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FLIGHT TESTING AND SIMULATION OF AN F-15 AIRPLANE USING THROTTLES FOR FLIGHT CONTROL

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Abstract

Flight tests and simulation studies using the throttles of an F-15 airplane for emergency flight control have been conducted at the NASA Dryden Flight Research Facility. The airplane and the simulation are capable of extended up-and-away flight, using only throttles for flightpath control. Initial simulation results showed that runway landings using manual throttles-only control were difficult, but possible with practice. Manual approaches flown in the airplane were much more difficult, indicating a significant discrepancy between flight and simulation. Analysis of flight data and development of improved simulation models that resolve the discrepancy are discussed. An augmented throttles-only control system that controls bank angle and flightpath with appropriate feedback parameters has also been developed, evaluated in simulations, and is planned for flight in the F-15.

Nomenclature

CG	center of gravity
CAS	control augmentation system
DEEC	digital electronic engine control
EMD	engine model derivative
HUD	heads-up display
PCA	propulsion controlled aircraft
PLA	power lever angle, deg
PLF	power for level flight, deg
VC	airspeed, kts
α	angle of attack, deg

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Introduction

A multi-engine aircraft with a major flight-control system failure (such as loss of hydraulic pressure) may use throttle manipulation for emergency flightpath control. Differential throttle control generates yaw, which through dihedral effect, results in roll. Collective throttle inputs may be used to control pitch. The DC-10, B-747, and L-1011 aircraft have had to use throttles for emergency flight control.[1]

To study the use of the propulsion system for emergency flight control, the NASA Dryden Flight Research Facility at Edwards, California, conducted flight, ground simulator, and analytical studies. The study had three objectives. The first objective was to determine the degree of control power available for various classes of airplanes. Results from this objective have shown a surprising amount of control capability for most multi-engine airplanes.[1] The second objective was to investigate control modes that could be developed for future airplanes. An augmented control system that uses pilot flightpath inputs and feedback control to provide throttle commands for emergency landings has been developed. This augmented system has been evaluated on a transport airplane simulation,[2] and an F-15 simulation.[3] A flight evaluation on an F-15 is planned. The third objective was to provide awareness of throttles-only control capability and suggested manual throttles-only control techniques for pilots. Reference 1 presents Dryden results of simulation and flight studies of several airplanes, including the B-720, Lear 24, F-15, B-727, C-402, and B-747.

More recently, additional flight tests have been flown to investigate the details of throttles-only control for the F-15 airplane, and to develop data to compare with the F-15 simulation. Significant discrepancies were found when the flight data were compared with

F-15 simulation data. Additional flights and a series of improvements to the simulation have been made to resolve the flight-to-simulation discrepancies.

This paper reviews the principles of throttles-only control, recent results of propulsion-only flight control for the F-15, comparisons of flight to simulation data, and simulation upgrades. Although the F100 engines are equipped with afterburners, all tests discussed in this paper were limited to nonafterburning power. Plans for implementation of an augmented system for flight on the NASA F-15 are also discussed.

Description of F-15 Airplane and Instrumentation

The F-15 airplane (Fig. 1) is a high-performance fighter airplane with a maximum Mach capability of 2.5. The F-15 (McDonnell Aircraft (McAir) Division of the McDonnell Douglas Corp., St. Louis, MO) has a high wing with 45° of leading-edge sweep and twin vertical tails. It is powered by two Pratt & Whitney (West Palm Beach, FL) F100 afterburning turbofan engines mounted close to the centerline in the aft fuselage. The thrust-to-weight ratio is very high, approaching 1 at low altitudes with maximum afterburning power. The NASA F-15 is the number 8 preproduction F-15A, has no weapons systems installed, and has additional extensive instrumentation. The zero-fuel weight is 29,450 lb. Fuel capacity is 11,600 lb.

The engines installed in the NASA F-15 are the developmental F100 engine model derivative (EMD) engines. These engines (company designation PW-1128) include a redesigned fan and other improvements. The F100 EMD engines are controlled by a digital electronic engine control (DEEC). Interim control system software was incorporated in these EMD engines. This software produces slower, nonproduction engine response characteristics at low power settings that make it more representative of higher bypass turbofan engines.

The inlets are mounted on the sides of the forward fuselage, and are external compression horizontal ramp inlets with variable geometry. A variable capture-area capability exists in which the inlet cowl rotates about a point near the lower cowl lip. At subsonic speeds, the inlet cowl angle is normally positioned by a control system as a function of angle of attack. The cowl may be moved to the full-up inlets emergency position by the pilot.

The NASA F-15 flight-control system has the standard mechanical flight-control system and a digital control augmentation system (CAS). For throttles-only control research, the CAS can be turned off and the mechanical system can be operated in an emergency mode. This eliminates any flight-control system motion except that caused by pilot inputs.

The F-15 is equipped with a heads-up display (HUD) which provides flight information such as airspeed and altitude. A velocity vector symbol is available for determining the precise flightpath relative to the ground. The F-15 airplane was instrumented to measure the

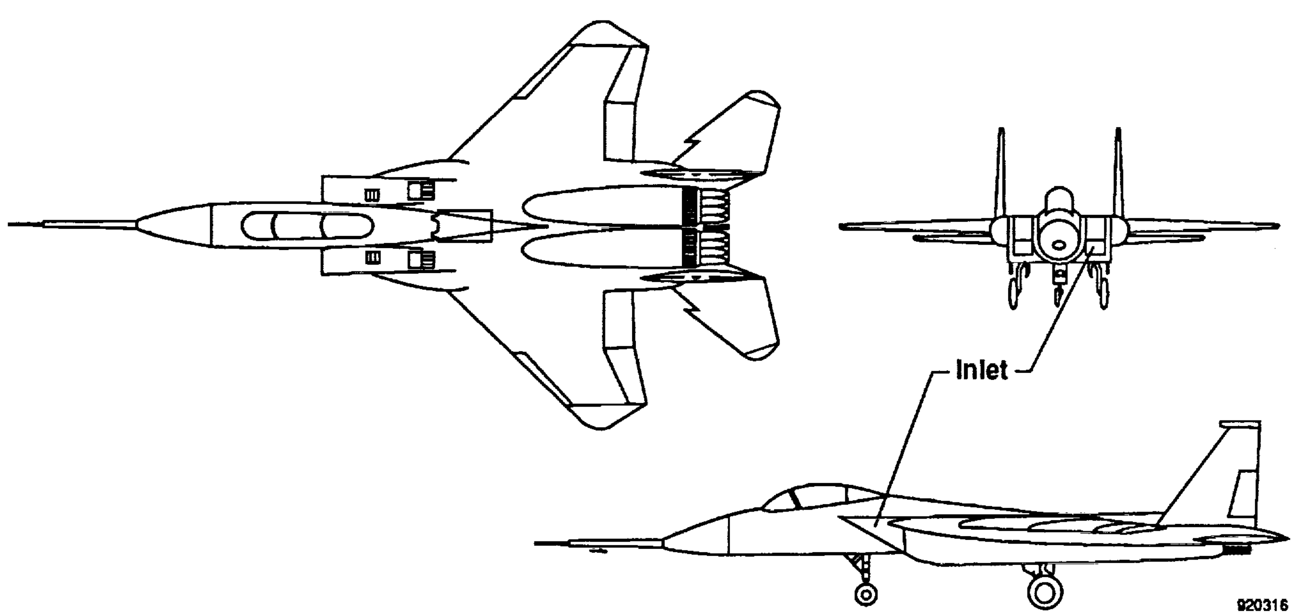


Figure 1. Three-view drawing of the F-15 airplane.

parameters required for the throttles-only flights. All typical engine and airplane parameters were measured. Data from individual sensors and from the digital control system data buses (each engine and the digital flight-control system) were recorded on an onboard pulse code modulation system and also telemetered to the ground. Data were presented in a ground control room for real-time monitoring and analysis. An HUD camera was also provided and the signal was telemetered to the ground for real-time display. Data were also recorded for post-flight analysis.

