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

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

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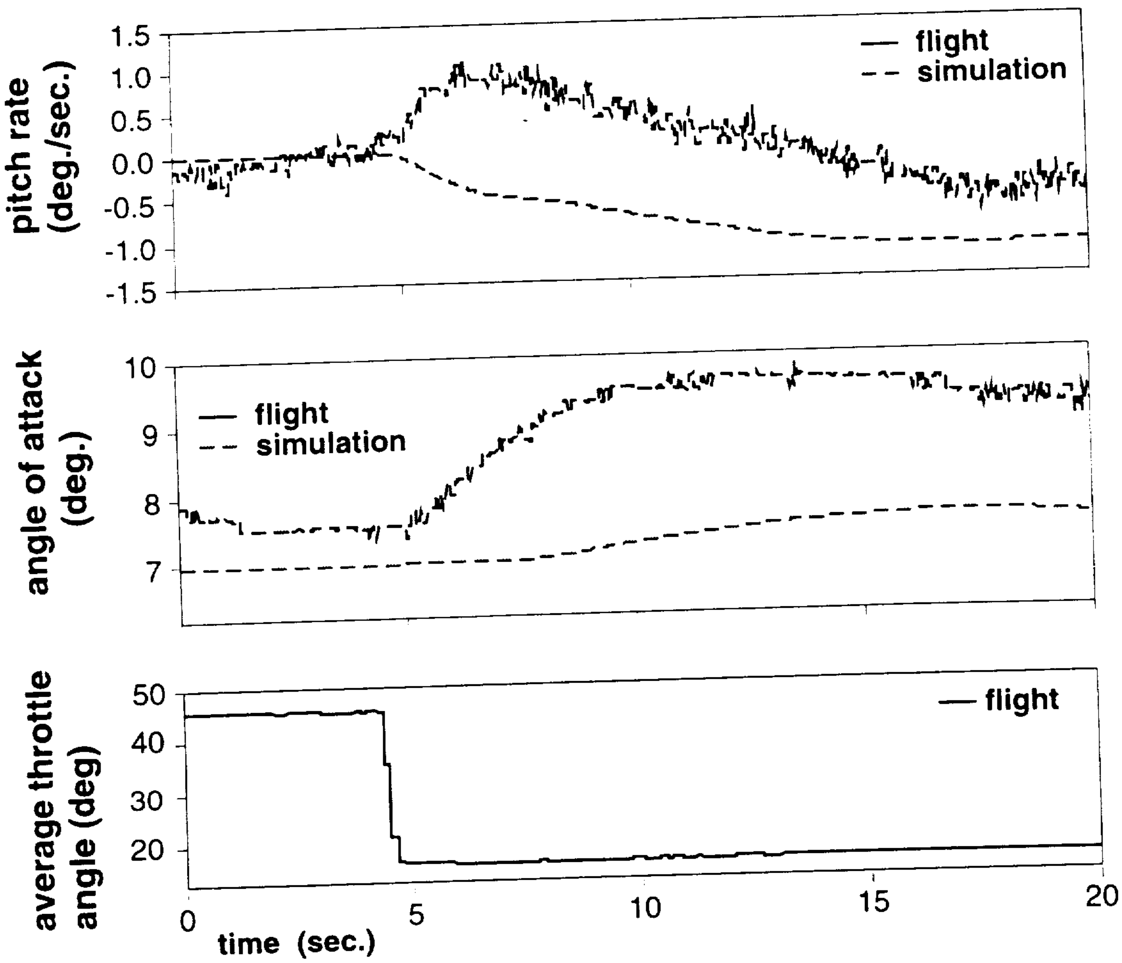
Abstract

