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Piloted Simulation Tests of Propulsion Control as Backup to Loss of Primary Flight Controls for a Mid-Size Jet Transport

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Piloted Simulation Tests of Propulsion Control as Backup to Loss of Primary Flight Controls for a Mid-Size Jet Transport

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Summary

Partial failures of aircraft primary flight-control systems and structural damages to aircraft during flight have led to catastrophic accidents with subsequent loss of lives (e.g., DC-10 crash, B-747 crash, C-5 crash, B-52 crash, and others). These accidents can be prevented if sufficient alternate control authority remains which can be used by the pilot to execute an emergency safe landing.

Dryden Flight Research Center (DFRC) investigated the use of engine thrust for emergency flight control and has presented results of simulation and flight studies of several airplanes, including the B-720, Lear 24, F-15, B-727, C-402, and B-747. Using an F-15 aircraft, NASA DFRC successfully demonstrated in 1993 in a series of 36 flights, including actual propulsion controlled aircraft (PCA) landings, that throttle control of engines alone can be used to augment or replace the aircraft primary flight-control system to safely land the aircraft. NASA DFRC conducted flight tests in Aug.–Dec. 1995 of the MD-11 jet transport utilizing engine thrust for backup flight control.

A series of three piloted simulation tests have been conducted at Ames Research Center to investigate propulsion control for safely landing a mid-size jet transport which has experienced a total primary flight-control failure. The first series of tests was completed in July 1992 for the purpose of defining the best interface for the pilot commands to drive the engines. The second series of tests was completed in Aug. 1994 for the purposes of investigating PCA display requirements and to compare various PCA command modes. The third series of tests was completed in May 1995 for the purpose of investigating expanded PCA operational capabilities.

This report describes the concept of a PCA, discusses pilot controls, displays, and procedures; and presents the results of a series of three piloted simulation evaluations of the concept by a cross-section of air transport pilots.

1 Introduction

Partial failures of aircraft flight-control systems and structural damages to aircraft during flight have led to catastrophic accidents with subsequent loss of lives (ref. 1) (e.g., DC-10 crash, B-747 crash, L-1011 crash, and C-5 crash). These accidents can be prevented if sufficient alternate control authority remains which can be used by the pilot to execute an emergency safe landing.

Following the DC-10 accident at Sioux City, Iowa in 1989, the National Transportation Safety Board recommended "Encourage research and development of backup flight-control systems for newly certified wide-body airplanes that utilize an alternate source of motive power separate from that source used for the conventional control system" (ref. 2). The problem in the general case is that currently there is no satisfactory method onboard the aircraft for effectively controlling the aircraft with a disabled primary flight-control system. In addition, manual throttle control of engines is extremely difficult because of pilot unfamiliarity with dynamic response of the aircraft in this mode.

Dryden Flight Research Center (DFRC) investigated the use of engine thrust for emergency flight control and has presented results of simulation and flight studies of several airplanes, including the B-720, Lear 24, F-15, B-727, C-402, and B-747 (refs. 3 and 4). Using an F-15 aircraft, DFRC successfully demonstrated in 1993 in a series of 36 flights, including actual propulsion controlled aircraft (PCA) landings, that throttle control of engines alone can be used to augment or replace the aircraft primary flight-control system to safely land the aircraft (refs. 5 and 6). The DFRC concept used specifically developed control laws in the aircraft flight-control computer system to drive the engines in response to pilot input commands for bank angle and flightpath angle. The PCA system flight hardware and software was developed and implemented by McDonnell Douglas Aircraft (MDA) Company. As a follow-on to the F-15 PCA flight tests, DFRC and MDA have developed and implemented PCA control laws for the MD-11 jet transport. Flight tests are planned to take place in Aug.–Dec. 1995 (ref. 7).

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Ames Research Center (ARC) has conducted three PCA piloted simulation tests for a mid-size jet transport in support of and complementary to the PCA tests conducted by DFRC.

This report describes the concept of a PCA, discusses pilot controls, displays, and procedures; and presents the results of a series of three piloted simulation evaluations of the concept by a cross-section of air transport pilots.

1.1 Purpose of Each Series of NASA Ames Piloted Simulation Tests

A series of three piloted simulation tests have been conducted at ARC to investigate propulsion control for safely landing a mid-size jet transport which has experienced a total primary flight-control failure. The first series of tests was completed in July 1992 for the purpose of defining the best interface for the pilot commands to drive the engines. The second series of tests was completed in Aug.1994 for the purposes of investigating PCA display requirements and to compare various PCA command modes. The third series of tests was completed in May 1995 for the purpose of investigating expanded PCA operational capabilities throughout the full-flight envelope.

2 Simulation Aircraft Description

The piloted simulations were conducted in the Advanced Concepts Flight Simulator (ACFS) at ARC (table 1).

2.1 ACFS Facility Description

The ACFS is a moving base simulator representative of a mid-size two-engine jet transport with engines located under the wings. The cab layout of pilot controls and displays is very similar to those of a typical Boeing jet transport with CRTs for pilot and copilot primary flight displays and map displays, and with a typical Boeing mode control panel (MCP) located above the instrument panel for selection of various autopilot modes. The visual out-the-window display is a night visual scene for landing at San Francisco Runway 28R.

Table 1. ACFS facility description

Cockpit
B-757 controls and displays
Autopilot
B-757 mode control panel
All auto modes functional
Out the window scene
High fidelity night visual scenes
Cab motion
High fidelity cab motion
Data collection
Time histories
Touchdown snapshots
Video and audio tape

2.2 ACFS Aircraft Physical Dimensions

The ACFS aircraft model physical dimensions are similar to those of a Boeing 757 aircraft (table 2). The ACFS aircraft model has a nominal landing weight of 180,000 lb and a wing span of 140 ft, with one engine located beneath each wing. The engines are located 23.8 ft outboard from the aircraft center of gravity (cg), and 11.7 ft beneath the aircraft cg.

2.3 ACFS Aircraft Flight Dynamics

The ACFS aircraft model flight dynamics characteristics are typical of a jet transport similar to a B-757. The

Table 2. ACFS Aircraft physical dimensions

Similar to a mid-size jet transport (B-757)	
Gross weight	
Empty	121,660 lb
Takeoff	225,000 lb
Landing	180,000 lb
Moments of inertia	
I_{xx}	2,111,000 slug-ft^2
I_{yy}	4,290,000 slug-ft^2
I_{zz}	6,063,000 slug-ft^2
I_{xz}	280,000 slug-ft^2
Dimensions	
Wing area	2169.9 ft^2
Wing span	139.7 ft
Mean chord	17.5 ft
Mean aerodynamic center	52.0%
Nominal landing cg	27.8%
Engines	
Max thrust	42,000 lb
Xeng	48.8 ft
Yeng	23.8 ft
Zeng	11.7 ft

frequency and damping of the ACFS open loop dynamics for a typical PCA approach configuration (table 3) is representative of a mid-size jet transport. Time histories of the longitudinal modes and lateral-directional modes are shown in figures 1 and 2.

2.4 ACFS Turbulence Model

ACFS turbulence mathematical models provide turbulence rms values and bandwidths (table 4) which are representative of values specified in Military Specifications Mil-Spec-8785 D of April 1989. Translational turbulence along each translational stability axis is generated by a random number generator driving a first order filter at a frequency dependent upon altitude and airspeed. Rotational turbulence about the pitch axis is generated by a first order filter driven by an output correlated with vertical gusts, rotational turbulence about the yaw axis is generated by a first order filter driven by an output correlated with lateral gusts, and rolling turbulence is generated by a random number generator driving a first order filter at a frequency dependent upon altitude and airspeed.

3 PCA Concept and Control Laws

PCA control laws provide aircraft longitudinal flight control through parallel throttle movement fore and aft to control climb or descent flightpath. PCA control laws provide aircraft lateral-directional flight control through asymmetric throttle movement to control bank angle. PCA concept implementation is depicted in figure 3. PCA control law implementation is shown in more detail in Appendix A, and PCA control law equations are shown in Appendices B, C, and D.

3.1 PCA Control Law Development

PCA control law structure and gains were developed using an analytical model of the ACFS aircraft and the MATLAB Control System Toolbox. Gains were initially optimized to provide sufficiently tight steady state tracking in light turbulence while keeping thrust excusions within acceptable limits. Gains were then refined to slightly increase damping for improved step transient responses.

The PCA control law initial exhaust pressure ratio (EPR) trim point is determined from an EPR trimmap rather than simply using the EPR values at PCA engage. This initialization method is used because the pilot, in an attempt to fly the aircraft on manual throttles, could possibly have moved the engines far from a desired straight and level trim condition prior to PCA engage. Appendix E shows the EPR trimmap for straight and level flight.

3.2 PCA Typical Step Response Time Histories

PCA time histories to step commands of –3 deg flightpath angle and 10 deg bank angle are shown in figures 4 and 5. The time constants for the longitudinal responses are approximately 4 sec at 2000 ft altitude, 8 sec at 15,000 ft altitude, and 15 sec at 35,000 ft altitude. The time constants for the bank command step responses are approximately 3 sec at 2000 ft altitude, 6 sec at 15,000 ft altitude, and 10 sec at 35,000 ft altitude.

Table 3. ACFS Open loop dynamics

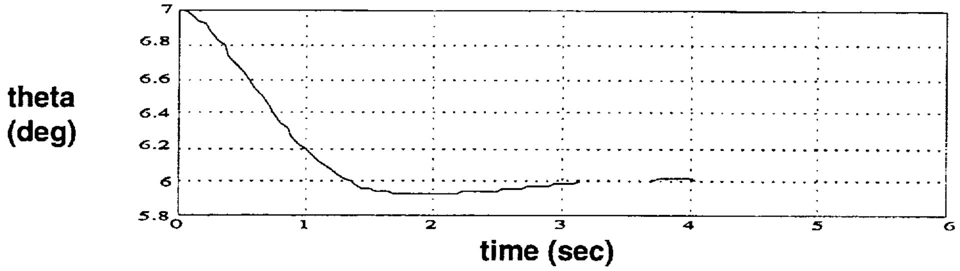
Trim condition		
Weight = 180,000 lb, altitude = 2000 ft		
No flaps, landing gear down, cg = 27.8%		
Longitudinal short period		
Freq. = 1.60 rad/sec	Period = 3.9 sec	Damping ratio = 0.60
Phugoid		
Freq. = 0.094 rad/sec	Period = 66.4 sec	Damping ratio = 0.090
Dutch roll		
Freq. = 1.04 rad/sec	Period = 6.0 sec	Damping ratio = 0.23
Spiral divergence		
tau = 31.0 sec	Time to double amplitude = 22.0 sec	
Roll-rate damping		
tau = 0.33 sec		

ACFS OPEN LOOP LONGITUDINAL DYNAMICS

W = 180,000 lbs; V = 180 kts; Alt = 2,000 ft
flaps = 0 deg; lg down; cg = 27.8%
All flight control surfaces at zero deflection.
Throttles at level flight trimmed thrust.