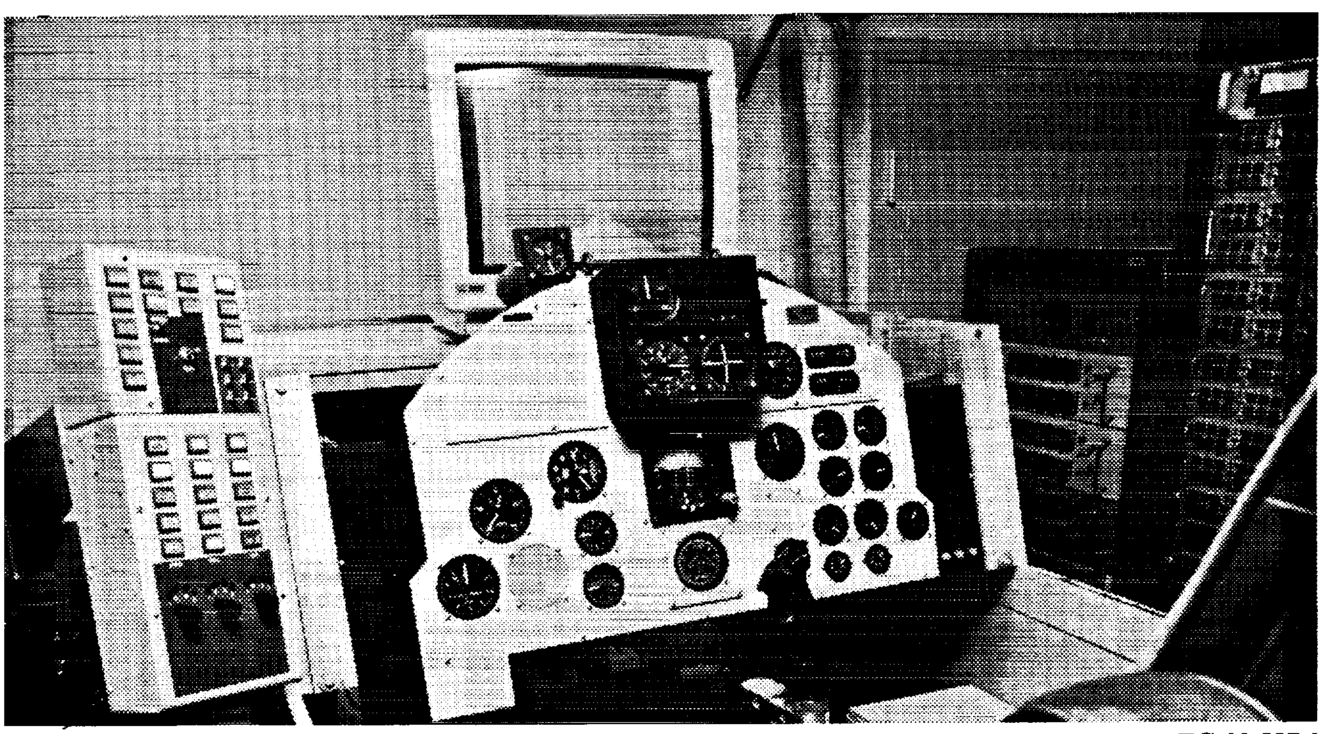
F-15 Simulation

Two F-15 simulations (Fig. 2) were used in this study, one at NASA Dryden and the other at the McAir Simulation Facility in St. Louis, MO. The NASA Dryden F-15 simulation is a fixed-base, full-envelope, six-degree-of-freedom aircraft simulation. This model contains nonlinear aerodynamics, a nonlinear flight-control system, and originally, a first-order engine response model. It is written in FORTRAN and is modular in construction. The integration interval is 25 msec. Because it is an engineering simulation, only those elements necessary to support the flight research programs are implemented.

The simulation may be run in a batch (non-real time) mode or may be flown from a simulated cockpit shown in Fig. 2(a). The cockpit simulates the key instruments in the NASA F-15 airplane. An actual F-15 stick and throttle quadrant are provided. The control panel on the left allows the operator to select special modes as required.

The visual display provides a limited out-the-window color view of the world with an optional HUD overlay. The HUD information is similar to that available in the F-15 airplane, and includes the velocity vector symbol. The lakebed, main runway, and Edwards area are modeled with adequate realism for the approach–landing task of this study. Upgrades to the Dryden simulation that have evolved over the course of this project will be discussed later in the Results and Discussion section.

Similar tests were conducted at the McAir simulation (Fig. 2(b)). This fixed-base simulation features an actual F-15 cockpit and high-fidelity visual equipment which projects scenery onto a 40-ft dome. The aerodynamic, control system, and propulsion system models were similar to those at Dryden.



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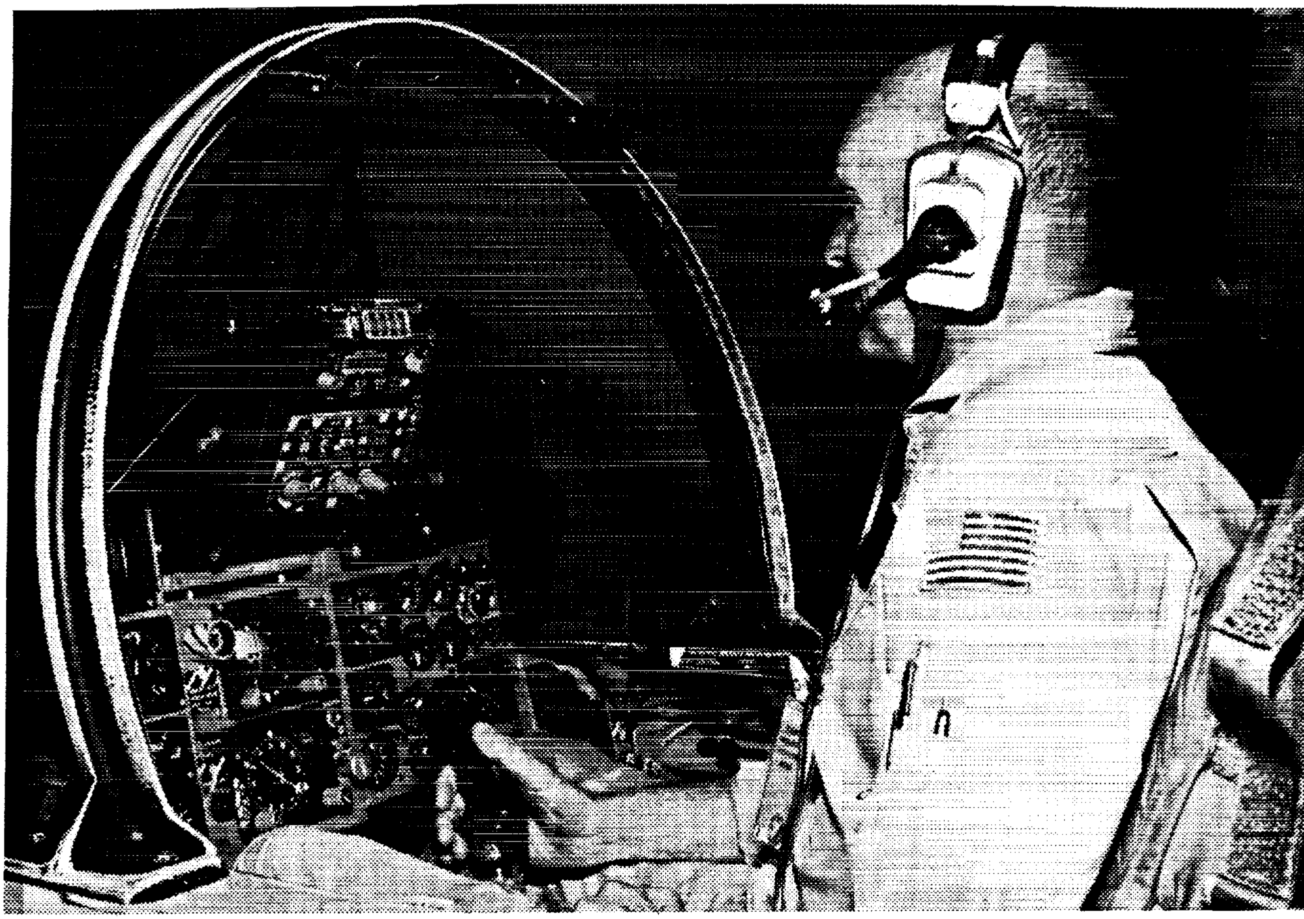
(a) Dryden F-15 simulation cockpit.

Figure 2. F-15 simulation cockpits.



(b) McAir F-15 simulation cockpit.

Figure 2. Concluded.

Principles of Throttles-Only Control

The principles of throttles-only flight control[1] will be reviewed here, using examples for the F-15 airplane.

Roll: Differential thrust generates sideslip, which, through dihedral effect, results in roll. Roll is controlled to establish a bank angle, which results in a turn and change in aircraft heading. Figure 3 shows a typical roll response to differential throttle. Once the differential throttle is applied, the differential thrust begins to increase, inducing sideslip and roll. As sideslip increases, the airplane directional stability generates a moment equal to the moment from differential thrust, and equilibrium is reached (in this case for the F-15) with approximately 12 deg/sec of roll rate.

Pitch: Pitch control due to throttle changes is more complex. There are several effects that may be present, depending on the aircraft characteristics. These effects are shown in concept in Fig. 4(a).

1. Flightpath angle change due to speed stability. Most airplanes exhibit positive speed stability. Over a short period of time (approx 15 sec), added thrust causes a speed increase, which increases lift, causing a pitch rate increase, and a climb (if allowed to continue for a longer period of time, this effect will be oscillatory, see Phugoid, page 5. The degree of change to the flightpath angle is proportional to the difference between the initial trim airspeed and the current airspeed, hence, the change in flightpath 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 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 flightpath angle change. The effect is more a function

of change in thrust than change in speed, and occurs near the time of the thrust increase, as seen in Fig. 4(a). High mounted engines result in a pitch down, which counters the effects of speed stability. Pitching moment due to thrust will cause a change in angle of attack, and hence, lift. For the F-15, the thrust line passes within ± 1 in. 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 flightpath, as is commonly the case, an increase in thrust will cause a direct increase in vertical velocity, i.e., rate of climb, and a resulting increase in flightpath angle. For a given aircraft configuration, this effect will increase as angle of attack increases (i.e., as speed decreases).

Figure 4(b) is an actual time history of pitch rate for the F-15 for a throttle increase to intermediate power. It shows the overall result of the effects previously mentioned, with a maximum pitch rate of 2 deg/sec.