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.*

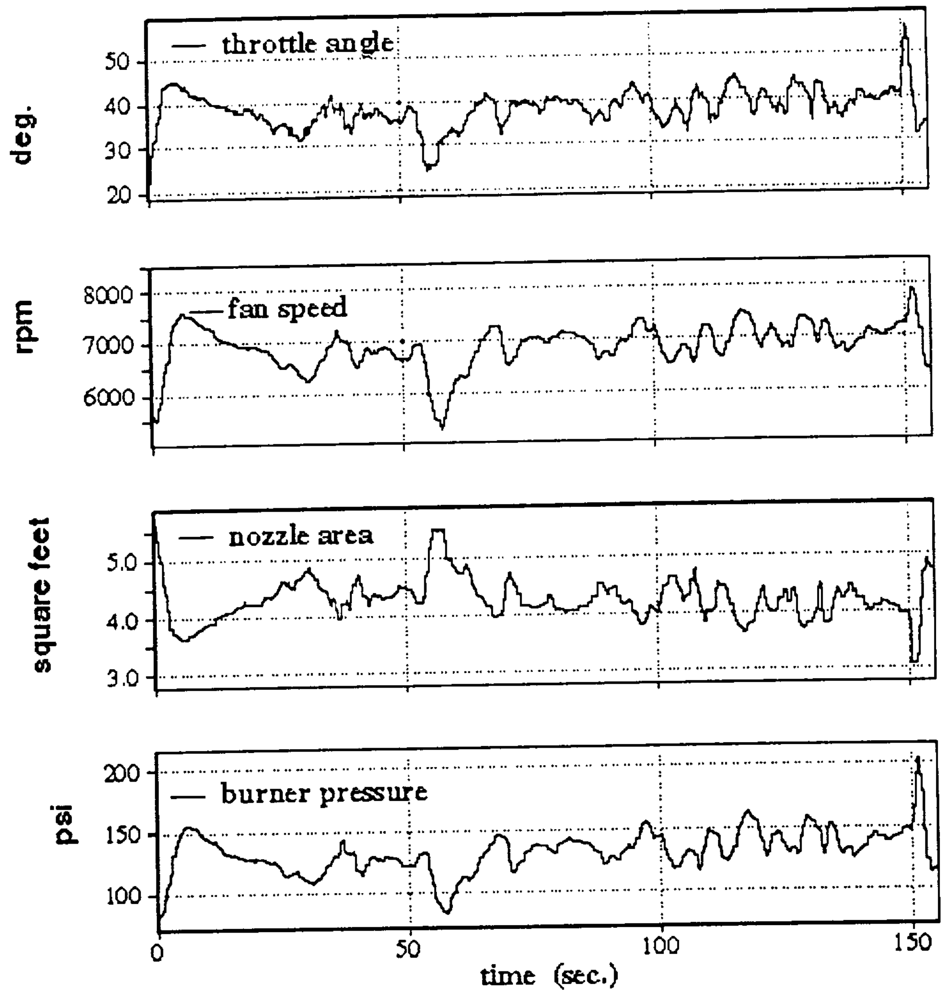
The inlet airflow effect is easily accommodated by the normal flight controls and would often be neglected in an airplane simulation . Because of the limited control power available when using the engines as the sole control effectors, normally neglected effects are likely to be significant. Moreover,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

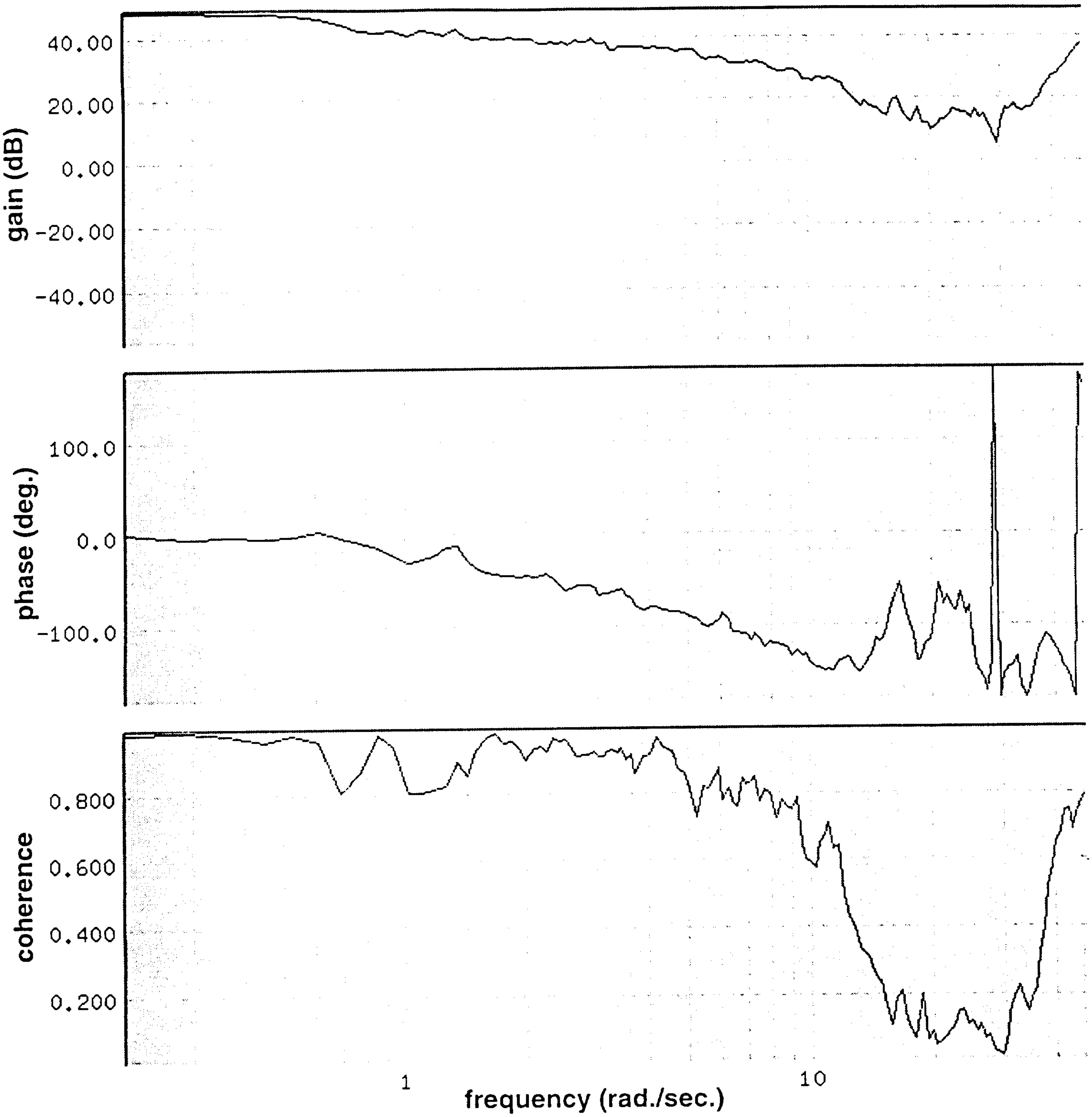
In an effort to refine the system analysis process, an effort was made to verify the match of the simplified engine model to in-flight engine performance. Ideally, flight data could be used to produce a transfer function model of throttle angle to net thrust. This was not possible because of high noise 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