SHORT PERIOD

natural freq = 2.00 rad/sec. period = 3.14 sec
damped freq = 1.60 rad/sec. period = 3.92 sec.
damping ratio = 0.60



PHUGOID

natural freq = 0.095 rad/sec. period = 66.1 sec
damped freq = 0.094 rad/sec. period = 66.4 sec.
damping ratio = 0.090

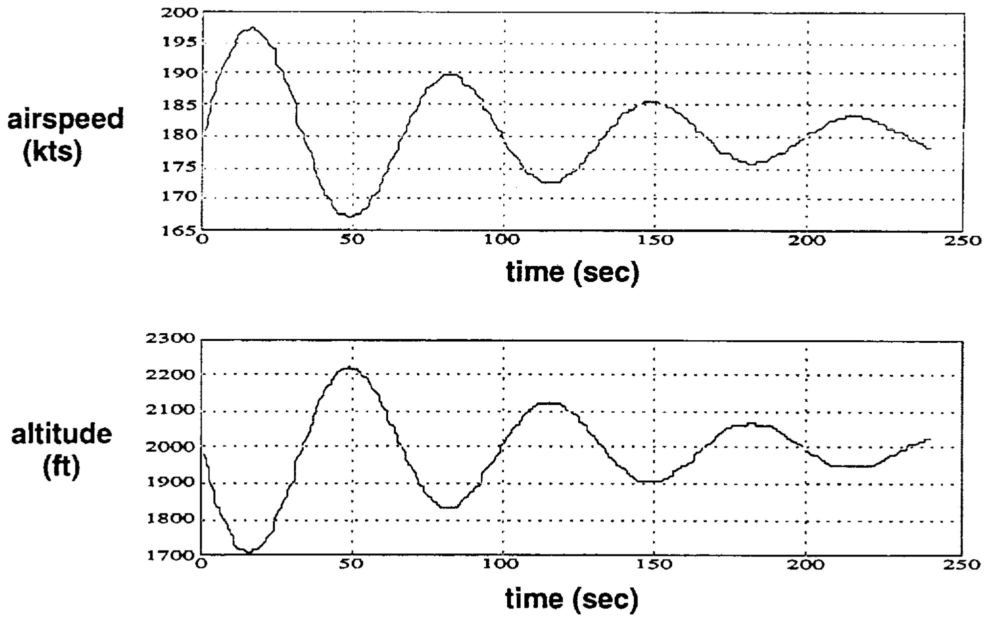


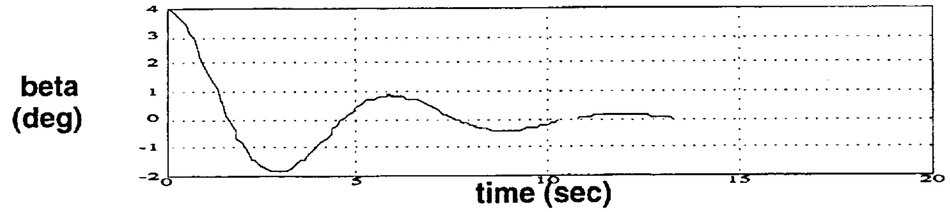
Figure 1. ACFS open loop longitudinal dynamics. The ACFS aircraft open loop longitudinal dynamics are very typical of a mid-size jet transport.

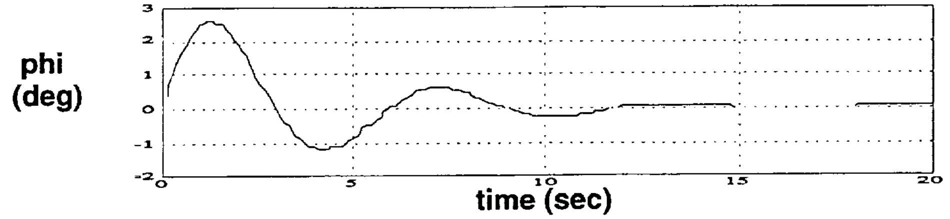
ACFS OPEN LOOP
LATERAL-DIRECTIONAL DYNAMICS

W = 180,000 lbs; V = 180 kts; Alt = 2,000 ft
flaps = 0 deg; lg down; cg = 27.8%
All flight control surfaces at zero deflection.
Throttles at level flight trimmed thrust.

DUTCH ROLL

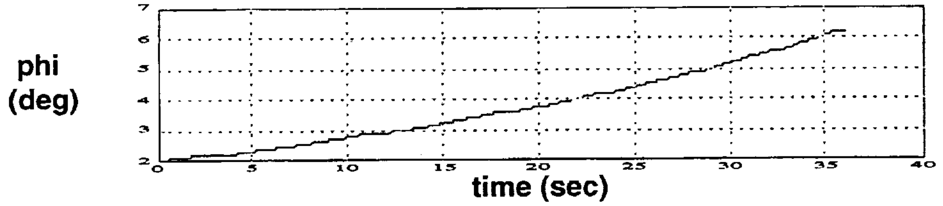
natural freq = 1.07 rad/sec. period = 5.9 sec
damped freq = 1.04 rad/sec. period = 6.0 sec.
damping ratio = 0.23





SPRIAL DIVERGENCE

tau = 31.0 sec.
time to double amp = 22 sec.



ROLL RATE DAMPING

tau = 0.33 sec

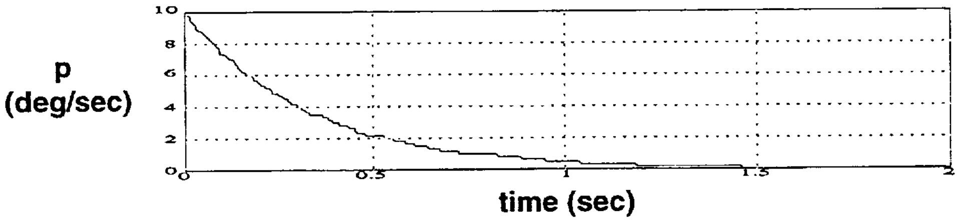


Figure 2. ACFS open loop lateral-directional dynamics. The ACFS aircraft open loop lateral-directional dynamics are very typical of a mid-size jet transport.

Table 4. ACFS Light turbulence model amplitude and bandwidth

Altitude = 1000 ft		Airspeed = 180 kts
Translational gusts		
	rms value (kts)	Bandwidth (rad/sec)
u axis	1.8	0.5
v axis	1.4	0.5
w axis	1.7	0.5
Total	2.9	
Rotational gusts		
	rms value (deg/sec)	Bandwidth (rad/sec)
p gusts	0.50	1.4
q gusts	0.40	1.4
r gusts	0.50	1.4
Total	0.84	

Note: Gust amplitude and bandwidth depend on airspeed and altitude.

3.3 PCA Industry Benefits

The results of a study (ref. 8) to identify PCA industry benefits are shown in table 5. The study was conducted for a the 30 year life cycle of a fleet of 300 aircraft in the category of 400,000 lb takeoff gross weight. It was assumed that PCA allows mechanical backup flight controls to be eliminated, PCA training costs are equal to mechanical backup costs, PCA saves one aircraft over a 30 year period, and insurance is 5 percent less for a PCA-equipped aircraft.

Table 5. PCA industry benefits

Safety	
• Eliminate catastrophic accidents due to loss of primary flight control	
Economic	
• Weight reduction saves	$295M
• Insurance savings	42M
• Saved airplane	110M
• PCA certifications costs	–10M
Total life cycle savings	$436M

4 Pilot Interface Tests (June 1992)

4.1 Pilot Interface Test Objective

Objective of Pilot Interface tests completed in July 1992 was to compare two PCA controller modes: (1) sidestick controller and (2) thumbwheel controller.

4.2 Pilot Interface PCA Modes

The PCA sidestick controller mode tested was one in which the pilot used the conventional sidestick controller to command roll rate and flightpath angle rate. The PCA thumbwheel controller mode tested was one in which the pilot used the bank angle knob and the vertical speed knob on the conventional autopilot MCP to command bank angle and flightpath angle.

4.3 Pilot Interface Test Displays

The primary flight display was programmed with symbology to assist the control task. Commanded and actual flightpath angle, relative to the aircraft symbol, were presented against the pitch ladder of the attitude director indicator, and commanded and actual roll angle were presented against the roll index.

4.4 Pilot Interface Test Description

A total of six NASA pilots participated in the tests and conducted over 100 simulated approaches and landings. Evaluation criteria included pilot comments, Cooper-Harper ratings, and touchdown performance. Approaches were conducted in two configurations: (1) no flaps and 170 kts airspeed, and (2) 40 deg flaps and 145 kts airspeed. Approaches were conducted in both light and moderate turbulence. Initial condition was trimmed straight and level flight at 1,800 ft above the ground (AGL), 10 nautical miles (nm) from the runway, and 1000 ft lateral offset to the left of centerline.