4. 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 degree of oscillation in speed and altitude is related to the speed stability. The phugoid oscillation is excited by a pitch, or velocity change, and will have a period of approximately 1 min., and may or may not damp naturally. Figure 5 is an example of the phugoid response from the F-15 simulation in its initial configuration as excited by a 10°-step increase in PLA. The flightpath angle increase results in a steepening climb and speed peaks, and begins to decrease after about 15 sec, oscillating about the initial trim speed. In the oscillatory phugoid motion, pitch rate is in phase with velocity, while flightpath angle (and rate of climb) lags by 90°, and altitude lags by 180°. Although a very small amplitude phugoid is nearly a constant angle-of-attack motion, for the size phugoid oscillations typically seen in throttles-only control, pitch rates are significant, as shown. This results in a variation in angle of attack, in this case varying over a 2- to 3°-range. Properly sized and timed throttle inputs can be used to damp unwanted phugoid oscillations.[1]

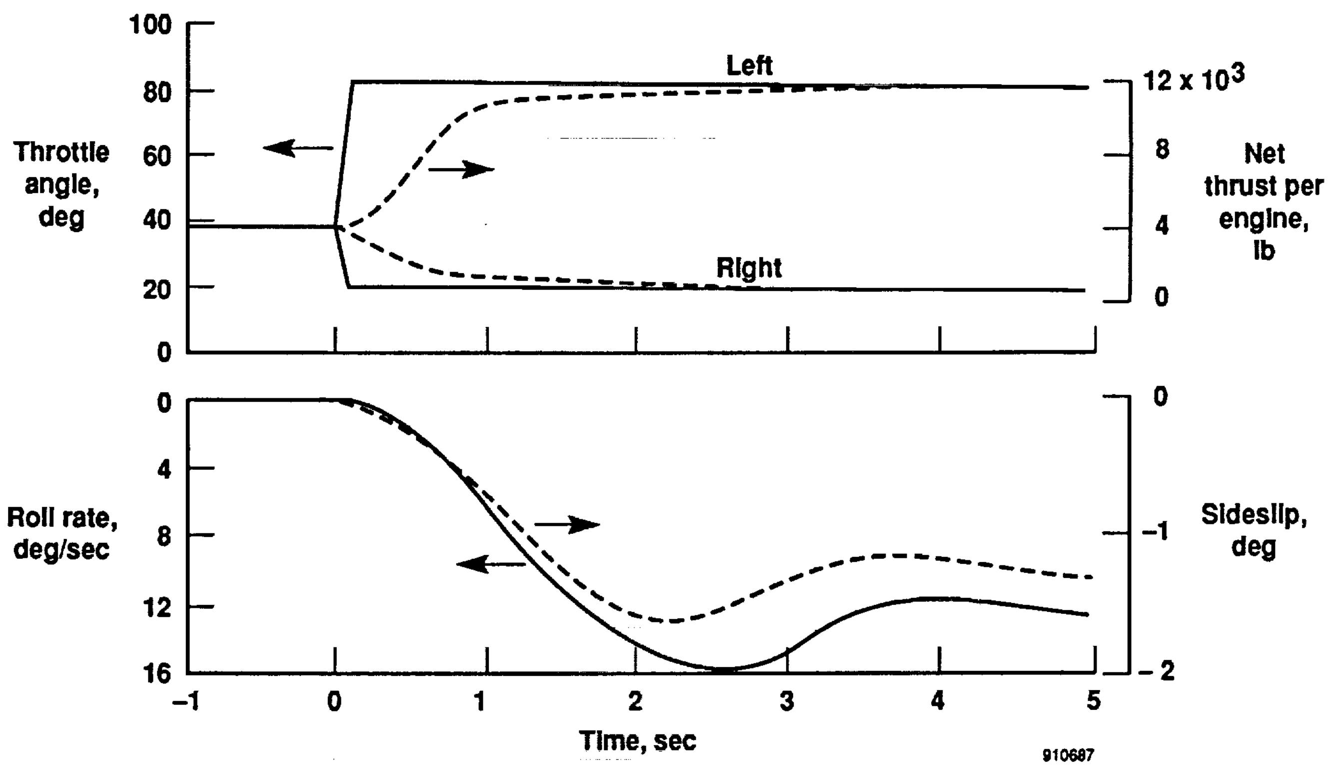
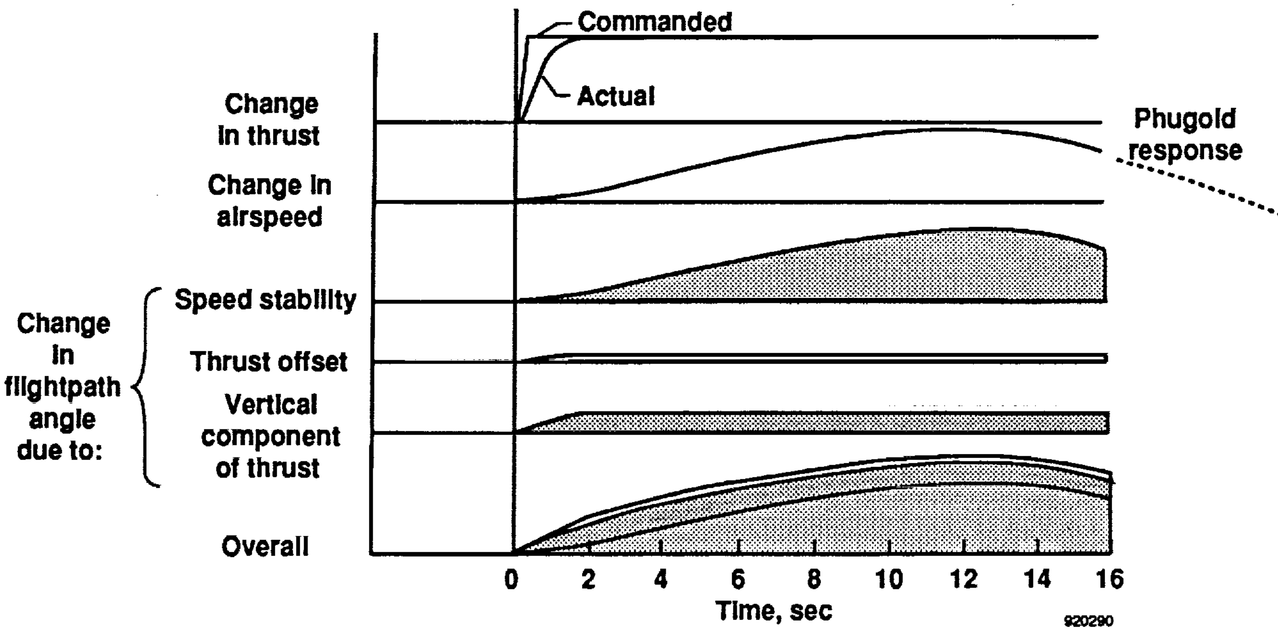
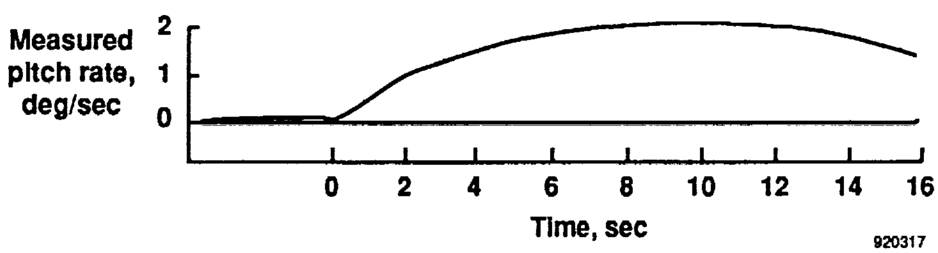


Figure 3. Roll control resulting from differential thrust.



(a) Schematic pitch effects of thrust increase.



(b) Flight data, NASA F-15, VC = 170 kts.

Figure 4. Pitch effects of a step increase in thrust on both engines.

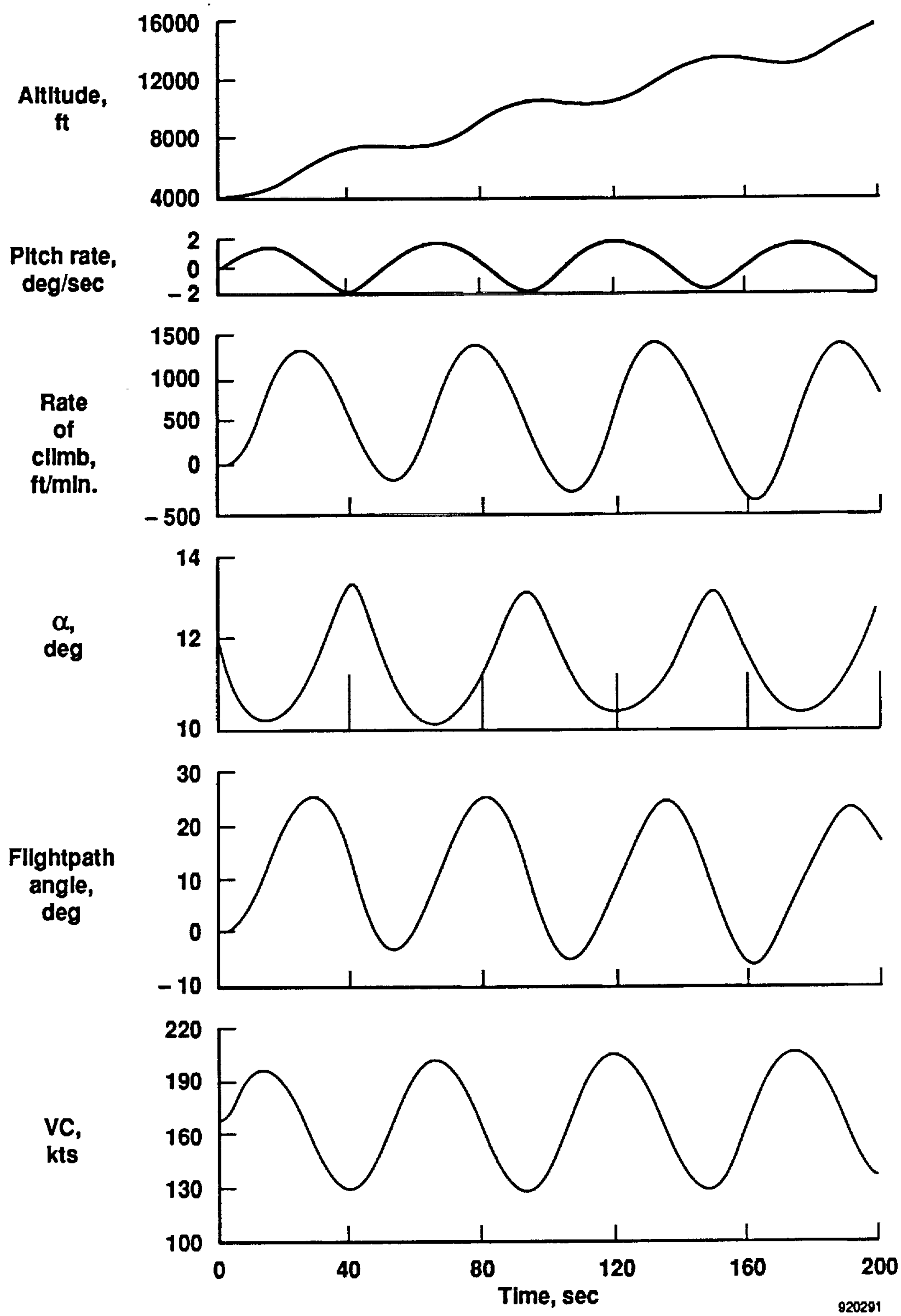


Figure 5. Phugoid oscillation from the F-15 simulation, VC = 170 kts, 10°-increase in PLA at 0 sec.