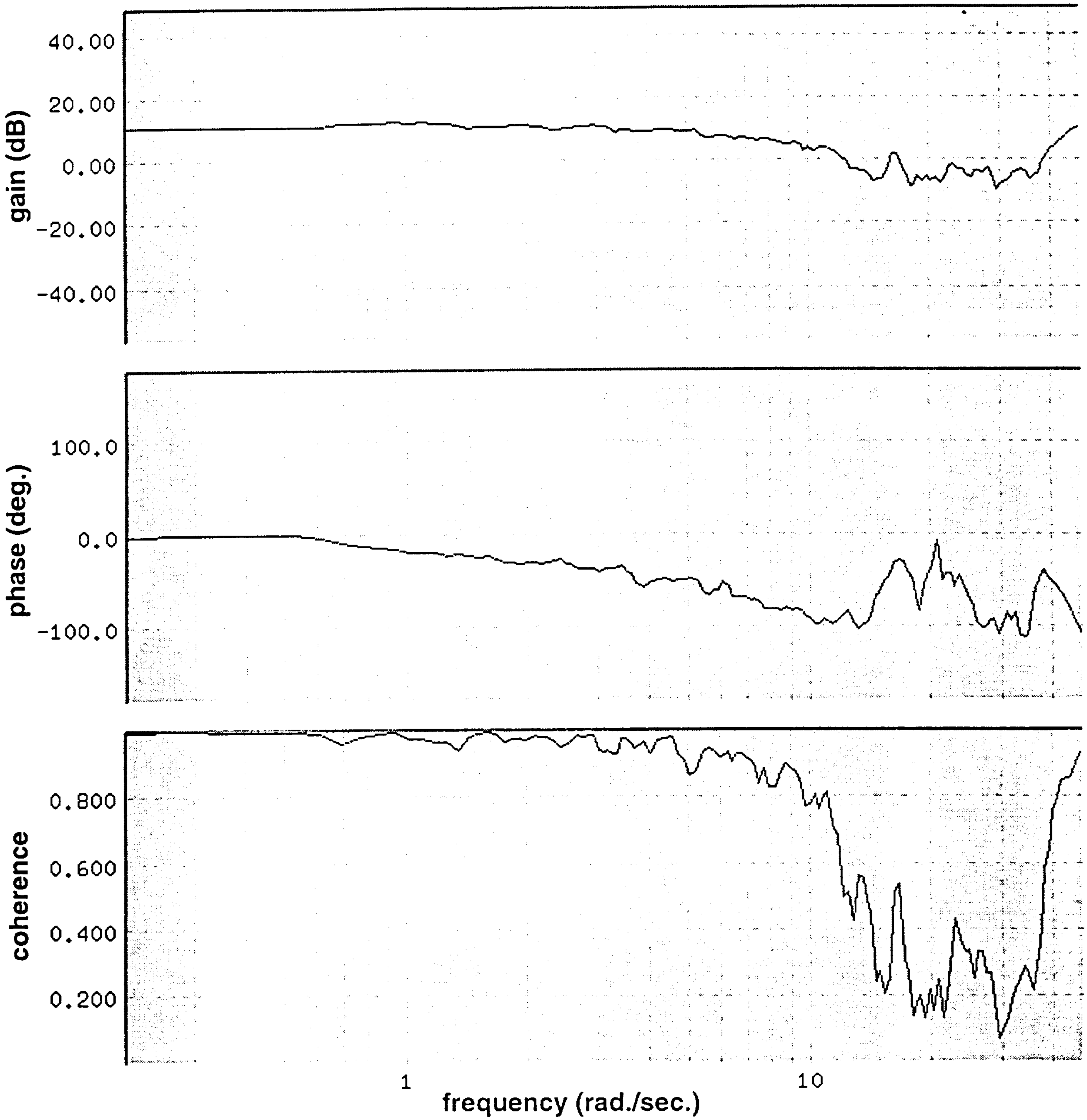
The data shown in this set of plots is from the left engine of the F-15 on a landing approach during a guest pilot evaluation flight. The engine activity is representative of typical engine workloads while the airplane is under PCA control. This particular segment of data is free of command saturation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