PCA IMPLEMENTATION

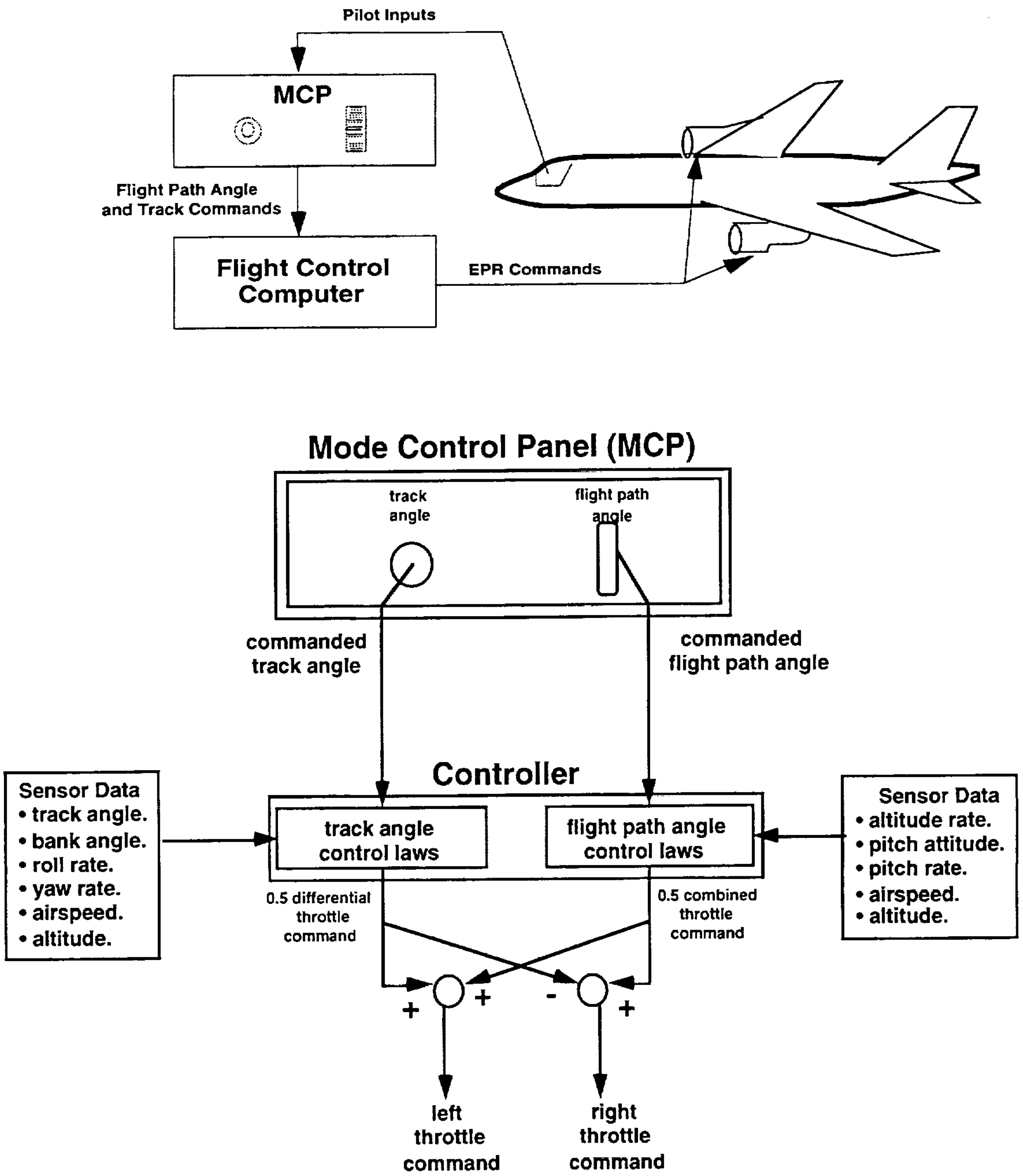
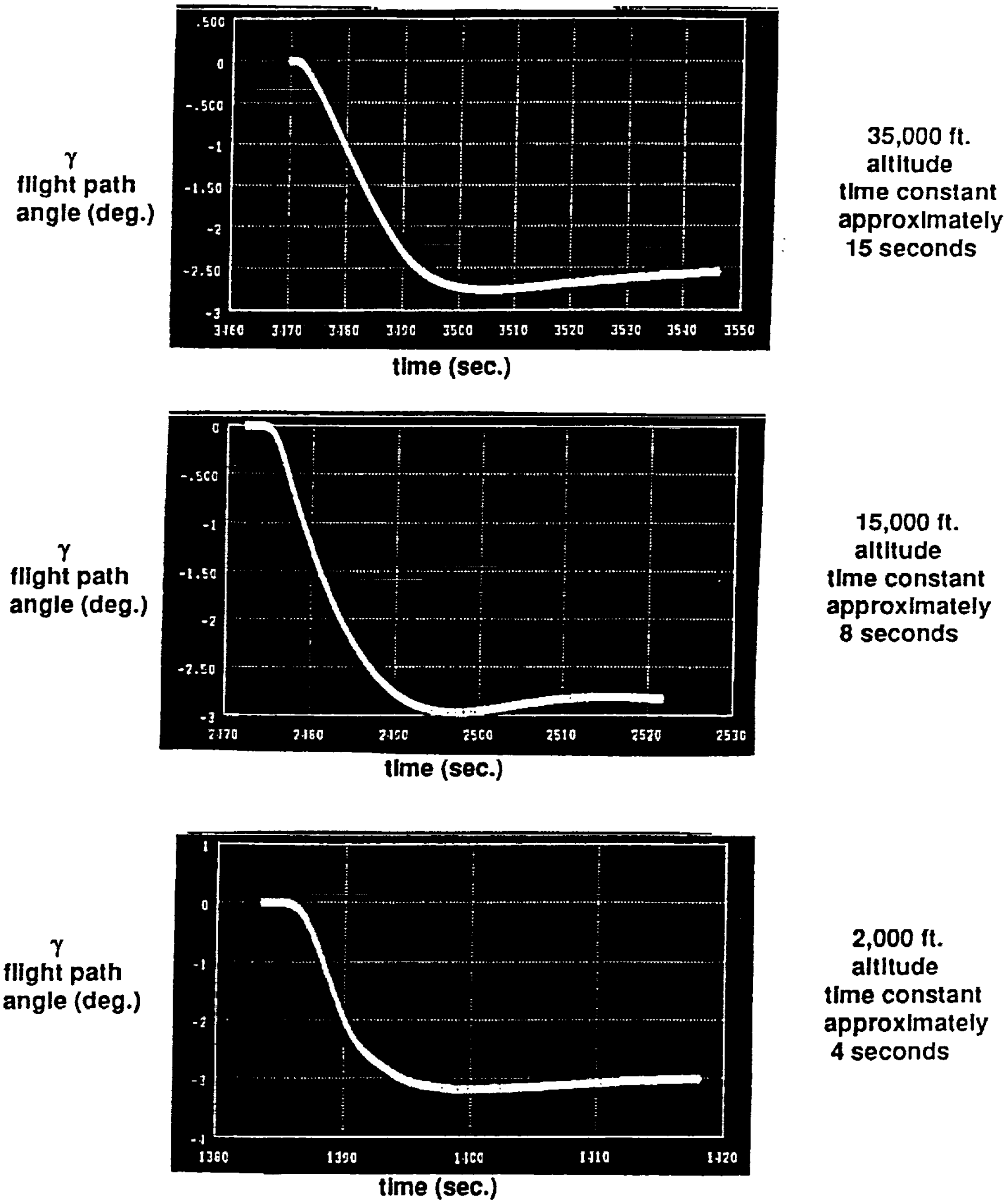

Pilot Inputs
MCP
Flight Path Angle and Track Commands
Flight Control Computer
EPR Commands
Mode Control Panel (MCP)
track angle
flight path angle
commanded track angle
commanded flight path angle
Controller
Sensor Data
• track angle.
• bank angle.
• roll rate.
• yaw rate.
• airspeed.
• altitude.
track angle control laws
flight path angle control laws
Sensor Data
• altitude rate.
• pitch attitude.
• pitch rate.
• airspeed.
• altitude.
0.5 differential throttle command
0.5 combined throttle command
+
+
-
+
left throttle command
right throttle command

Figure 3. PCA implementation. The PCA cockpit controls and displays, sensors, and pilot procedures are the same as for conventional autopilot operation. PCA hardware and software implementation costs, and pilot training requirements are minimized.

**PCA STEP RESPONSE TO
-3 DEGREE FLIGHT PATH ANGLE STEP COMMAND
FOR LOW, MEDIUM, AND CRUISE ALTITUDE**



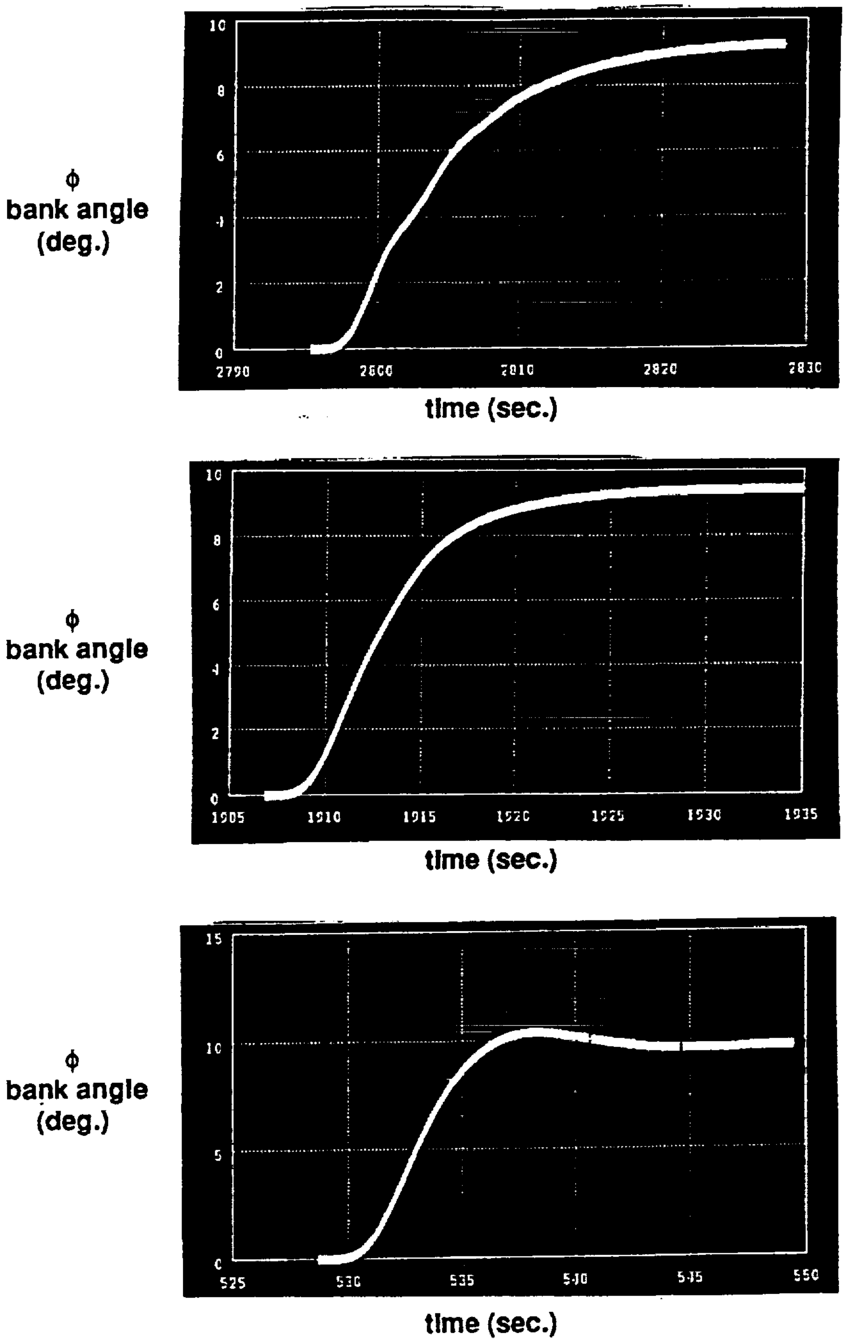
35,000 ft.
altitude
time constant
approximately
15 seconds

15,000 ft.
altitude
time constant
approximately
8 seconds

2,000 ft.
altitude
time constant
approximately
4 seconds

Figure 4. PCA flightpath angle time history step response. The PCA flightpath angle closed loop control time constants at low altitude are sufficiently fast for approach and landing; and at medium and cruise altitudes are slower, but sufficiently fast for satisfactory flightpath control.

PCA STEP RESPONSE TO
10 DEGREE BANK ANGLE STEP COMMAND
FOR LOW, MEDIUM, AND CRUISE ALTITUDE



35,000 ft.
altitude
time constant
approximately
10 seconds

15,000 ft.
altitude
time constant
approximately
6 seconds

2,000 ft.
altitude
time constant
approximately
3 seconds

Figure 5. PCA bank angle time history step response. The PCA bank angle closed loop control time constants at low altitude are sufficiently fast for approach and landing; and at medium and cruise altitudes are slower, but sufficiently fast for satisfactory flightpath control.