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, CG control, lowering of flaps, landing gear, etc. 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 the flaps, and extending the landing gear. For the F-15, moving the inlets to the full-up emergency position reduces the trim speed by 20 kts.

Thrust Response

Thrust response of turbofan engines may be slow relative to piston or turbojet engines. The F100 EMD engine controllers in the NASA F-15 have interim software, and respond quickly at higher thrust levels, but at low thrust levels, respond more slowly. Idle to intermediate power throttle snaps take approximately 2.5 sec. Reductions to idle power exhibit a rapid response until low thrust is reached, but a very slow spooldown taking up to 10 sec occurs before idle thrust is reached.

Effects of Speed on Propulsive Control Power

For turbine-powered airplanes, engine thrust is not a strong function of airspeed, however, the stabilizing effects of vertical and horizontal stabilizers are a function of dynamic pressure, and are inversely proportional to the square of airspeed. The result of these characteristics is that the relative propulsion system control power increases as airspeed decreases.

Test Techniques

Test techniques were developed to assess the throttles-only control capability of the F-15 airplane and simulation. To avoid flight-control system inputs, the CAS was turned off, and the emergency mode was selected for the mechanical system. In this mode, the flight-control surfaces would not move as long as the pilot did not move the stick or rudder pedals. One test used was the full-throttle (maximum nonafterburning) range test. Although full throttles are rarely used during throttles-only flight, this test provides an assessment of the maximum capability, and an easily repeatable metric with which to make comparisons between flight and simulation.

From power for level flight (PLF) conditions, both throttles were advanced to intermediate power (maximum nonafterburning) to determine the maximum pitch rate capability. The same test was then repeated by going from PLF to idle power to determine the maximum negative pitch rate. Tests were repeated over a range of speeds, and in some cases, for a suitable range of fuel quantities (with resulting CG positions).

Another test was the full-differential throttle test, used to determine the maximum roll rate. The airplane was gently rolled to 30°-bank, then full-differential throttle was applied, and the airplane rolled back through level and to at least 30° in the other direction. This test was also conducted over a range of speeds.

The small throttle movement test was also performed on the F-15 airplane. In this test, beginning at PLF, the throttles were advanced–retarded by 1 in., and the resulting pitch rates were measured. For roll rate tests, the throttles were split by 1 in. These results are more like the types of throttle movements that are commonly used in engines-only flight control.

Typical pilot-in-the-loop maneuvers were also used to evaluate throttles-only control capability of the F-15. With the flight-control surfaces fixed, the pilot was asked to fly tests which included (1) achieve and maintain level flight, (2) turn to and hold a given heading, (3) initiate and attempt to maintain a constant rate of descent, (4) use various techniques to damp a phugoid oscillation, and (5) make approaches to a runway. In the simulator, the pilot was also asked to make landings on a runway and make go-arounds from a low-approach situation.

Results and Discussion

This section discusses the development of the simulation and flights of the NASA F-15 airplane for throttles-only control in chronological order. All data presented are with the landing gear down. Also included are the plans to implement the augmented throttles-only control system on the NASA F-15 airplane.

The initial throttles-only control tests were conducted on the NASA Dryden F-15 simulation. It was found that the F-15 had pitch capability at speeds below 300 kts, and roll capability at all speeds. The airplane was quite stable in the initial simulation configuration. Flightpath control with throttles worked well; if the HUD velocity vector was below the desired flightpath, the pilot simply added thrust until it reached the desired position. If the flightpath was higher than desired, the pilot reduced the thrust until the desired flightpath was reached. With some practice, the F-15 simulation could be landed repeatedly on a runway.[3] Some initial throttle step tests were also conducted. At this point, initial flight tests were flown on the NASA F-15 airplane. Open-loop tests, including full-throttle steps, were flown and control capability appeared like the simulation.

Full-Throttle Steps

Typical results from the full-throttle step tests on the F-15 airplane and simulation are shown in Figs. 6 and 7. The flight and simulation maximum–minimum pitch rates are shown in Fig. 6, and exhibit a response inversely proportional to the square of the speed. For the F-15 and most other turbine-powered airplanes, PLF in the approach to landing phase is rather low, typically 25 to 35 percent of thrust. This means that more PLA increase is available than decrease, and that more nose-up than nose-down control is available. The flight data for thrust decreases are less than predicted by the simulation and will be discussed later.

Full-differential thrust test results are shown in Fig. 7. Again, the inverse square relationship to speed is evident. The flight data show somewhat less roll rate than the simulation results.

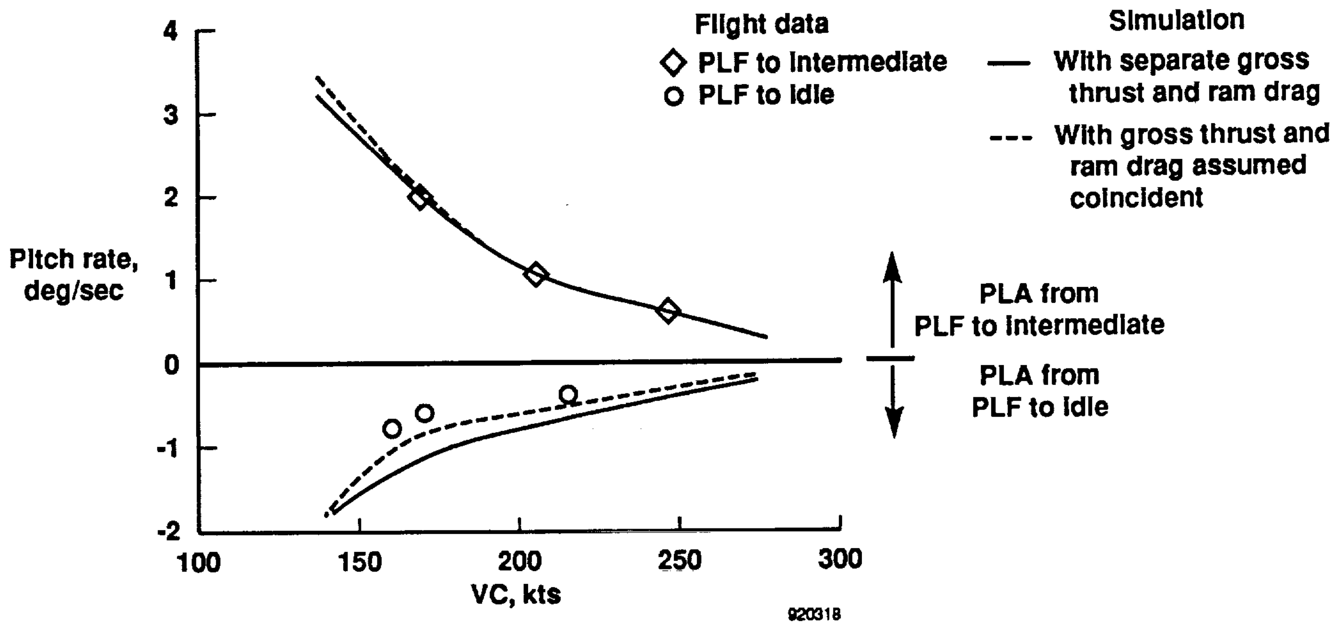


Figure 6. Effect of calibrated airspeed on pitch rate for the F-15 flight and simulation.

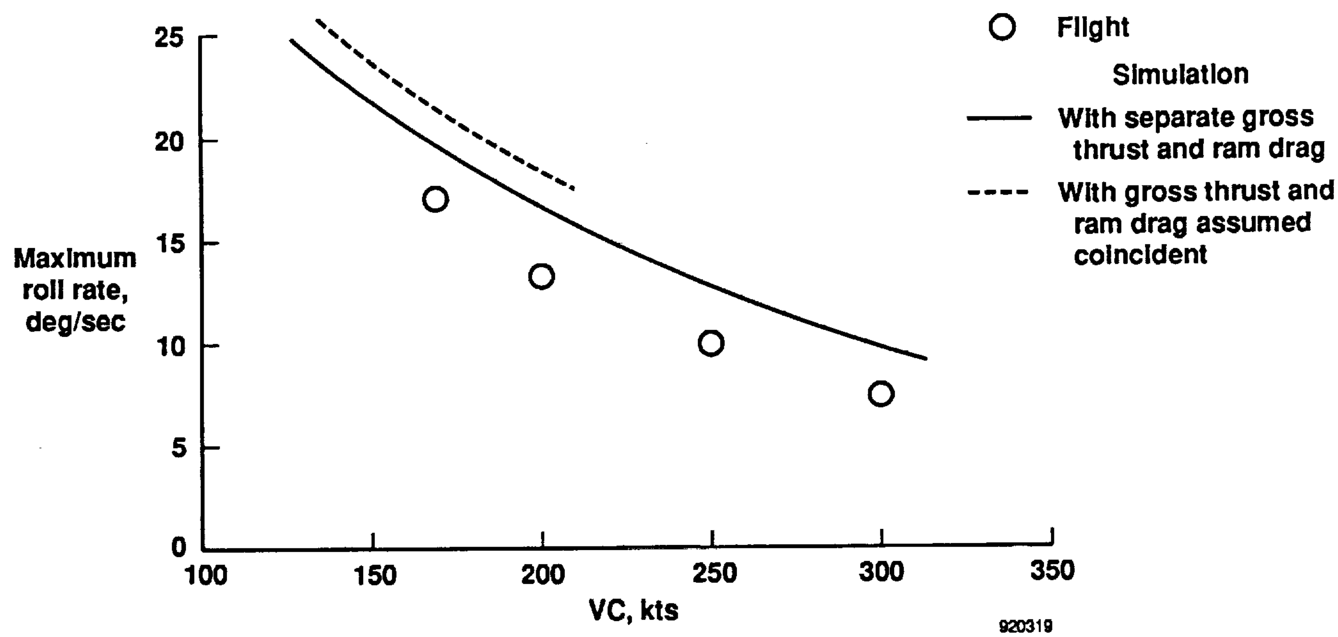


Figure 7. Effect of calibrated airspeed on maximum roll rate for F-15 flight and simulation, full differential thrust.