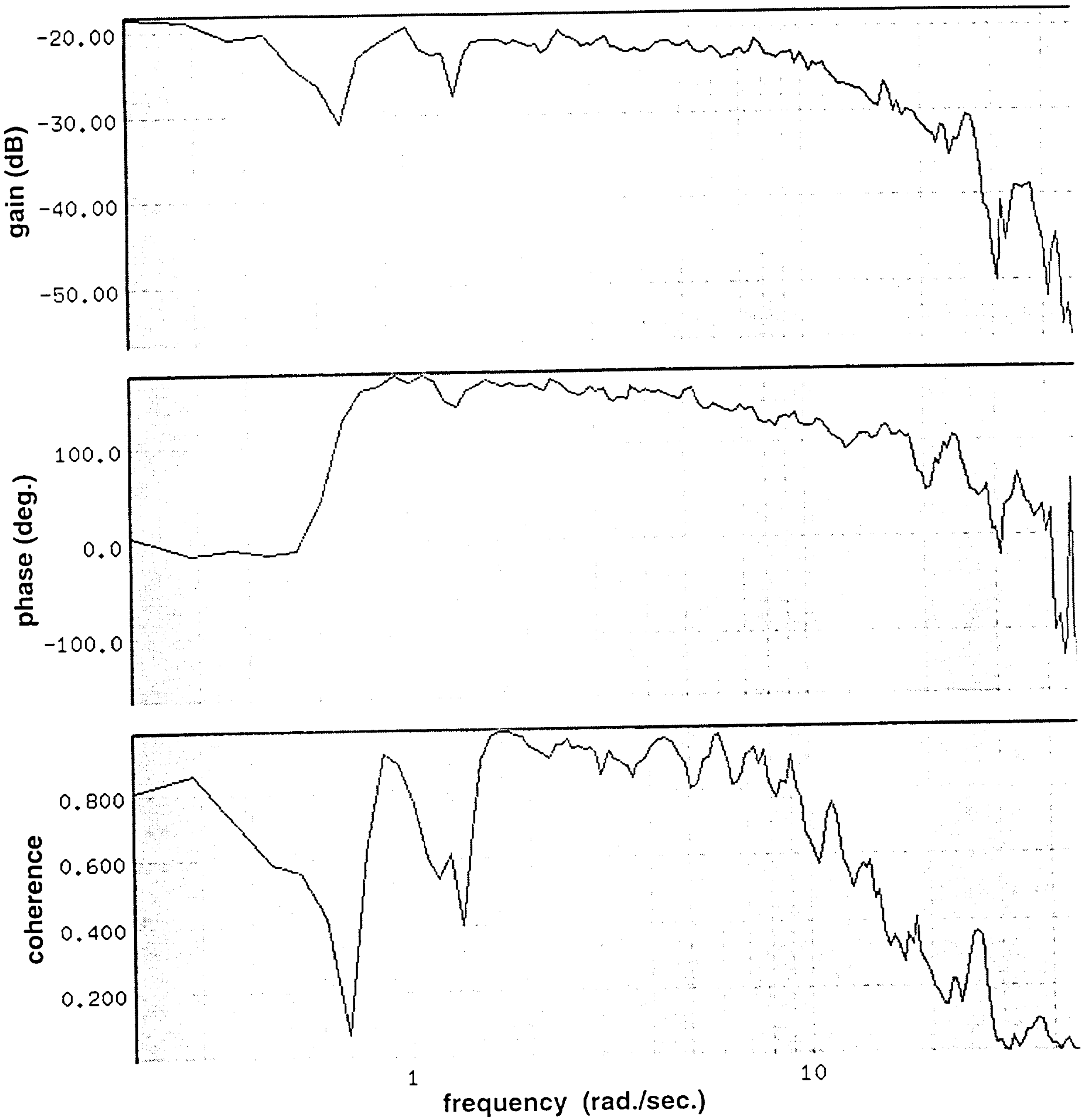
Fan Speed Frequency Response to Throttles

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.