4.5 Pilot Interface Test Results

The sidestick control mode was slow and required continuous pilot attention to achieve a desired command. It was difficult to make precise simultaneous multiaxis inputs with the sidestick. The thumbwheel mode allowed desired commands to be set quickly using the digital window as feedback. A disadvantage of the thumbwheel bank command was that the control knob had no zero angle detent, thus requiring the pilot to look down in the cockpit to determine if he had commanded zero bank angle.

The task defined for the Cooper-Harper ratings was to land on the runway with a sink rate of less than 16 fps, bank angle of less than 10 deg, and touchdown on the first half of the runway. In all cases investigated (no flaps, 40 deg flaps, light and moderate turbulence), pilots preferred the thumbwheel controller to the sidestick controller. Average Cooper-Harper ratings for each case is shown in figure 6. The mean rating with 0 deg flaps in the sidestick mode was 4.5 compared to a mean rating with the MCP thumbwheel of 3.6. The mean rating with 40 deg flaps in the sidestick mode was 5.1 compared to a mean rating with the MCP thumbwheel of 3.9.

4.6 Pilot Interface Test Conclusions

Pilots preferred the MCP thumbwheel controller to the sidestick controller for PCA approach and landing.

5 PCA Mode/Display Tests (Aug. 1994)

5.1 PCA Mode/Display Test Objectives

Objectives of the PCA Mode tests completed in Aug. 1994 were (1) to evaluate PCA bank mode vs. PCA heading mode, and (2) to investigate PCA performance enhancement with additional displays.

5.2 PCA Mode/Display Test Modes Tested

The PCA heading mode was one in which the pilot controlled aircraft heading by commanding heading through the heading select knob on the MCP. The PCA bank mode was one in which the pilot controlled aircraft bank angle by commanding bank angle by using the same heading select knob on the MCP. In the bank mode, the signals from the heading select knob represent bank commands rather than heading commands. PCA flightpath angle control was provided by pilot inputs using the MCP vertical speed knob. A digital command readout was provided above both the heading knob and the vertical speed knob.

5.3 PCA Mode/Display Test Displays Tested

Symbology was added to the conventional primary flight director display to provide feedback to the pilot on commanded flightpath angle and commanded bank angle in addition to normal digital readouts on the MCP. The commanded flightpath angle was a horizontal green bar which moved vertically to the commanded flightpath angle on the pitch attitude indicator. The commanded bank angle command was achieved by rolling the same horizontal green bar to the commanded bank angle.

5.4 PCA Mode/Display Test Description

The test matrix and approach sequence flown by each pilot was carefully planned in order to obtain statistically significant and valid data for comparison purposes. Prior to conducting test data approaches, each pilot received an hour of checkout of the cab conventional controls and displays, three approach and landings with conventional sidestick and conventional autopilot modes, and three PCA training approaches. In addition, the order of PCA test data approaches was varied for each subject pilot to eliminate mode sequence from statistical significance.

A total of 13 pilots (NASA, FAA, airline, and industry) participated in the tests and conducted 261 approaches in either bank mode or heading mode (half with and half without the additional PCA displays on the primary flight director). Approaches were conducted in both light and moderate turbulence. Initial approach point condition was trimmed straight and level flight at 2000 ft above the ground (AGL), 10 nautical miles (nm) from the runway, and 2000 ft lateral offset to the left of centerline. Evaluation criteria included pilot comments, Cooper-Harper ratings, approach flightpath control performance, and touchdown performance.

5.5 PCA Mode/Display Test Results

The PCA heading command mode required significantly less pilot workload for approach and landing than did the PCA bank command mode. This was because the pilot is required to input fewer commands using the MCP heading command knob than is required when using the bank command MCP knob. In addition, the bank angle command knob had no zero detent, thus requiring the pilot to look down at the digital readout to determine if he had commanded zero bank angle. However, pilots commented that they felt they had more immediate control in the bank command mode, particularly when crossing the runway

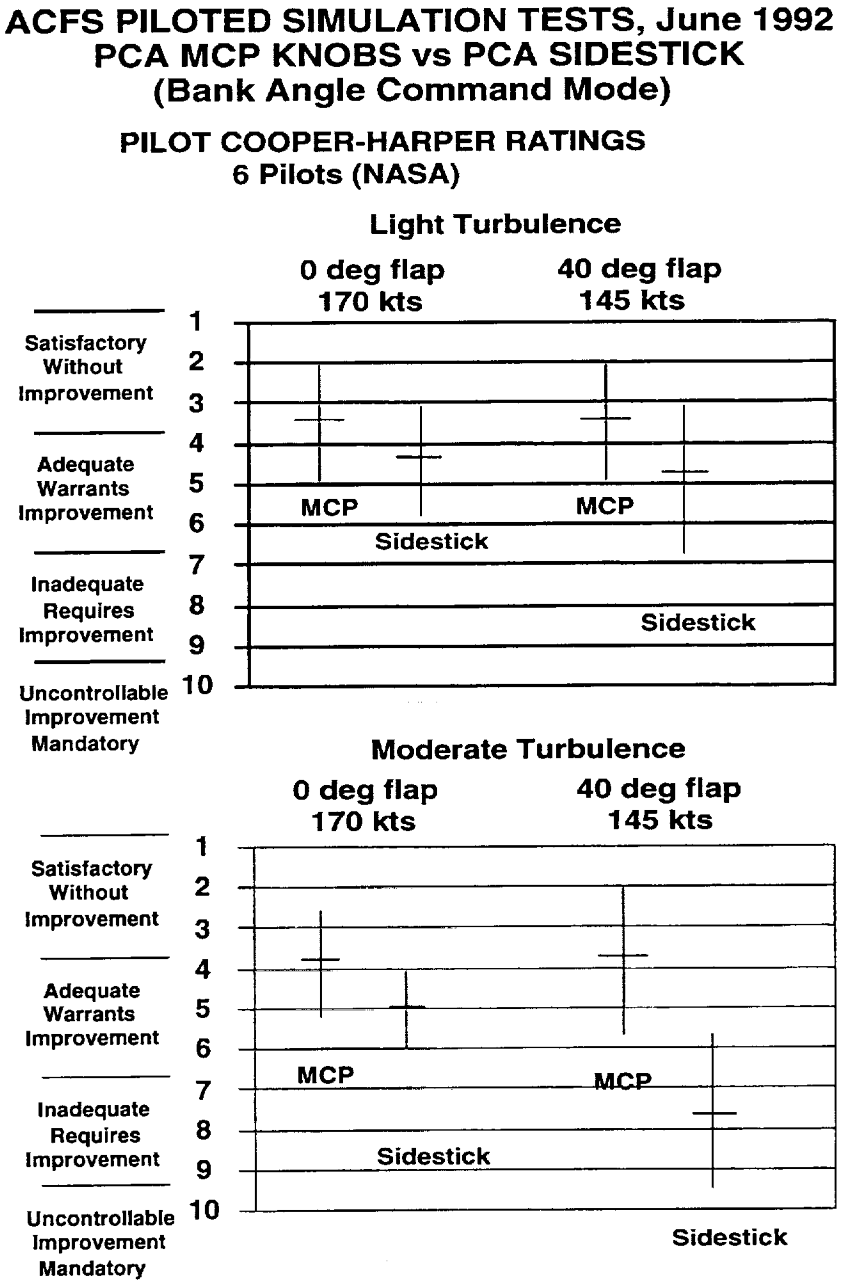


Figure 6. MCP vs. sidestick pilot Cooper-Harper ratings. Pilot preferred the autopilot Mode Control Panel (MCP) thumbwheel and vertical speed knob as the best interface for pilot commands to the PCA flight-control laws.

threshold and preparing for touchdown. Both the PCA heading command mode and the PCA bank command mode received mean Cooper-Harper ratings (3.4 and 3.2) in the "satisfactory to adequate" range (fig. 7). Pilots preferred slightly the PCA heading command mode over the PCA bank command mode (fig. 8).

The PCA symbology displays provided feedback to the pilot on the commanded bank/heading angle and flight-path angle, and the aircraft response to the command. This feedback did not provide pilots with information that was useful to the task of approach and landing, and required pilots to spend more time "heads down" in the cockpit.

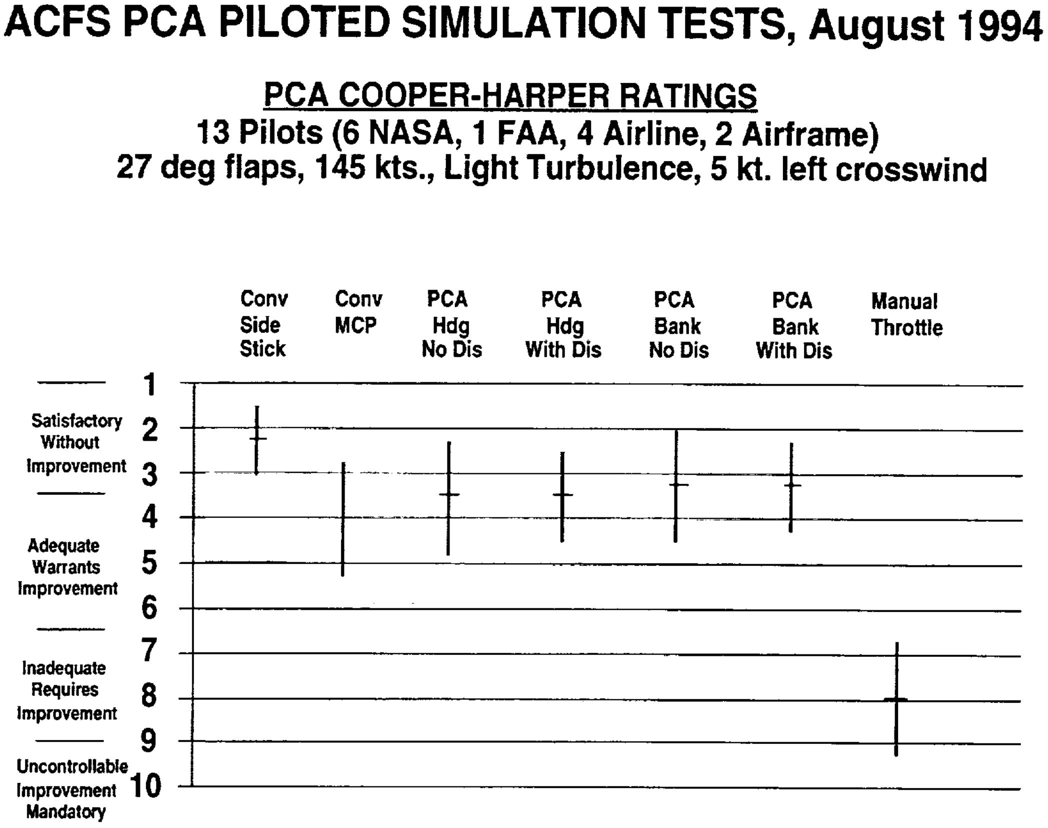


Figure 7. PCA Mode pilot Cooper-Harper ratings. PCA heading and bank modes were both rated in the adequate to satisfactory range, while the PCA manual throttle mode was rated as unacceptable.

