permitted changes in gains, constants, sensitivities, and control modes made it possible to substantially exceed the project goals in a short flight program.

11. The ground effect had an adverse effect on F-15 PCA landings, making the touchdown sink rate 8 ft per second for a range of lower sink rates out of ground effect. On the F-15, the ground effect was exacerbated by the adverse inlet airflow effect; this should not be the case on a transport airplane.

12. Flight data showed that the engine bandwidth was about 2 rad/sec. In turbulence, the lateral control degraded in the 1.5 rad/sec range, and some pilot-induced oscillation tendency was seen.

Lessons Learned

Taking the PCA experiment to flight was critical in maturing propulsive control technology. The "better than expected" results would not likely have been found from a simulation experiment.

The PCA control law design could have achieved better gust rejection if that had been a goal during the design. Originally, it was not envisioned that PCA approaches would be flown in anything other than smooth air. Flight data showed that the engine bandwidth was about 2 rad/sec, whereas the engine model used in the design had a bandwidth of about a 1 rad/sec. The lateral control degradation in the 1.5 rad/sec range could have been reduced if the design had taken full advantage of the engine capabilities.

Future PCA designs would benefit from a more in-depth study of cross-coupling issues. Because PCA landings are often conducted at relatively low thrust levels, there is a possibility of control saturation on idle. Explicit logic should be considered to minimize cross-coupling due to saturation while maximizing the limited control power available, and also limiting control authority where necessary.

The PCA guest pilots showed that PCA can be learned and used with a minimal degree of training. The thumbwheel concept was an excellent way to provide good control capability while still reminding the pilot that he has a sluggish flight control system.

Having the F-15 HIDEC integrated controls testbed airplane already available was critical for the PCA program. If this entire capability had to be built up from scratch, it would have been way too costly and time-consuming to consider.

Flexible flight software is a very powerful flight research tool. Building in software flexibility allowed the airplane to be used as the development and evaluation tool when the simulations were not adequate.

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Flight research for the F-15 HIDEC (Highly Integrated Digital Electronic Control) program was completed at NASA Dryden Flight Research Center in the fall of 1993. The flight research conducted during the last two years of the HIDEC program included two principal experiments: (1) Performance Seeking Control (PSC); an adaptive, real-time, on-board optimization of engine, inlet, and horizontal tail position on the F-15, and (2) Propulsion Controlled Aircraft (PCA); an augmented flight control system developed for landings as well as up-and-away flight that used only engine thrust (flight controls locked) for flight control. In September 1994, the background details and results of the PSC and PCA experiments were presented in an electronic workshop. An overview paper that summarized the experiments conducted on the Dryden F-15 airplane during the last 12 years of the F-15 flight research program was also included. The PCA session also included four videos that showed a Manual Throttles-Only Approach; the First PCA-Controlled Landing; an Upset, PCA Recovery and Descent; and a PCA Final Approach. After September, the workshop, including questions and responses, was available as an archived workshop accessible through the Dryden World Wide Web (WWW) home page and as a compact disk (CD). The uniform resource locator (URL) address through the NASA Dryden home page is:

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