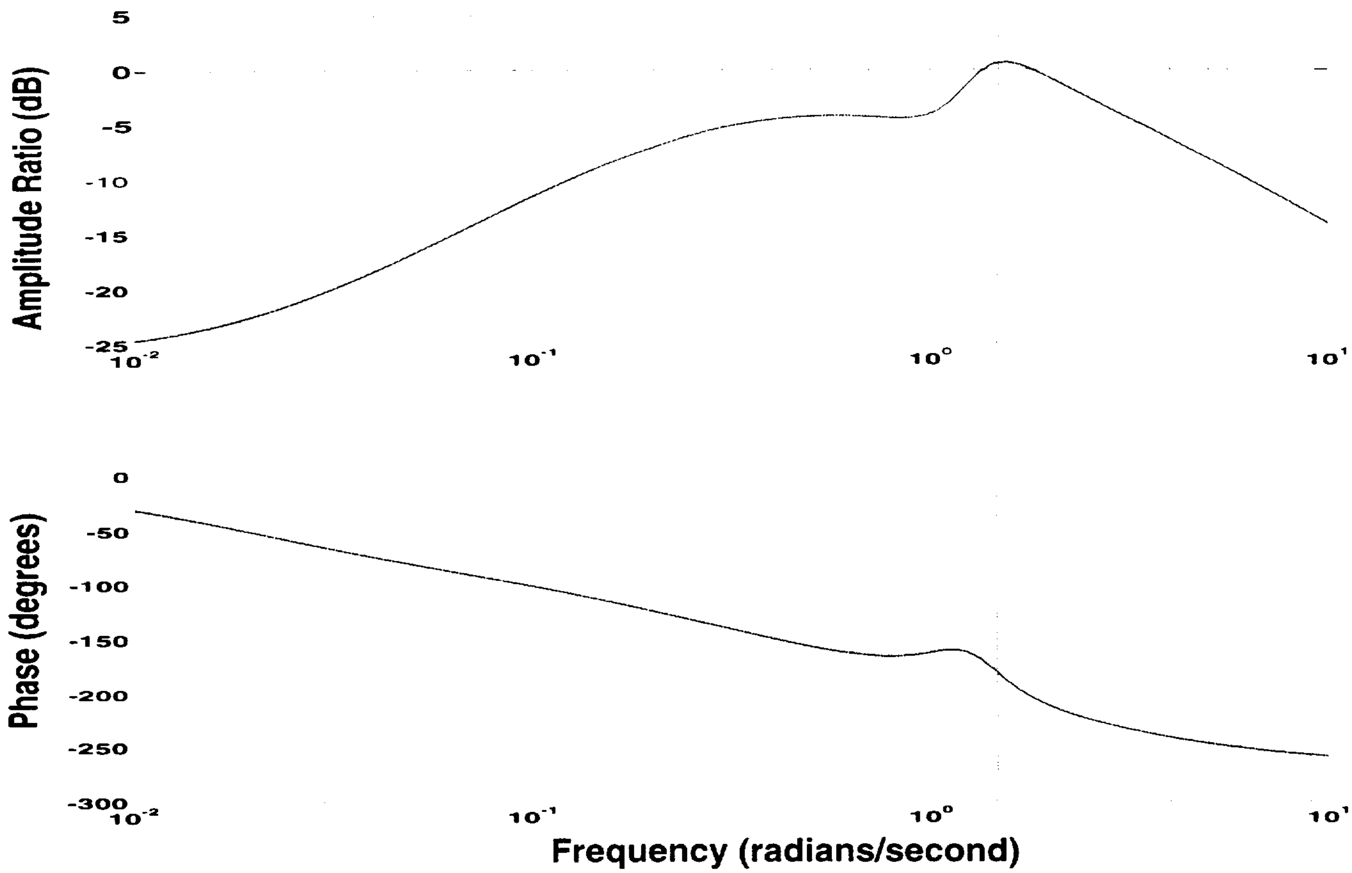
Nozzle Area Frequency Response to Throttles

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

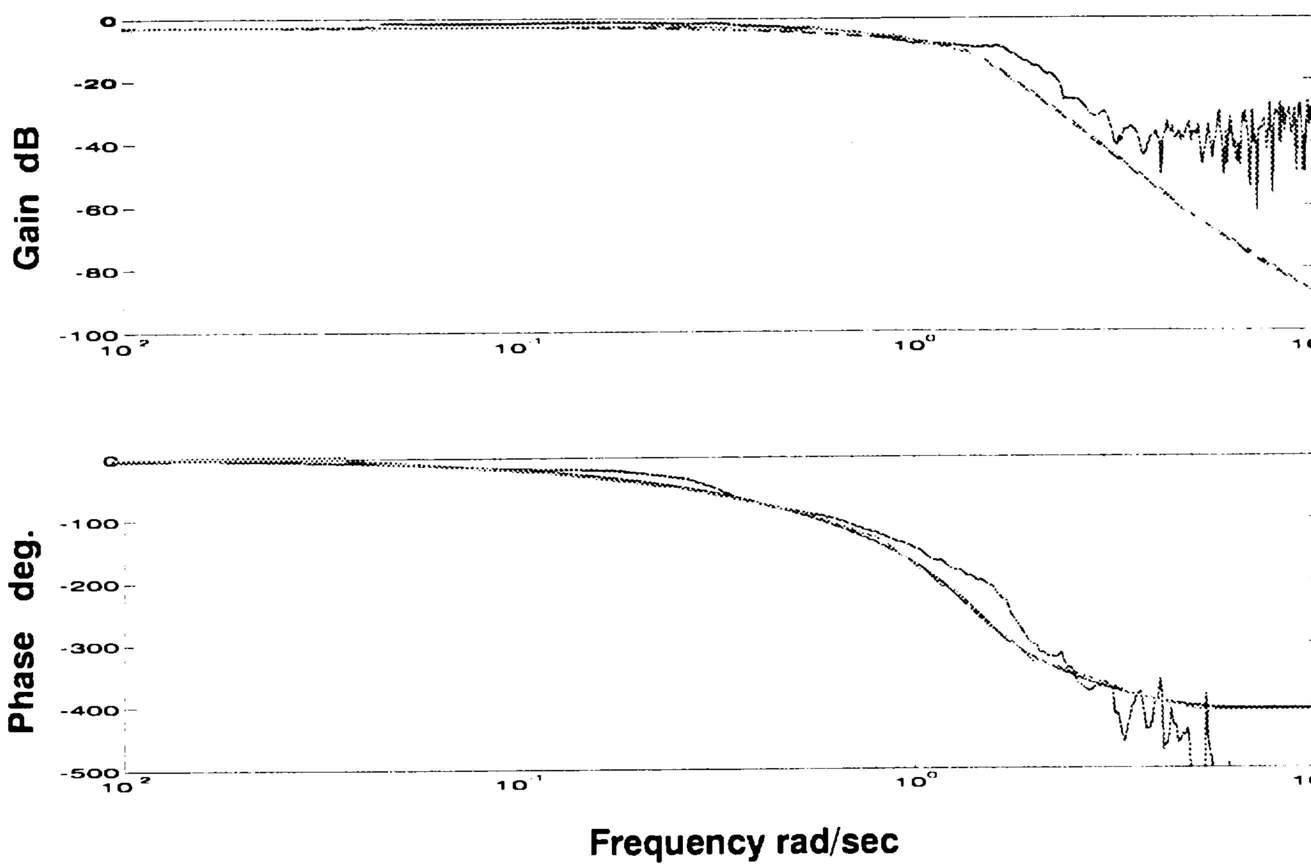
All three of these parameters support the use of a first order model of the engine response. The flight data indicate the bandwidth of the engine is higher than the linear model that was used in the design process which had a cutoff frequency of .9 rad./sec.. Using the fan speed as the most conservative 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.