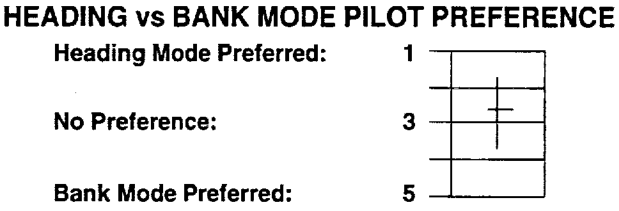


Figure 8. Heading vs. bank mode pilot preference. The PCA heading mode was preferred slightly over the PCA bank mode, primarily due to less number of required pilot MCP knob inputs during the approach.

Pilots relied primarily on the information feedback of the digital readouts of commanded bank/heading command and flightpath angle command was As a result, pilots did not desire or need additional PCA symbology (fig. 9).

PCA touchdown statistical dispersion data is shown in figure 10. Over half of the pilots were unable to complete a "manual throttle" approach on their first try. The longitudinal "phugoid" mode was particularly difficult for pilots to control because the natural dynamic damping of this mode was so small. Typically, aircraft flightpath divergence was amplified when pilots allowed the bank angle to get too large while they were attempting to damp the phugoid mode. Pilot skill in conducting "manual throttle" approaches did improve with training, but the overall performance of "manual throttle" approaches was very poor even after some training, and pilots rated the "manual throttle" mode unacceptable.

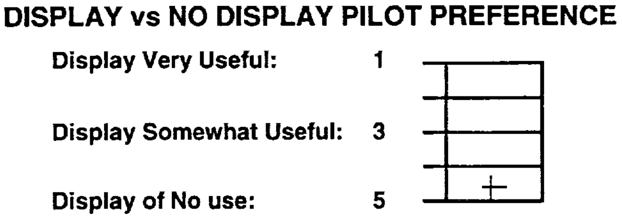
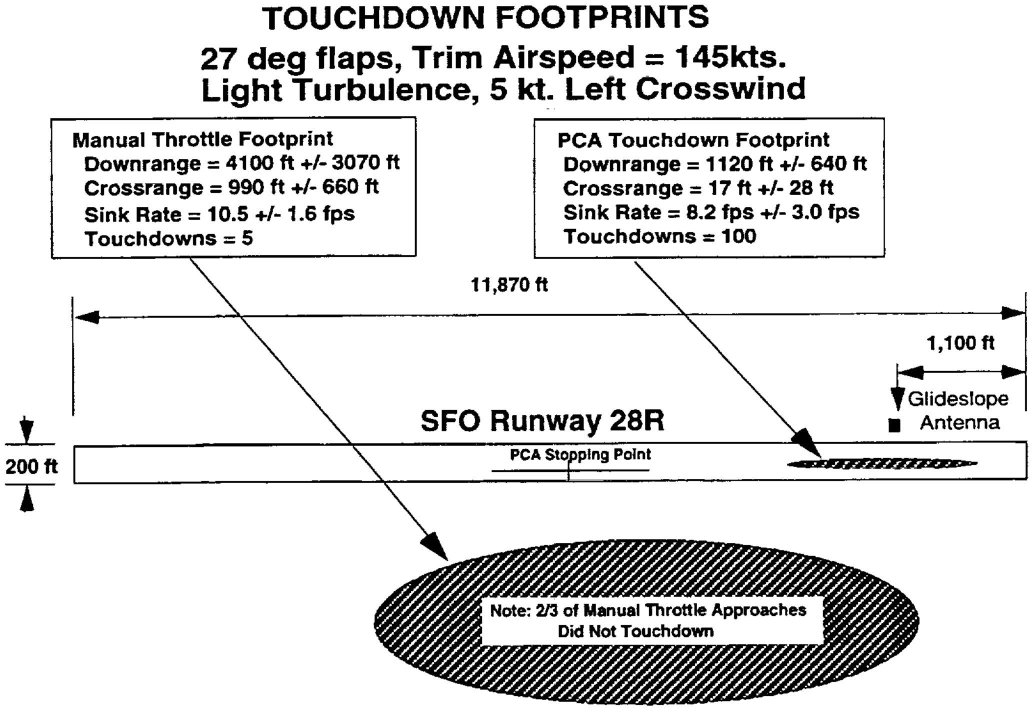


Figure 9. Display vs. no display pilot preference. Specific PCA displays did not enhance pilot performance or reduce pilot workload.



Manual Throttle Footprint
Downrange = 4100 ft +/- 3070 ft
Crossrange = 990 ft +/- 660 ft
Sink Rate = 10.5 +/- 1.6 fps
Touchdowns = 5

PCA Touchdown Footprint
Downrange = 1120 ft +/- 640 ft
Crossrange = 17 ft +/- 28 ft
Sink Rate = 8.2 fps +/- 3.0 fps
Touchdowns = 100

Note: 2/3 of Manual Throttle Approaches Did Not Touchdown

Figure 10. PCA touchdown footprints. PCA touchdown footprints and sink rates were consistently satisfactory, while manual throttle mode touchdown footprint and sink rate were unacceptable. Over half of the pilots were unable to complete a "manual throttle" approach on their first try. The longitudinal "phugoid" mode was particularly difficult for pilots to control because of the low natural dynamic damping of this mode. Typically, aircraft flightpath diverged when pilots allowed the bank angle to get too large while attempting to damp the phugoid mode.

5.6 PCA Mode/Display Test Conclusions

Pilots rated the bank mode and heading mode about equal (Cooper-Harpers both about 3.8), but preferred the heading mode over the bank mode. Additional displays for PCA on the primary flight director were not helpful in flying the approach and landing.

6 PCA Full-Flight Envelope Tests (Apr. 1995)

6.1 PCA Full-Flight Envelope Test Objectives

Objectives of the PCA full-flight envelope tests were to (1) evaluate and compare MCP knob track mode, fully coupled mode, and coupled localizer-only mode, (2) evaluate performance at medium and cruise altitudes, and (3) define operational limits with various turbulence levels, with various out-of-trim yaw moments and roll moments, and with various cg locations.

6.2 PCA Full-Flight Envelope Test Modes Tested

The PCA MCP knob track mode was one in which the pilot controlled aircraft ground track by commanding ground track through the heading select knob on the MCP, and controlled the flightpath angle through the vertical speed knob on the MCP. The PCA fully coupled mode was one in which the Instrument Landing System (ILS) glide slope and localizer signals were used to compute appropriate PCA bank angle and flightpath angle commands, thereby allowing the aircraft to be flown "hands off" in a fully automatic mode to touchdown. An autoflare mode initiated at 120 ft altitude was included in the PCA fully coupled mode. The PCA coupled localizer-only mode was one in which the ILS localizer signal was used to compute PCA bank angle command to automatically track runway centerline, while the pilot controlled flightpath angle with the MCP vertical speed knob.

6.2 PCA Full-Flight Envelope Test Description

A total of 10 pilots (table 6) participated in the tests and conducted 160 approaches (table 7). Evaluation criteria included pilot comments, Cooper-Harper ratings, approach performance time history data, touchdown performance "snapshot" data, and post-test pilot questionnaires. Approaches were conducted at 180 kts and 250 kts with no flaps. In addition, PCA was flown at 15,000 ft altitude and 35,000 ft altitude. A range of parameters relevant to PCA was tested (table 8).

Table 6. PCA full-flight envelope test subject crews

ALPA	2 Airline captains
ATA	1 Airline pilot
Airline training	1 MD-11 Instructor
Air cargo	1 Air cargo pilot
	1 Military pilot
Airframe companies	2 Aircraft company test pilots
NASA	2 Test pilots

Table 7. PCA full-flight envelope test matrix

	Initial airspeeds			
Altitude (ft)	Manual throttle	PCA MCP knobs	PCA coupled	PCA loc-only
2000	180 kt	180 kt	180 kt	180 kt
5000		250 kt	250 kt	
15,000		240 kt		
35,000		260 kt		

Table 8. PCA full-flight envelope parameter test ranges

Failed rudder offsets	0–4 deg
Failed aileron offsets	0–2 deg
Failed stabilator	Trimmed airspeeds from 145 kt to 260 kt
cg positions	24% – 36%
Turbulence	None, light, moderate, heavy
Mean wind	20 kts from 30 deg left and right

6.3 PCA Full-Flight Envelope Test Results

The PCA MCP track command mode using the MCP heading select knob and vertical speed knob required less pilot workload than heading command mode and bank angle mode did in previous tests (table 9). This was because the track mode automatically establishes correct crab angles for the pilot in crosswinds. In addition the track mode produced smaller engine thrust excursions in turbulence because of the less noisy inertial feedback signal of track angle as compared to heading or bank angle feedback in turbulence.

The PCA MCP track mode, fully coupled mode, and coupled loc-only mode all received adequate to satisfactory mean pilot Cooper-Harper ratings (fig. 11). PCA mode order of pilot preference was PCA coupled localizer-only slightly over the PCA fully coupled mode, and PCA fully coupled mode slightly over the PCA MCP track knob mode (fig. 12).

PCA approach and landing performance was acceptable in no turbulence up to a maximum of 3 deg rudder out of trim yaw moment. As turbulence is increased, engines began to hit idle sooner and more often. Thus, there was an operationally acceptable limit tradeoff of rudder offset vs. turbulence (fig. 13). PCA was acceptable in no turbulence up to a maximum of 1.5 deg of aileron out of trim roll moment. It is important to recognize that these maximum values of rudder and aileron out of trim moments are very vehicle dependent, and would vary substantially with the number of engines and physical thrust moment arms

Table 9. PCA pilot workload

Approach Initiated in Trimmed Condtion; 180 kts; no flaps; 12 nm from runway; 2000 ft offset to left; and 2000 ft altitude	
	Typical number of pilot MCP knob inputs on PCA approach and landing
Longitudinal mode	
Flightpath angle	8 (1 per 25 sec)
Lateral-directional modes	
Bank-angle mode	50 (1 per 4 sec)
Heading mode	16 (1 per 12 sec)
Track-angle mode	8 (1 per 25 sec)
Loc only track angle	1 (1 per 200 sec)

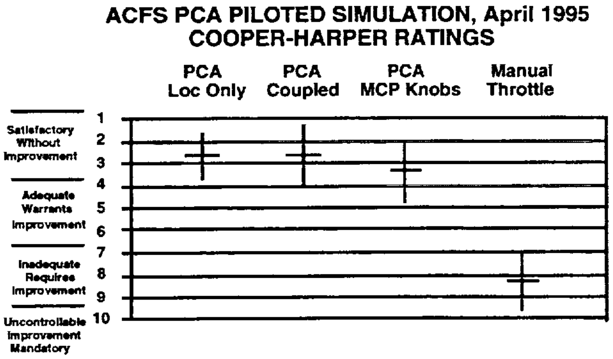


Figure 11. PCA pilot Cooper-Harper ratings. PCA coupled localizer-only mode and fully coupled mode were rated in the satisfactory range, PCA MCP track mode was rated in the adequate to satisfactory range, while PCA manual throttle mode was rated in the inadequate range.