The engine gross thrust and ram drag terms needed to be separated since the inlet and nozzle axes were significantly displaced. This was done on the Dryden simulation, and resulted in approximately 10-percent less roll due to differential thrust, slightly less pitch up due to increased thrust, and significantly more pitch down due to decreased thrust. The same change was also made to the McAir simulation. The effect of the changes to separate the gross thrust and ram drag effects on pitch rate and roll rate is shown in Figs. 6 and 7.

Pilot-in-the-Loop Tests

In the next flight phase, the manual throttles-only flight tests (with the pilot actively controlling flightpath in a closed-loop fashion) were flown. These tests showed that the F-15 airplane was much more difficult to fly than the simulation. Figure 8 shows a comparison of approaches to a runway for the F-15 airplane and simulation. The simulation is relatively stable, and only small PLA changes were required. The actual F-15 airplane was never stabilized, large throttle

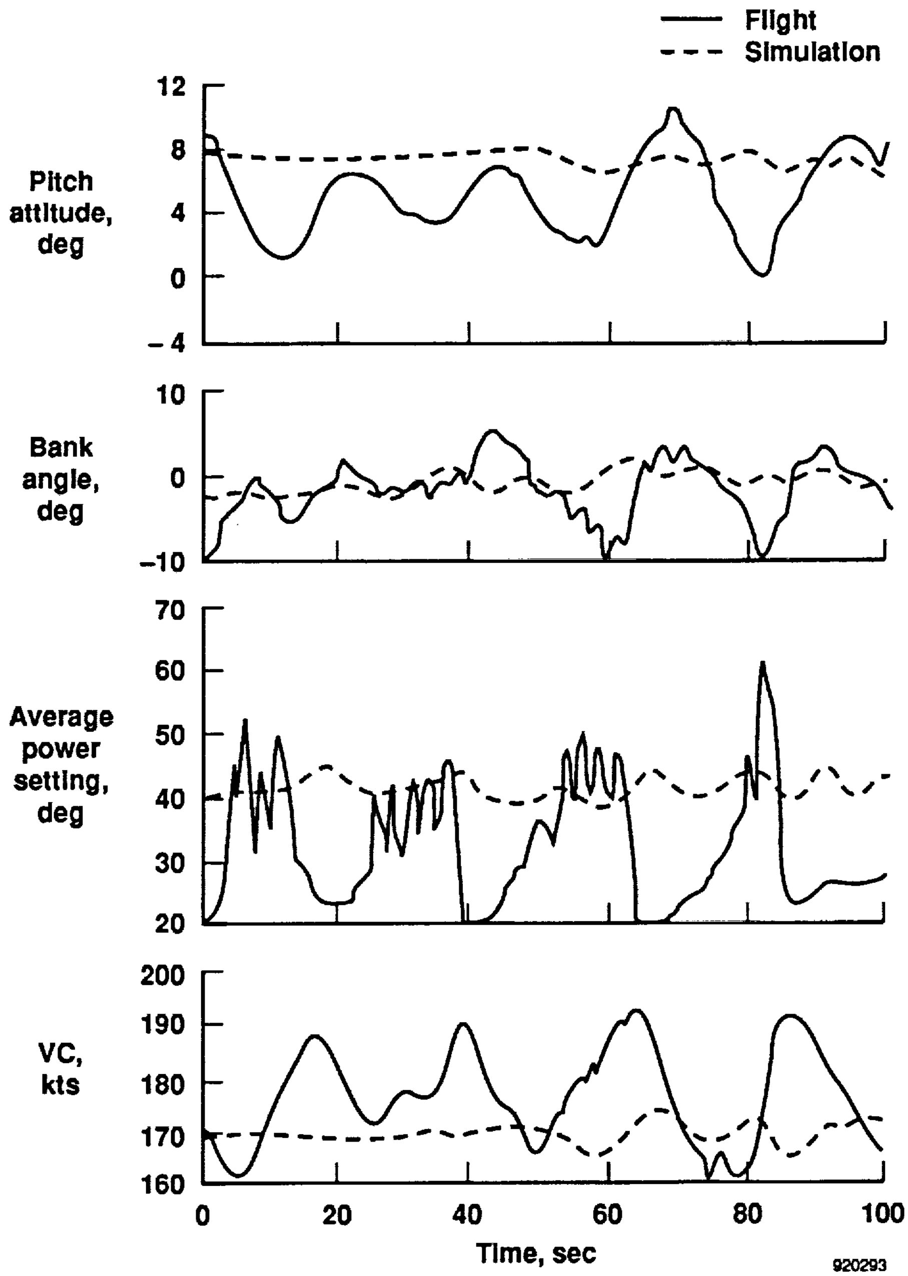


Figure 8. Comparison of flight and simulation results for a landing approach, landing gear down, VC = 170 kts.

excursions were evident, and the flightpath control was much poorer. The pilot reported strong coupling between the pitch and roll axes, large thrust lags, and mismatches between engines. Even maintaining level flight was difficult; it was not possible to attain a hands-off trim condition for more than a few seconds, even in perfectly smooth air. The flightpath control technique in which thrust was modulated relative to the velocity vector position resulted in a large amplitude oscillation.

The McAir F-15 simulation was flown by the same pilot who had flown the NASA F-15 airplane. The McAir simulation flew much like the Dryden simulation, and also did not predict the great difficulty found in the flights.

Since the F-15 simulation model was being used to design and evaluate the augmented mode, it was critical to resolve the major differences between the flight and simulation pilot-in-the-loop results. First, the engine model in both simulations was improved to incorporate the nonlinear response characteristics of the F100 EMD engines present at low throttle settings. This made the F-15 simulation more difficult to fly, but with practice, it was still possible to make repeatable runway landings in the Dryden and McAir simulations. There was an additional destabilizing effect in the airplane not being modeled in the simulation that made the airplane much more difficult to control.

Additional effects were modeled, including engine gyroscopic moments, which were found to be insignificant. Vertical CG effects were also investigated. Extreme values (thrust line 6 in. above the vertical CG) could destabilize the simulation to the degree seen in flight, but the actual range of vertical CG travel is only ± 1 in.

Fuel slosh was investigated. It was thought that increasing power would move the fuel aft, adding more nose-up pitching moment, and adding to the pitch response. In the roll axis, differential thrust could move fuel in the wing tanks in a direction to reduce the rolling moment.

An additional flight was flown and small (approximately 1-in.) throttle steps were tested. In addition, tests were flown at high, medium, and low fuel levels to investigate the effects of fuel quantity. The amount of fuel affects fuel slosh and horizontal and vertical CG, but only small effects of fuel quantity were seen.

A batch version (non-real time) of the Dryden F-15 simulation was modified to permit throttle positions measured inflight to drive the simulation. This way, some of the small throttle step maneuvers were used to compare the simulated response to that of the actual aircraft. The following describes the method used to make the comparisons. The simulator was set to attain a straight and level trim that matched the flight Mach, altitude, and fuel weight with the CAS off and flight control in emergency, the inlets in the emergency position, the gear down, and the speed brake in the proper position. The pilot had been asked to re-trim the aircraft before each maneuver, and for this study an effort was made to select time segments that started with the aircraft more or less in trim.

To avoid step jumps caused by any mismatch between the simulation trim and the flight trim, the initial values of the left and right PLA from flight were subtracted from the respective time histories to create incremental PLA time histories. These incremental PLA time histories were then added to the simulation trim values to drive the simulation. The flight time histories were plotted with the time histories generated by the simulation for a variety of variables characterizing the response of the aircraft. There were several problems with this analysis. Since this is an open-loop comparison between the flight data and the simulation, even small differences between the model and flight tend to accumulate and become large with time. Thus, these comparisons are only potentially useful for short-term responses. Second, there is no record of the random external forces acting on the aircraft available to drive the simulation. The pilot reported still air during these maneuvers so it can be assumed that the effects of unmodeled atmospheric disturbances are at a minimum. Third, reflecting the overall difficulty of flying the aircraft engines-only, the pilot had considerable difficulty establishing a trim condition prior to the step inputs.

There were three cases where both throttles were increased about 1 in. In all three cases the simulation properly predicted the direction of the response, but somewhat underpredicted the pitch rate. The throttle step also excited roll rate oscillations in all three cases. A typical case is shown in Fig. 9. Fan RPM is shown responding to the throttle increase, along with the corresponding pitch rate, roll rate, and angle of attack. These small roll oscillations resulting from engine mismatches were adequately modeled in the simulation, the primary difference was that the oscillations in the simulation damped out more quickly than those in the airplane. These differences are in accord with pilot comments on the differences observed between the flight and simulation. Note that only a very small decrease in angle of attack occurred, whereas the simulation showed a larger decrease.