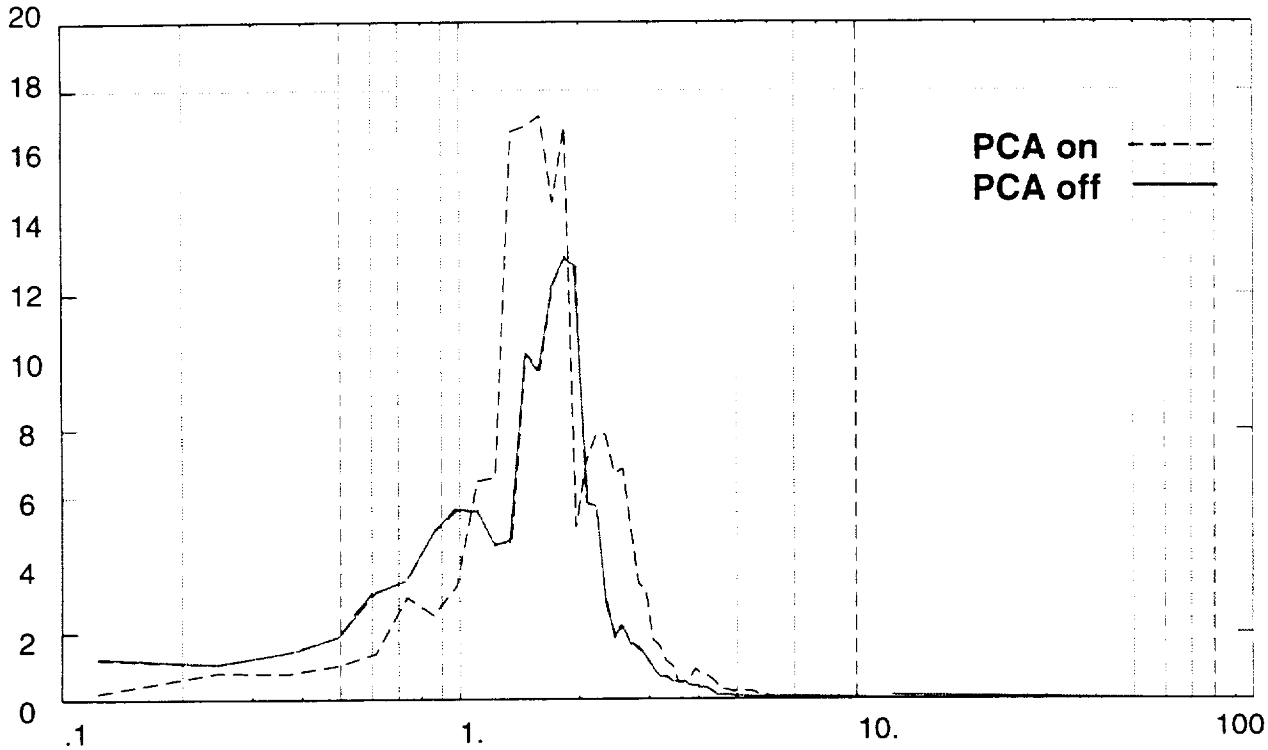
Linear Open-Loop Roll Rate Response to Roll Gust Disturbance