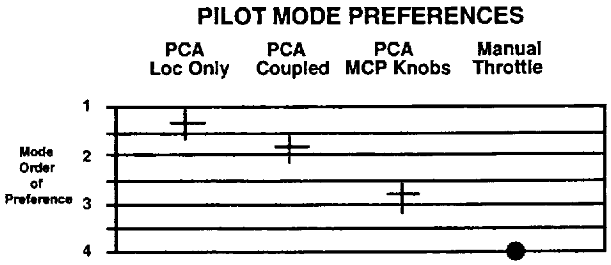


Figure 12. Pilot PCA mode preferences. Pilot mode order of preference was coupled localizer-only over the fully coupled, and then the MCP track knob mode. Coupled localizer-only mode allows the pilot to concentrate on glideslope control with the MCP vertical speed knob while the localizer is tracked automatically.

of any particular aircraft. In the case of the DC-10 accident (ref. 2) at Sioux City Iowa, the out of trim yaw moment due to airflow out of the hole in one side of the center engine nacelle due to the explosion, was approximately equal to a 3 deg rudder offset.

Time histories of typical PCA approaches are shown in figures 14 and 15 for comparison purposes.

In the event of a complete flight-control failure, a major consideration is the fact that the resulting trim airspeed is dependent on three factors: (1) failed stabilator position, (2) aircraft gross weight, and (3) aircraft cg position. Of major importance is the fact that the trimmed calibrated airspeed at time of flight-control failure will be close to the trimmed calibrated airspeed for all altitudes, including landing (App. E). Thus, if the failure occurs at cruise altitude and airspeed (for example, 270 kts calibrated), the pilot will be faced with a fairly high trimmed airspeed for approach and landing. If the failed stabilator has no backup, then trim airspeed is subject primarily to aircraft gross weight and cg position. The pilot then has the option, if available, to reduce the trimmed airspeed for landing by either dumping fuel to reduce gross weight or by moving the cg aft. In the case of the ACFS aircraft, trim airspeed could be reduced approximately 6 knots per 10,000 lb of fuel dumped, or 11 knots per 1 percent of aft cg movement.

6.4 PCA Full-Flight Envelope Test Conclusions

Pilot mean Cooper-Harper ratings were in the "satisfactory" range for the PCA coupled localizer-only mode (2.7) and the PCA fully coupled mode (2.8), and in the "adequate" range for the PCA MCP track knob mode (3.2). Pilot mode order of preference was PCA coupled localizer-only slightly over the PCA fully coupled mode, and PCA fully coupled mode slightly over the PCA MCP track knob mode.

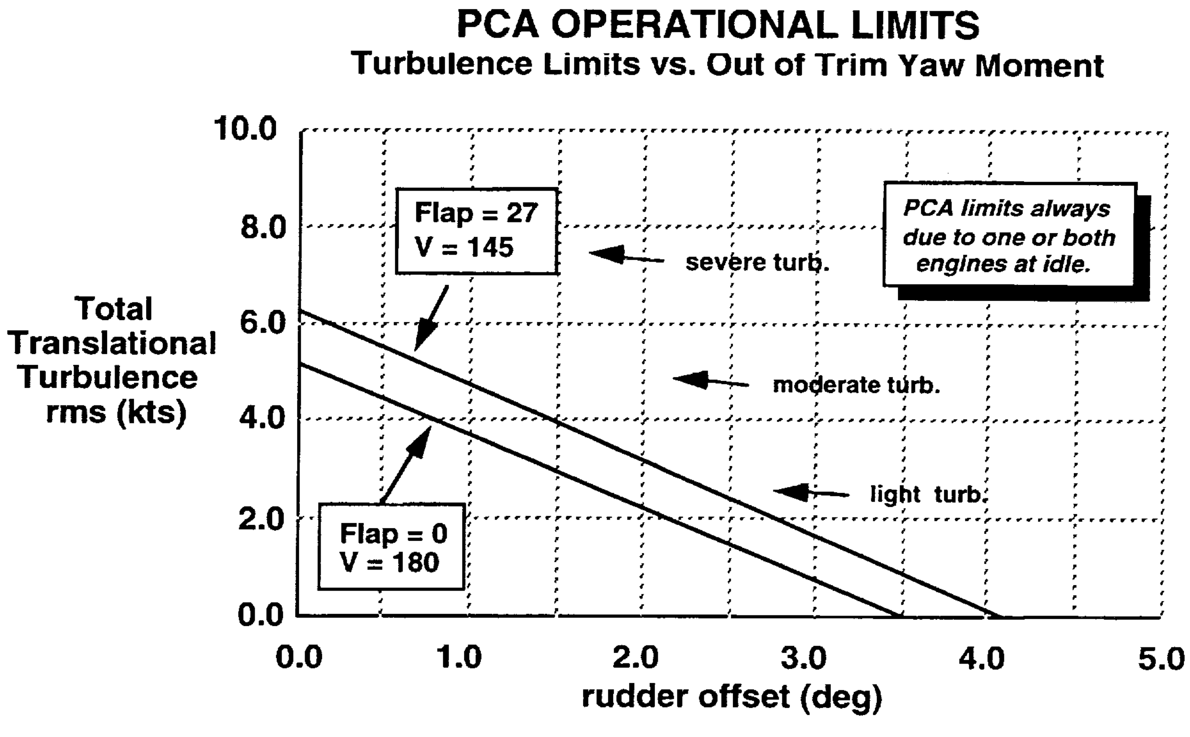


Figure 13. PCA operational limits. PCA control authority to out of tirm yaw moment was limited to approximatley 3 deg rudder offset due to one engine beginning to remain too long at the idle stop. Maximum values of rudder and aileron out of trim moments are very vehicle dependent, and would vary substantially with the number of engines and physical thrust moment arms of any particular aircraft. In the case of the DC-10 accident (ref. 2) at Sioux City, Iowa; the out of trim yaw moment due to airflow out of the hole in one side of the center engine nacelle due to the explosion, was approximately equal to a 3 deg rudder offset.

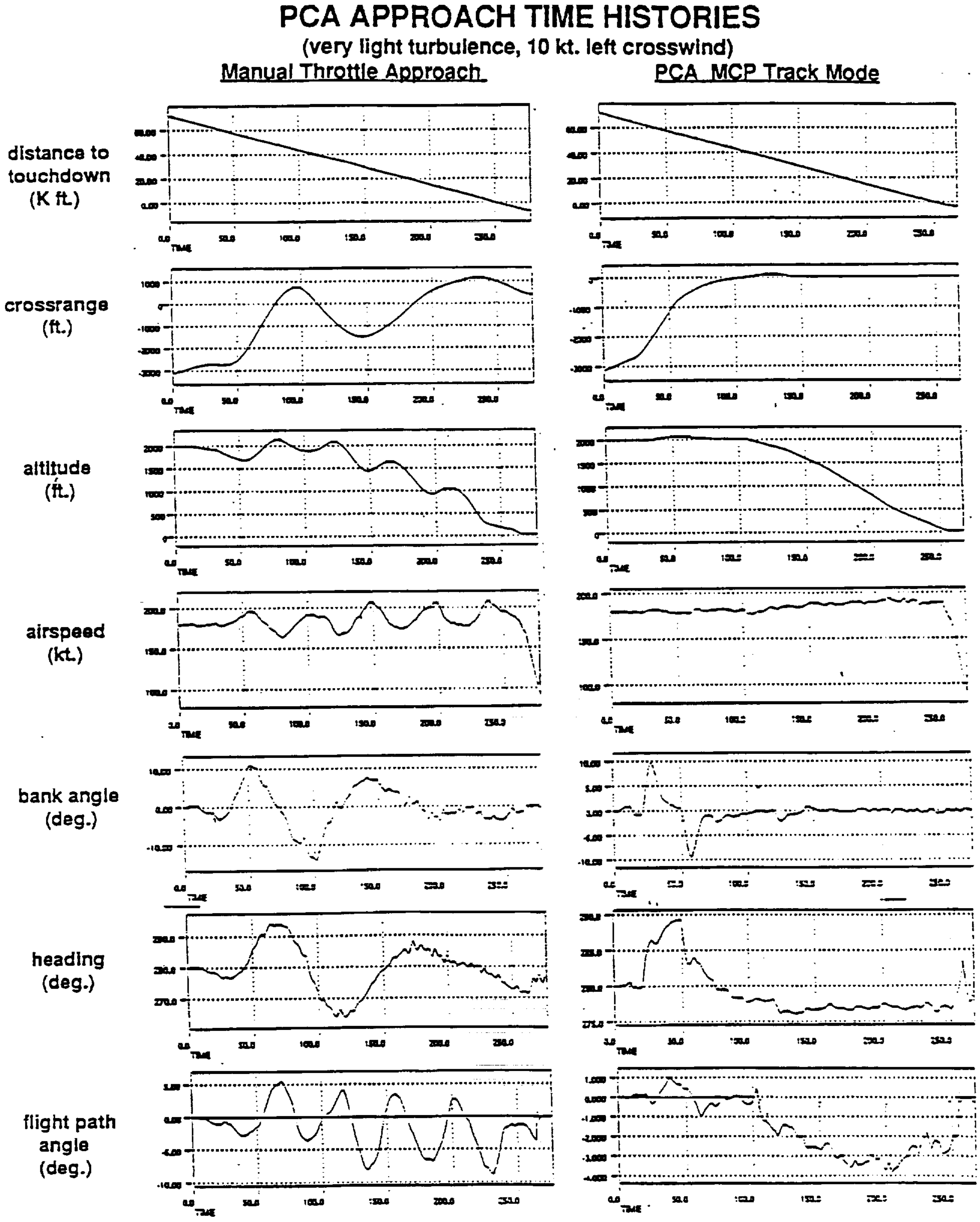


Figure 14. Manual throttle approach vs. PCA MCP track mode approach time histories. Phugoid damping was extremely difficult in the manual throttle mode. PCA MCP track mode control laws provided good damping.