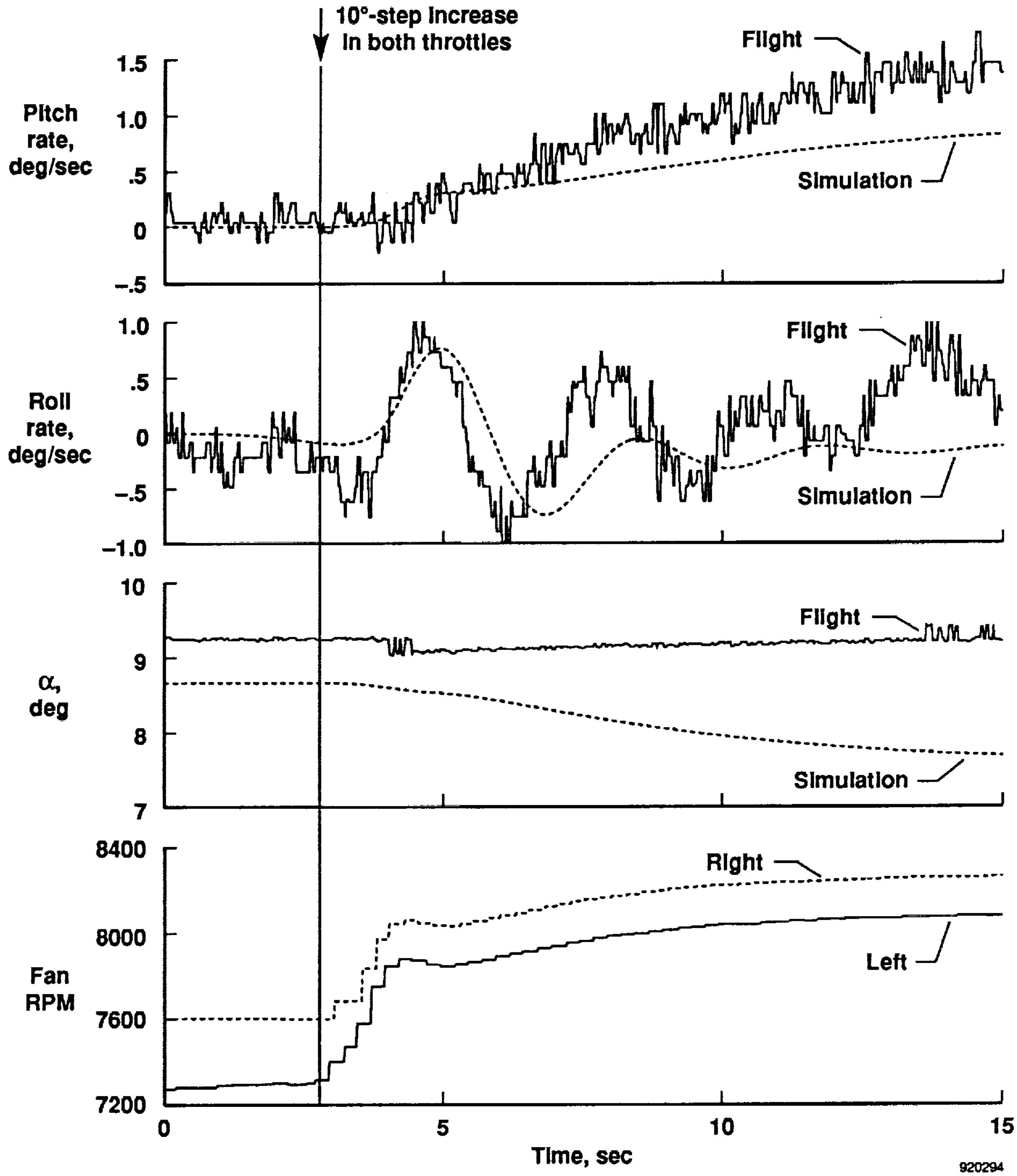


Figure 9. Comparison of flight and simulation data for a 10°-step increase in throttle setting, VC = 175 kts.

Figure 10 shows results for a typical 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 showed a serious discrepancy between the simulation and flight. Fan RPM and thrust take almost 9 sec to stabilize because of the slow responding engine control logic. Fan RPM and angle of attack show a direct inverse relationship. Figure 11 shows a cross plot of fan RPM and angle of attack for the data of Fig. 10 and also for several other cases, including another step throttle reduction and phugoid damping tests. These data represent a range of airplane weights and therefore, CG positions and inertias. The right scale of Fig. 11 is the approximate pitching moment that is required to obtain such a change in angle of attack. Although there is some variability in the data, the trend with fan RPM is clear.

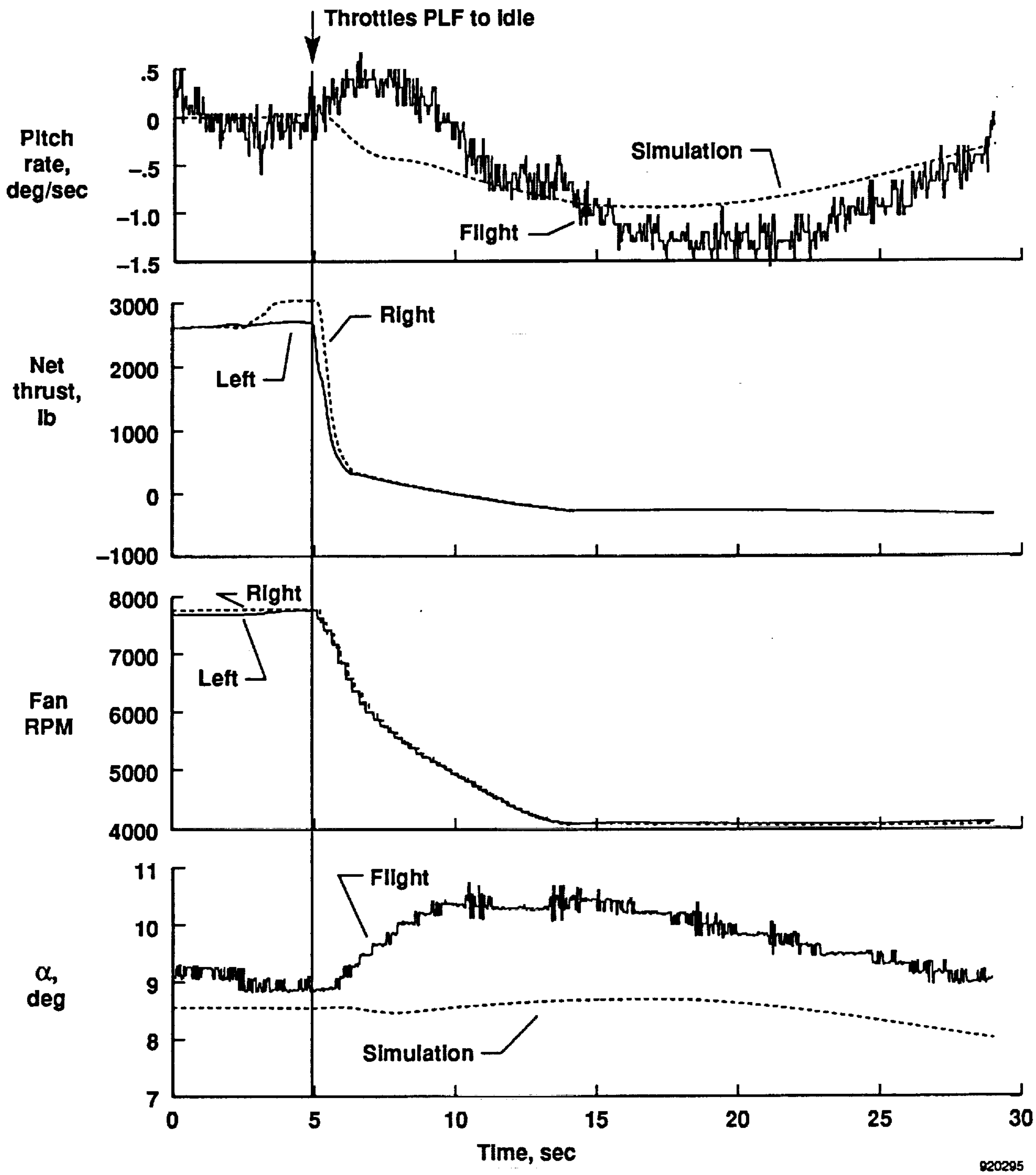


Figure 10. Comparison of flight and simulation data for a step throttle decrease to idle, VC = 175 kts. (Simulation without inlet airflow effect modeled).

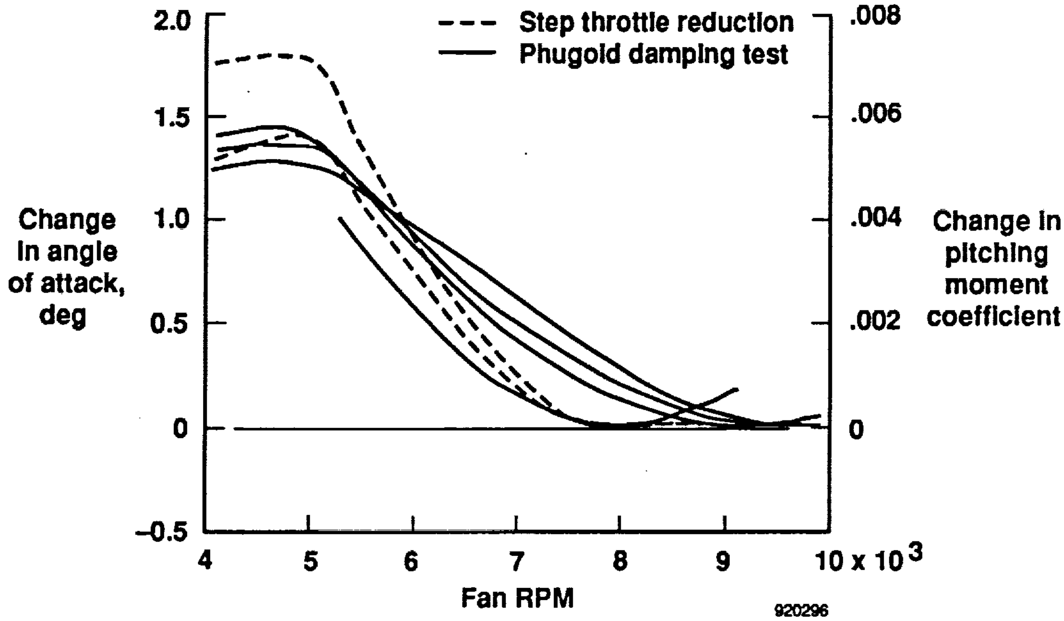


Figure 11. Effect of fan RPM on change in angle of attack and pitching moment coefficients, landing gear down, VC = 175 kts, angle-of-attack range 7.7 to 11°.