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

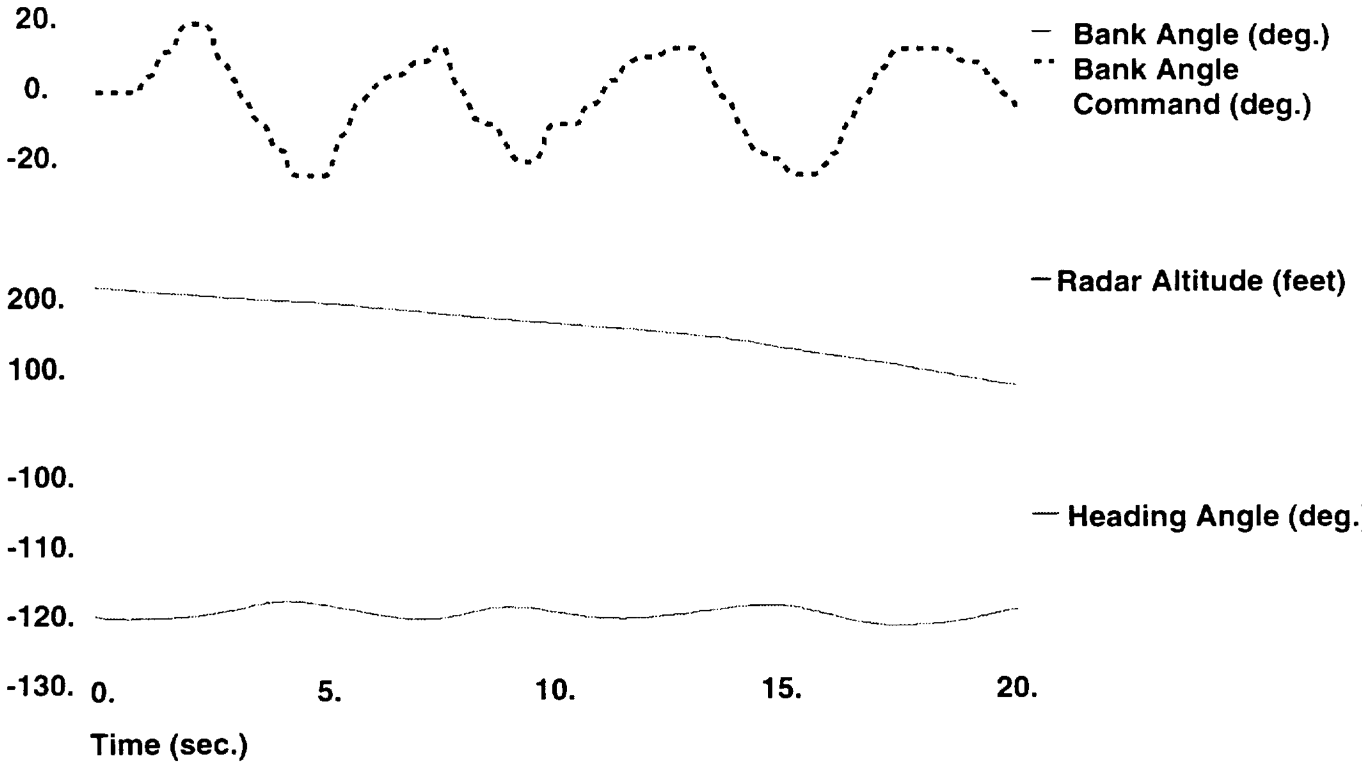
This figure shows the both the analytical (red) and a flight-derived (blue) frequency response of the closed-loop lateral response of bank angle to pilot command. The flight-derived response was determined through a pilot-conducted frequency sweep using the lateral thumbwheel. From this figure, it is 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

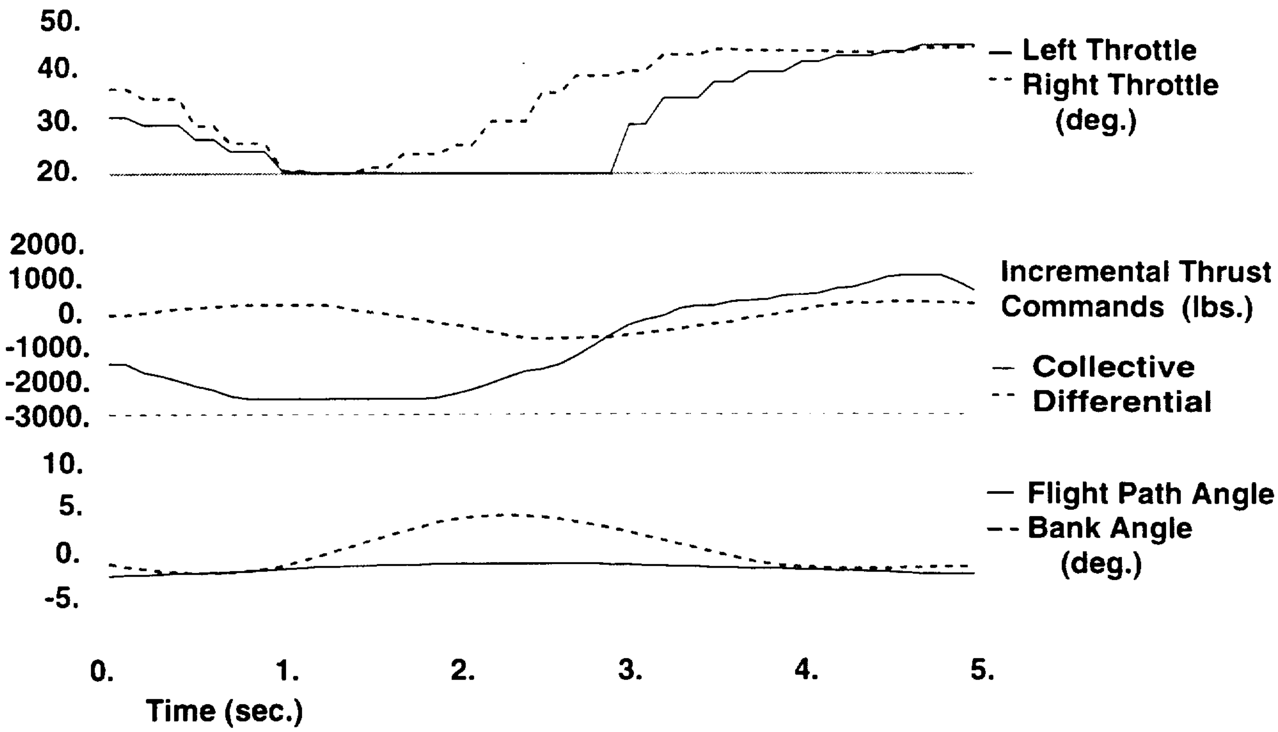
To further investigate the PCA systems difficulties with lateral gust disturbances, the F-15 airplane was flown through turbulent air with the PCA system on and then was flown again through the same air mass with all control augmentation off. Comparisons of the power spectrum of roll rate activity show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