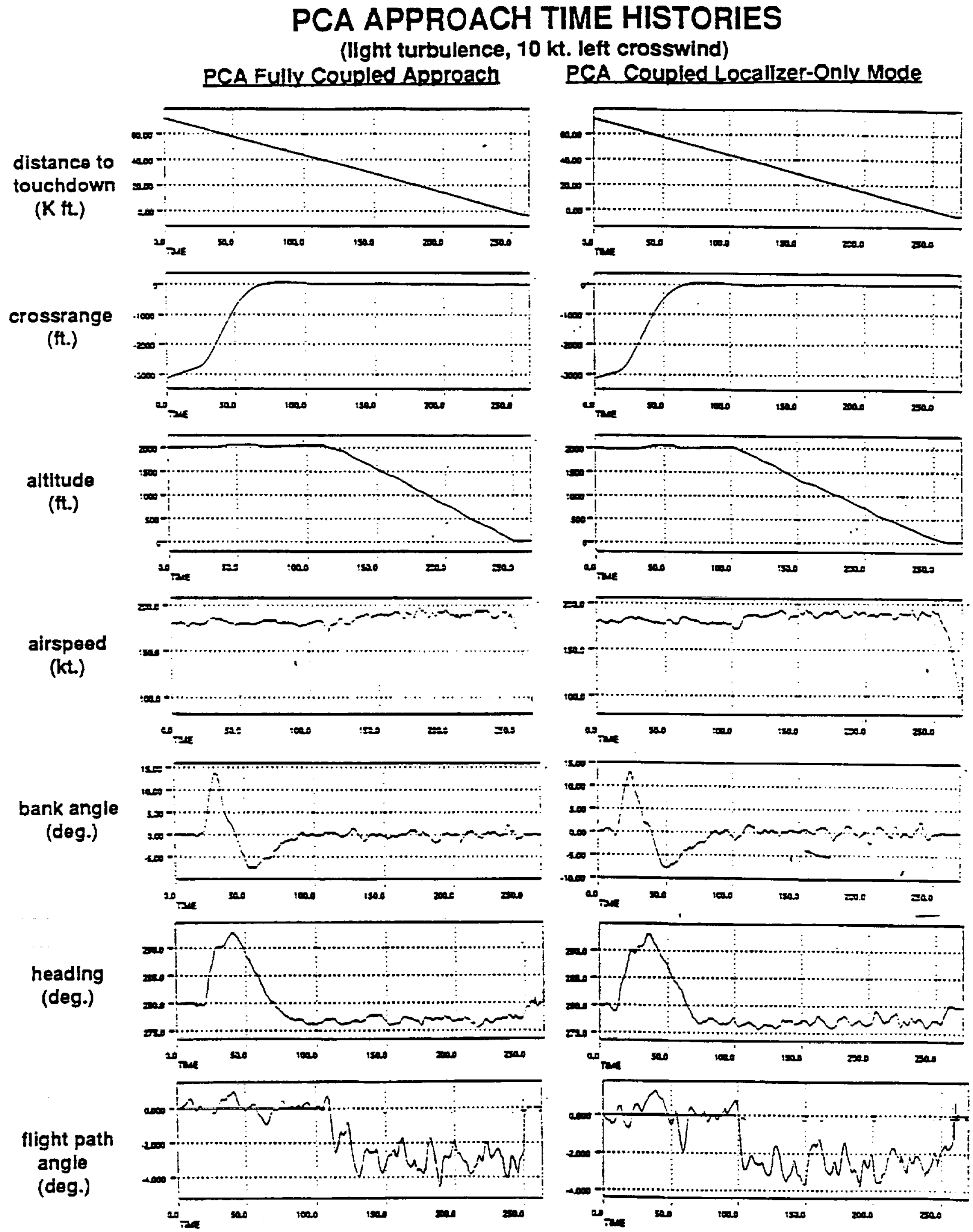


Figure 15. PCA coupled approach time histories. PCA coupled approach performance was acceptable up to moderate levels of turbulence. Increased levels of turbulence resulted in engines remaining too long and too often at idle thrust.

PCA workload in terms of total MCP knob inputs was significantly less for the coupled modes compared to the MCP track mode.

PCA approach and landing acceptable performance limit in turbulence with no out of trim moments was moderate turbulence (5 kts translational rms, 1.8 deg/sec rotational rms).

PCA approach and landing acceptable performance out of trim limits in no turbulence were a maximum of 3 deg rudder out of trim yaw moment and a maximum of 1.5 deg aileron out of trim roll moment. These maximum values of rudder and aileron out of trim moments are very vehicle dependent, and would vary substantially with the number of engines and physical thrust moment arms of any particular aircraft.

PCA performance was slower, but adequate at medium and cruise altitudes.

Aircraft trim airspeed could be reduced approximately 11 knots per 1 percent of aft cg movement, and approximately 6 knots per 10,000 lb of fuel dumped.

7 Summary of Conclusions

Industry Benefits Study

Eliminate catastrophic accidents due to loss of primary flight control. Save approximately $436M over the 30 year life cycle of a fleet of 300 jet transports (400K lb takeoff gross weight).

Operational Consideration

If a total primary flight-control failure occurs at cruise altitude and airspeed (for example, 270 kts calibrated), the pilot is faced with a fairly high trimmed airspeed for approach and landing. If the failed stabilator has no backup, then trim airspeed is determined primarily by aircraft gross weight and cg position. The pilot then has the option, if available, to reduce the trimmed airspeed for landing by either dumping fuel to reduce gross weight or by moving the cg aft.

June 1992, PCA Pilot Interface Tests

Pilots preferred the MCP thumbwheel controller to the sidestick controller for PCA approach and landing.

Aug. 1994, PCA Mode/Display Tests

Pilots rated the bank mode and heading mode about equal (Cooper-Harpers both about 3.8), but preferred the heading mode over the bank mode. Additional displays for PCA were not helpful in flying the approach and landing.

Apr. 1995, Full-Flight Envelope Tests

Pilot mean Cooper-Harper ratings were in the "satisfactory" range for the PCA coupled localizer only mode (2.7) and the PCA fully coupled node (2.8), and in the "adequate" range for the PCA MCP track knob mode (3.2). Pilot mode order of preference was PCA coupled localizer only slightly over the PCA fully coupled mode slightly over the PCA MCP track knob mode.

PCA workload in terms of total MCP knob inputs was significantly less for the Coupled Modes compared to the MCP Track Mode.

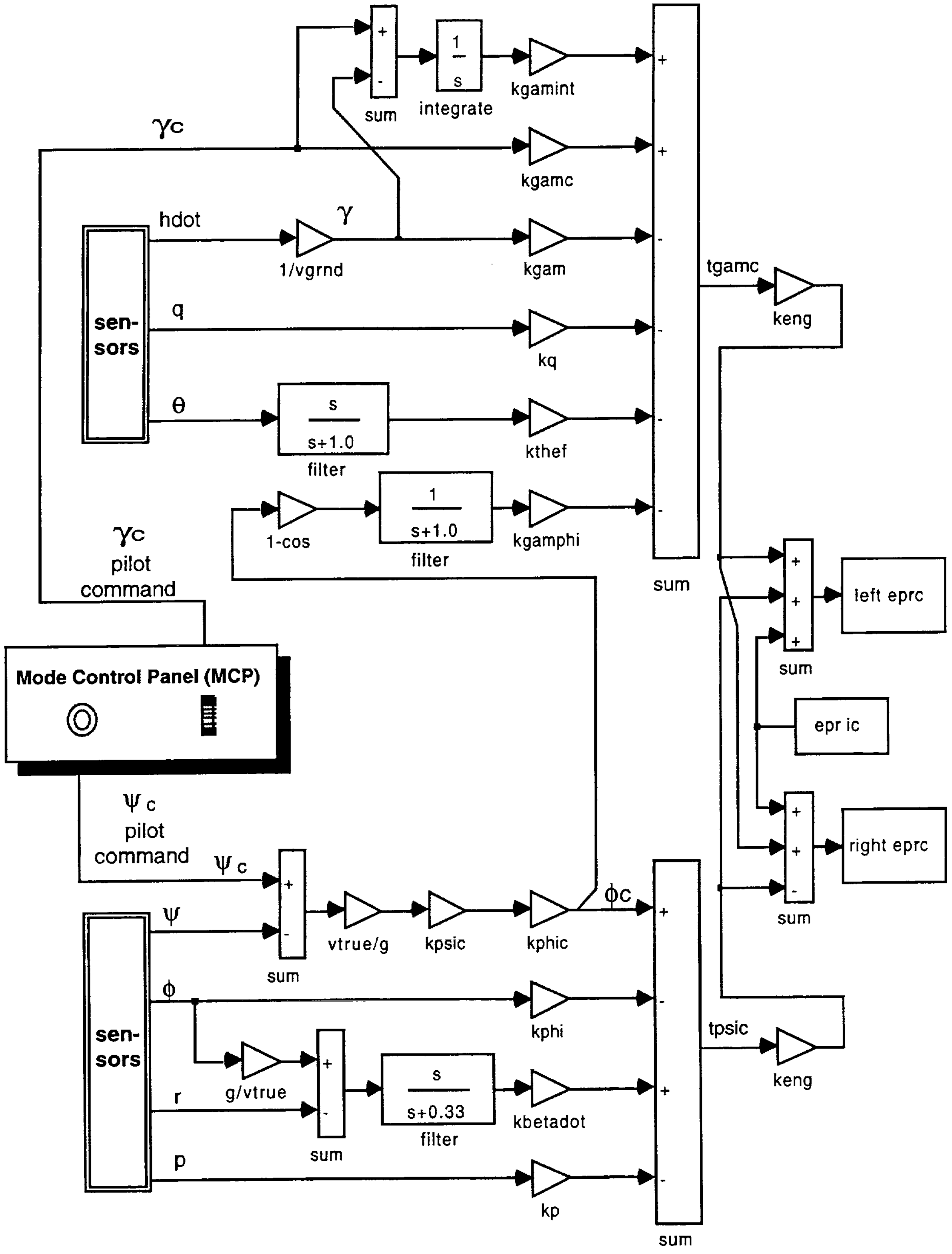
PCA approach and landing acceptable performance limit in turbulence with no out of trim moments was moderate turbulence (5 kts translational rms, 1.8 deg/sec rotational rms).

PCA approach and landing acceptable performance out of trim limits were a maximum of 3 deg rudder out of trim yaw moment and a maximum of 1.5 deg aileron out of trim roll moment. Maximum values of rudder and aileron out of trim moments are very vehicle dependent, and would vary substantially with the number of engines and physical thrust moment arms of any particular aircraft.

Aircraft trim airspeed could be reduced approximately 11 knots per 1 percent of aft cg movement, or approximately 6 knots per 10,000 lb of fuel dumped.

PCA performance was slower, but adequate at medium and cruise altitudes.