Effects of Inlet Airflow

Since the fan RPM is proportional to engine airflow, possible airflow effects of the inlet on airplane pitching moment were investigated. There had been extensive wind-tunnel tests previously conducted on the effects of inlet airflow on F-15 inlet and overall airplane drag, lift, and pitching moment.[4] These data show that reducing the inlet airflow increases the inlet lift and drag, and also increases the overall airplane lift, drag, and pitching moment (this would be expected with the overhanging ramp configuration of the F-15 inlet). The wind-tunnel pitching moment coefficient data is shown in Fig. 12 for the inlet ramp–full-up emergency position. The fairing extrapolates, based on other data, to higher values of mass flow ratio that occur at lower speeds. This pitching moment effect would produce an

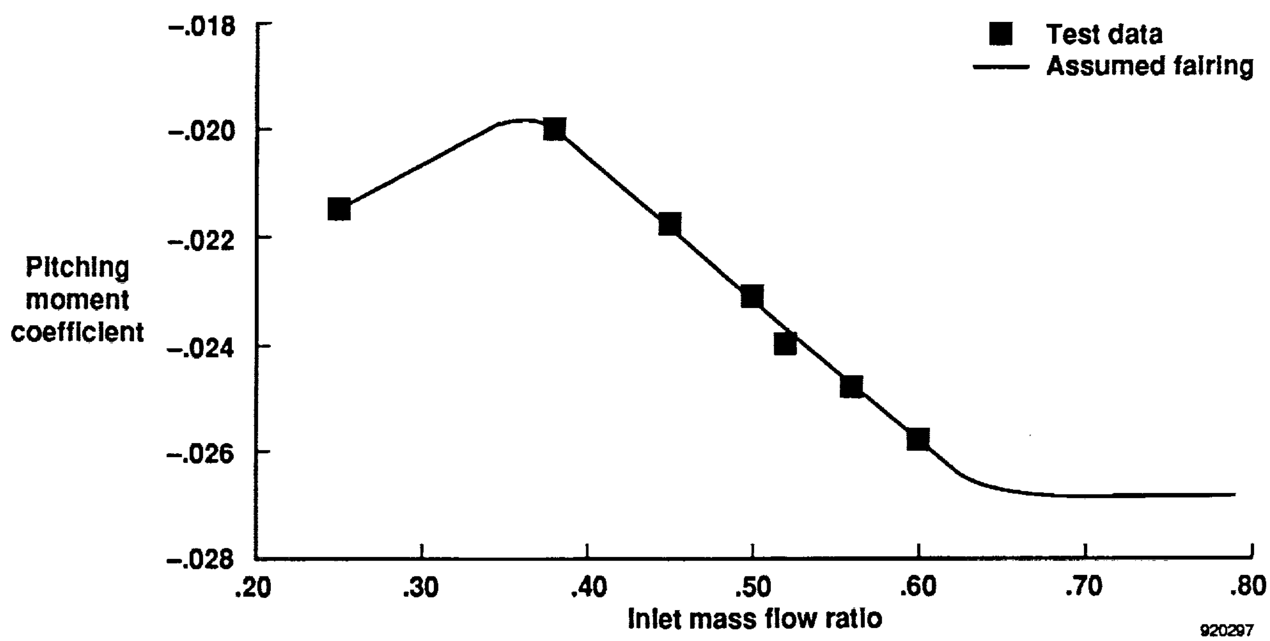


Figure 12. Pitching moment due to inlet mass flow ratio, F-15 7.5-percent wind-tunnel model test results, $\alpha = 8°$, Mach = 0.6.

effect in accordance with the flight data, i.e., a throttle reduction would result in a pitch up and an increase in angle of attack, which would eventually be overcome by the speed stability effects as the velocity is reduced.

The lowest Mach number in the wind-tunnel study was 0.6. It is not clear how to extrapolate the results to Mach 0.3 where the flight studies are being conducted, particularly since the mass flow ratio would have been higher at the lower Mach number. Two things are noted from the flight data. First, the significant change in angle of attack as a function of engine RPM seems to be limited to an intermediate range of fan speeds. Second, the cases where the engine was stepped up instead of down did not have a comparable initial pitch down or significant angle-of-attack decrease as seen in Fig. 9. These effects are consistent with the wind-tunnel inlet airflow effects shown in Fig. 12.

Based on these observations, the data from Figs. 11 and 12 were used to develop a piecewise linear increment to the pitching moment as a function of inlet airflow with no increment being added at the higher airflow. With this airflow effect, it has been possible to substantially improve the simulator's ability to match the flight data. The results of this airflow effect are shown in Fig. 13, the flight data of Fig. 10 are shown with the original and updated simulation. The changes in pitch rate are properly modeled, and the trend for angle of attack is predicted well. Although only one case is shown, similar results were observed for all other tests. This airflow effect has also been incorporated in the piloted simulation. The pilot commented that with the inlet airflow effects modeled, the simulator flies much more like the airplane. Attempts are continuing to refine this pitching moment effect to better match the flight data.

The inlet airflow effect is 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 podded engines where the inlets tend to be simple pitot inlets normal to the flow.

Differential Throttle Tests

There were four cases with primarily differential throttle input. In all cases, the simulator responded with somewhat more roll rate in response to the differential throttle input than the aircraft did. A typical case is shown in Fig. 14 where the pilot initially split the throttles approximately 2 in. and held that for 3 sec, then split the throttles 2 in. in the opposite direction. The yaw rate match is very good. The resulting roll rate oscillations were comparable in frequency

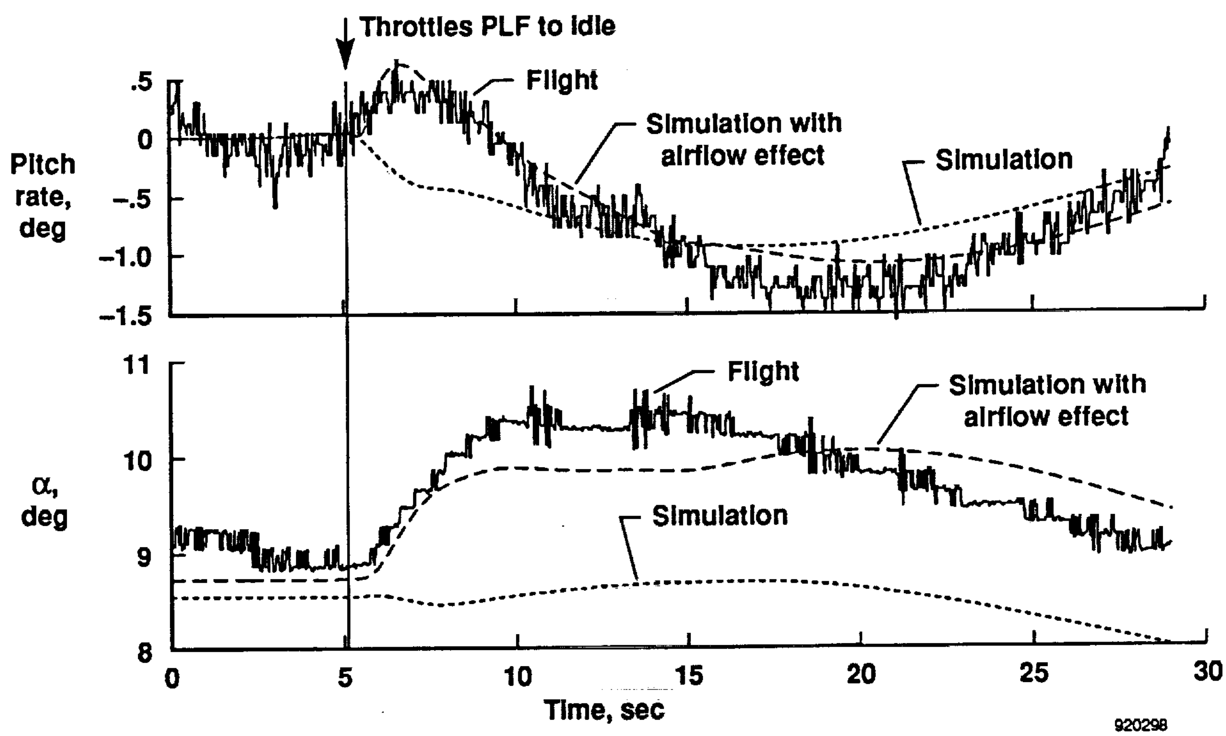


Figure 13. Comparison of flight and simulation results for a throttle step from PLF to idle, VC = 175 kts (simulation with and without inlet airflow effect modeled).

and damping in the flight and the simulator response, although the roll rates were higher in the simulation than in the flight data. These roll rates agree with the previously collected data comparing flight and simulation roll rates shown in Fig. 6. The inlet airflow effects that are important in pitch have only a minor effect on the yawing and rolling moments due to differential throttle.