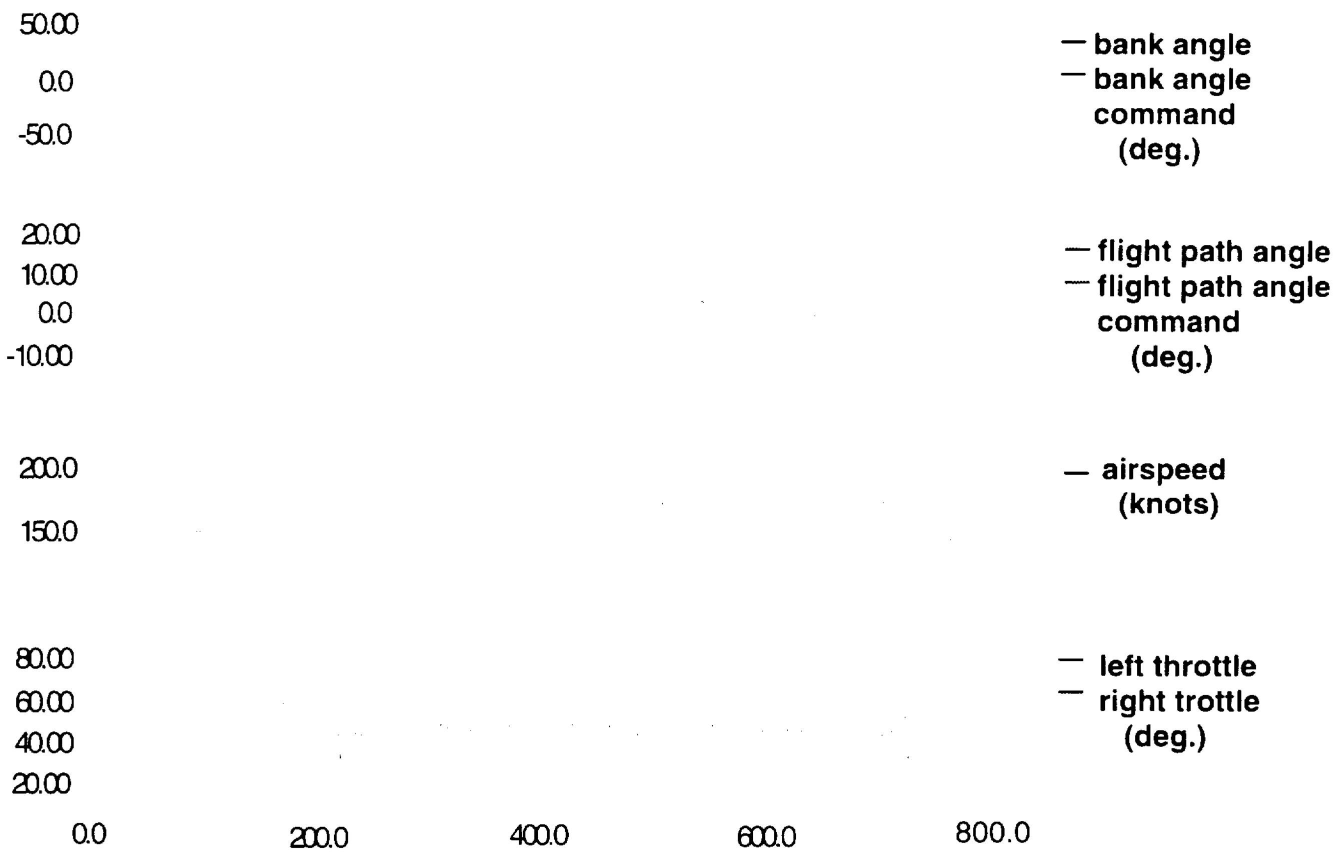
Both the disturbance amplification and the command-to-bank-angle phase lag at 1.5 radians shown in the previous 3 figures, result in a condition in which a pilot-induced oscillation can easily occur. This figure shows the pilot attempting to damp the gust-excited bank oscillation (blue) by applying a 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 airspeed 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.

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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:

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

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