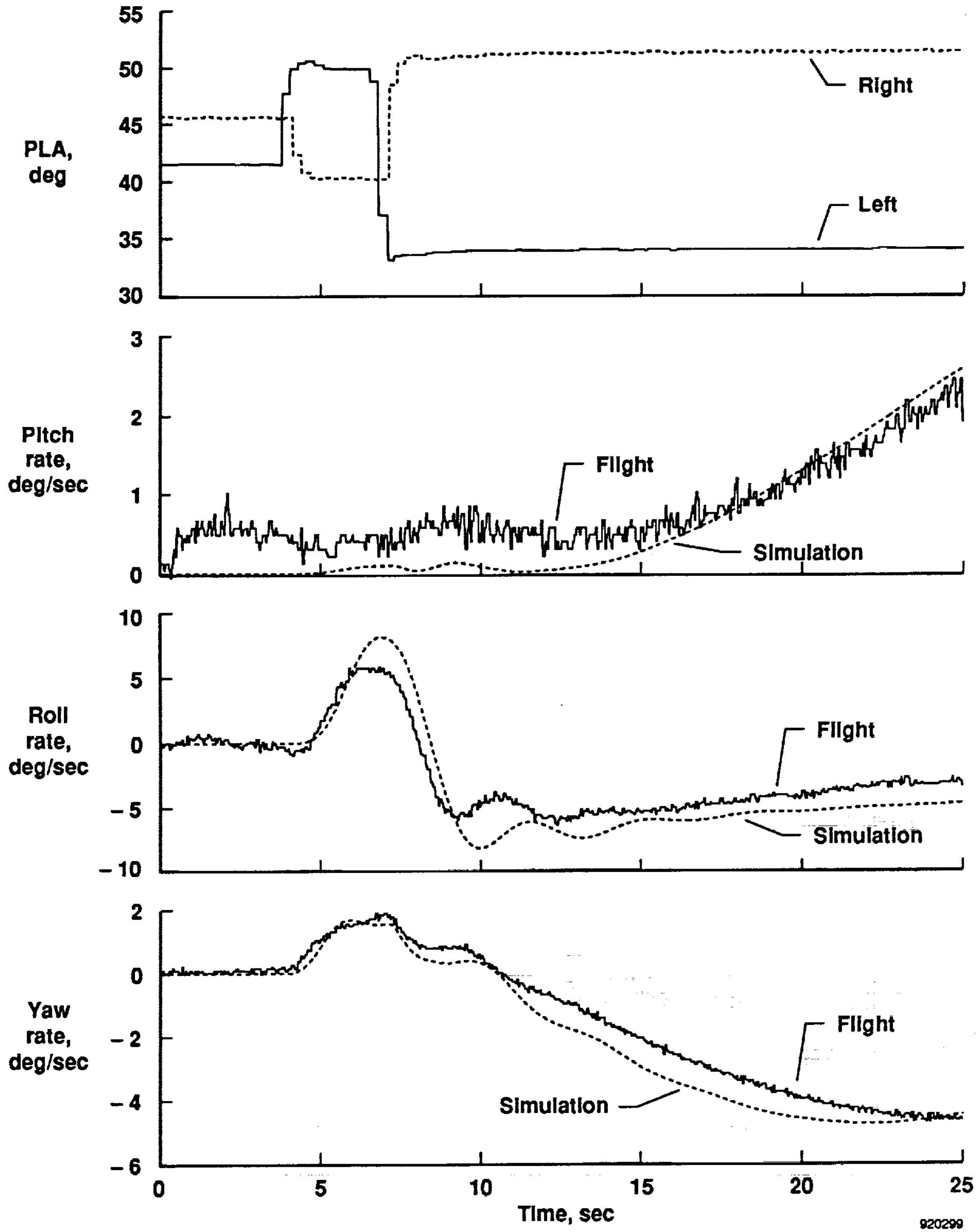


Figure 14. Comparison of flight and simulation response for a differential throttle input, VC = 175 kts.

Augmented Throttles-Only Control System

Manual throttles-only control is difficult for up-and-away flight and a successful landing on a runway would be extremely unlikely for the NASA F-15, based on pilot comments. However, an augmented propulsion controlled aircraft (PCA) concept[2] shows promise of being able to make repeatable runway landings. Figure 15 shows an augmented PCA system designed for the F-15.[1] Appropriate feedbacks are used to stabilize the pitch and roll axes. Thumbwheel controllers remind the pilot that the system is a slow-response, low-authority system. Initial simulation results based on the first NASA Dryden and McAir simulation showed that the system worked well. More recently, the updated simulation model, which flies much like the airplane and incorporates inlet airflow effects, has been used to evaluate the PCA system. Although phugoid damping is reduced, PCA system performance is still adequate at the lower speeds. At higher speeds, gain changes and the addition of airspeed feedback make the performance of the PCA system satisfactory. The flight-test control laws have the capability for changing gains, which will help with solving problems that occur during the flight evaluation. Based on the simulation, repeatable runway landings with this PCA system should be practical.

A flight demonstration of this PCA system on the NASA F-15 is planned. The digital flight-control system will provide the feedback signals and digital engine control systems on each engine will be used to move the throttles to the commanded position. The PCA control logic will reside in the digital flight-control computer.

Concluding Remarks

A flight and simulation evaluation of the throttles-only control capability of the F-15 airplane has been conducted. Principles of throttles-only control have been shown. Initial flight-to-simulation comparisons were good for differential throttle and increasing throttle, but were poor for decreasing throttle. Detailed comparisons of flight and simulation data have revealed an unmodeled pitching moment effect thought to be caused primarily by inlet airflow. The inlet airflow effect is small. However, when the only moments being used for control are from the propulsion system, normally neglected effects may become significant. This is true for airplanes with highly integrated propulsion systems such as fighters where inlet and engine interactions are strong, but less true for airplanes with podded engines. Incorporating this effect into the simulations has greatly improved the simulation-to-flight comparisons. Based on simulation results, an augmented throttles-only feedback control system shows promise of making repeatable runway landings of the F-15 airplane practical.

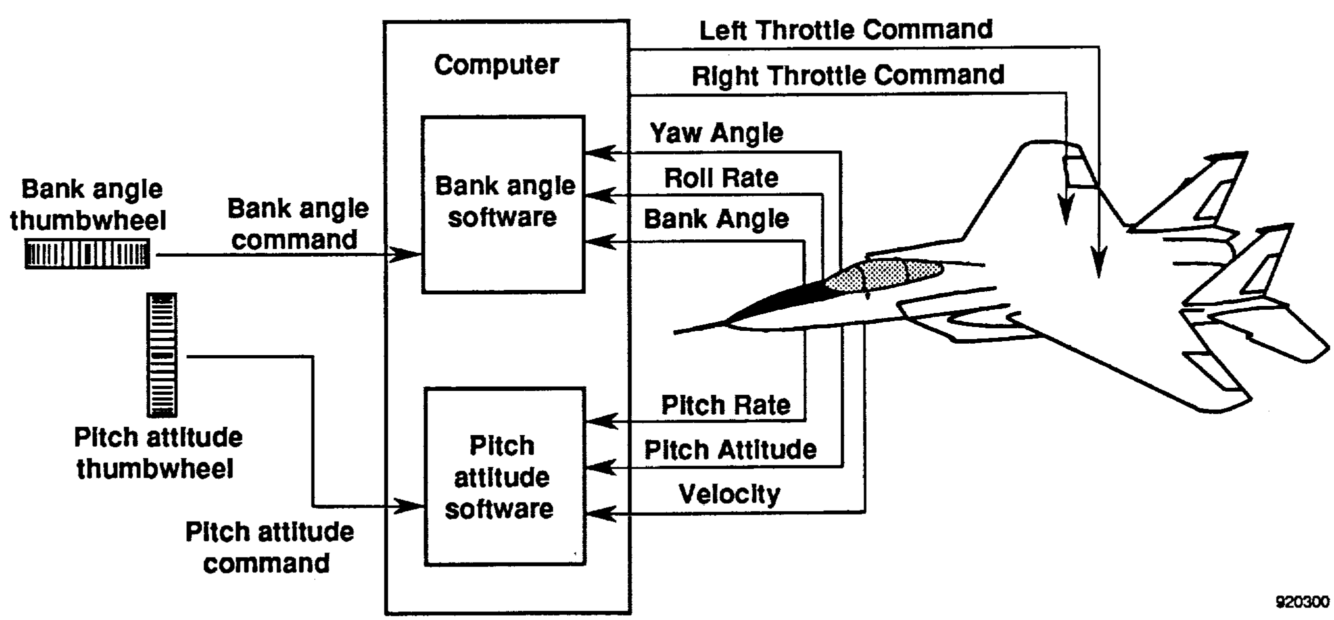


Figure 15. Schematic view of the augmented propulsion controlled aircraft system for the F-15.

References

[1]Burcham, Frank W. Jr. and C. Gordon Fullerton, *Controlling Crippled Aircraft - With Throttles*, NASA TM-104238, 1991.

[2]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.

[3]Burcham, F., Jr., C. Fullerton, G. Gilyard, T. Wolf, and J. Stewart, "A Preliminary Investigation of the Use of Throttles for Emergency Flight Control," AIAA-91-2222, June 1991.

[4]Kamman, J.H. and H.W. Wallace, "Assessment of Installed Inlet Forces and Inlet/Airframe Interactions," AFFDL-TR-76-62, July 1976.

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Flight tests and simulation studies using the throttles of an F-15 airplane for emergency flight control have been conducted at the NASA Dryden Flight Research Facility. The airplane and the simulation are capable of extended up-and-away flight, using only throttles for flightpath control. Initial simulation results showed that runway landings using manual throttles-only control were difficult, but possible with practice. Manual approaches flown in the airplane were much more difficult, indicating a significant discrepancy between flight and simulation. Analysis of flight data and development of improved simulation models that resolve the discrepancy are discussed. An augmented throttles-only control system that controls bank angle and flightpath with appropriate feedback parameters has also been developed, evaluated in simulations, and is planned for flight in the F-15.

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