Appendix A – PCA Control Law Block Diagram



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Appendix B – Longitudinal PCA Control Laws

eprgamc = delta exhaust pressure ratio (EPR) commanded/engine for flightpath angle control

tgamc = delta thrust commanded/engine (lb/eng) for flightpath angle control

γ_c = commanded flightpath angle (deg)

(pilot input from MCP knob in MCP mode, calculated in ILS Coupled mode)

ϕ_c = commanded bank angle (deg)

(pilot input from MCP knob in Bank mode, calculated in MCP Track mode)

Longitudinal Control Law Structure

tgamc = kgamref*[(kgamc*γ_c – kgam*γ) + kgamint*γ_{int} – kq*q – kthef*θ_f + kgamphi*$\gamma\phi$]

eprgamc = tgamc*keng

γ_{int} = $(\gamma_c - \gamma)/s$, absolute value $\gamma_{int} < 40$

θ_f = [s/(s + 1/tauthef)]*θ

$\gamma\phi$ = $[1/(s + 1)][1 - \cos(\phi_c)]$

Longitudinal Control Law Gains

keng = 1/42000

kgamref = 0.5*W*tgain*keng/57.3

kgamc = 2.60

kgam = 2.60

kgamint = 0.15

kq = 4.00

kthef = 8.00

tauthef = 1.00

W = a/c gross weight (lb)

Gain Scheduling (tgain, kgamc, kgamphi) with Altitude and Airspeed

h = altitude (ft)

vcal = calibrated airspeed (fps)

tgain = 1.0000 + 0.43123*h1 – 0.0000525*h2 + 0.0000423*h3

h1 = h/1000, h2 = h1*h1, h3 = h1*h2

if h > 3000 ft

kgamc = 2.6 – 0.11*(h1 – 3)

if h > 11000 ft

kgamc = 1.8*(1 – hrat*hrat), hrat = h/43000

kgamphi = 45*(vrat*vrat), vrat = 270/vcal

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Appendix C – Lateral-Directional PCA Control Laws

eprpsic = delta EPR commanded/engine for psi track angle control

tpsic = delta thrust commanded/engine (lb/eng) for psi track angle control

ϕ_c = commanded bank angle, deg (pilot input from MCP knob in bank mode, or calculated when in track mode)

ψ_c = commanded track angle, deg (pilot input from MCP knob in track mode, or calcuated when in loc coupled mode)

Lateral-Directional Control Law Structure

tpsic = kphiref*[(kphic*ϕ_c – kgam*f) – kp*p – betastar]

EPRpsic = tpsic*keng

betastar = [kbetadot*s/(s + 1/taubdot)][g*f/vtrue – r]

ϕ_c = kpsic*(vtrue/g)*[ψ_c – ψtrk] when in Track mode

Lateral-Directional Control Law Gains

keng = 1/42000

kphiref = 0.0175*tgainphi

kphic = 1.53

kphi = 1.70 + 0.1*flap/27

kp = 2.5

kbetadot = –4.00

taubdot = 3.00

taupsi = 7.00

kpsic = 1/taupsi

Gain Scheduling (tgainphi, kpsic) with Altitude

h = altitude (ft)

h1 = h/1000, h2 = h1*h1, h3 = h1*h2

tgain = 1.0000 + 0.43123*h1 – 0.0000525*h2 + 0.0000423*h3

tgainphi = tgain*(1 – 0.72*h/43000)

kpsic = 1/taupsi – 0.072*h/43000

Appendix D – PCA Ils Coupled Control Laws

Glideslope Capture and Track Mode

gsdev = ILS Glideslope deviation (deg)

gsref = ILS Glideslope (deg)

- Glideslope Capture

if coupled approach is armed, and if glideslope deviation signal is active:

then gamtest = kgamc*[gsref + kgs*gsdev] – kgam*γ

if gamtest < 0:

then initiate glideslope track mode

- Glideslope Track Mode

tgamc = same as in PCA MCP mode, except that gc is now calculated as follows:

γ_c = kgamc*[gsref – kgs*gsdev] – kgam*γ

- Glideslope Track Gains

kgamc = $2.8 + 0.4*(287/\text{vtrue})^2$

kgamint = 0.04

kgs = (xnavgs – 600)/(taugs*vtrue)

taugs = 17.9

xnavgs = x dist. to gs touchdown (ft)

vtrue = true airspeed (fps)

Localizer Capture and Track Mode

locdev = ILS Localizer deviation (deg)

psiref = Localizer ground track (deg)

- Localizer Capure

if localizer approach is armed, and if localizer deviation signal is active:

then phitest = psiref + kloc*locdev – ψtrk

if sign(ynav)*phitest > 0: then initiate localizer track mode

- Localizer Track Mode

tpsic = same as in PCA MCP mode, except that yc is now calculated as follows:

ψ_c = psiref + kloc*locdev + kpsiint*ψ_{int}

- Localizer Track Gains

kloc = xnavloc/(tauloc*vtrue)

tauloc = 16.4

xnavloc = x dist. to loc antenna (ft)

vtrue = true airspeed (fps)

kpsiint = 0.025*220/vtrue

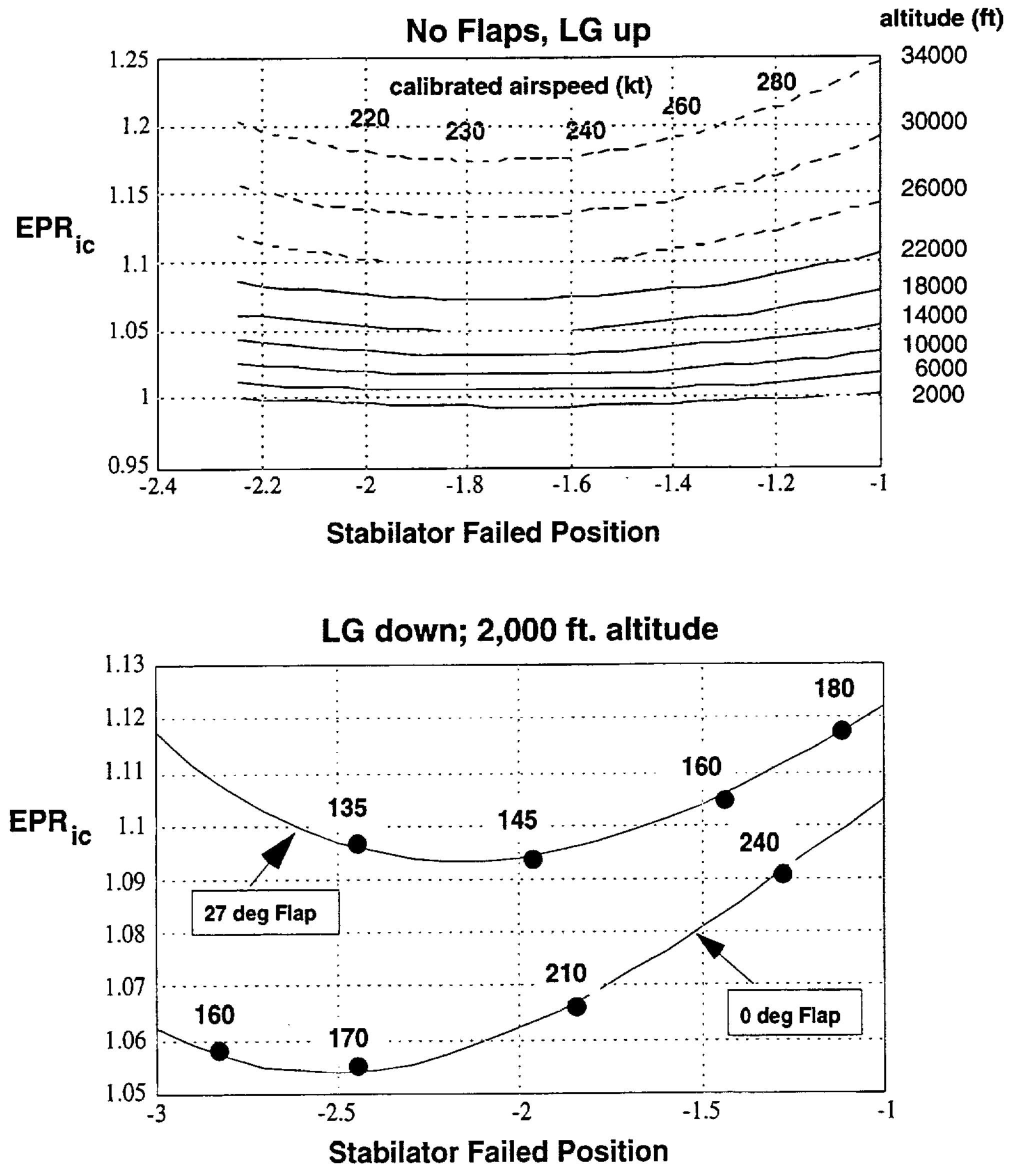
Autoflare

if altitude above runway < 120 ft: $\gamma_c = -2.2 - 4.6*304/\text{vtrue}$ ($-2.2 < \gamma_c < -1.5$ deg)

If altitude above runway < 60 ft: $\phi_c = 0$ deg

Appendix E – PCA EPR Initial Conditions

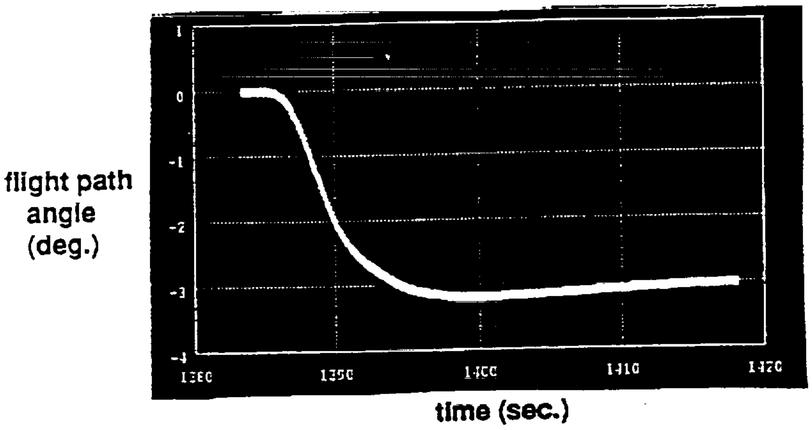
The PCA control law initial EPR trim point is determined from an EPR trimmap rather than simply using the EPR values at PCA engage. This initialization method is used because the pilot, in an attempt to fly the aircraft on manual throttles, could possibly have moved the engines far from a desired straight and level trim condition prior to PCA engage.

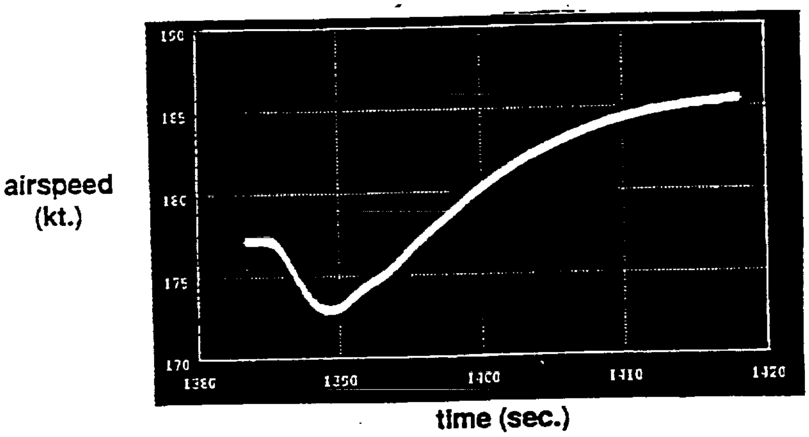


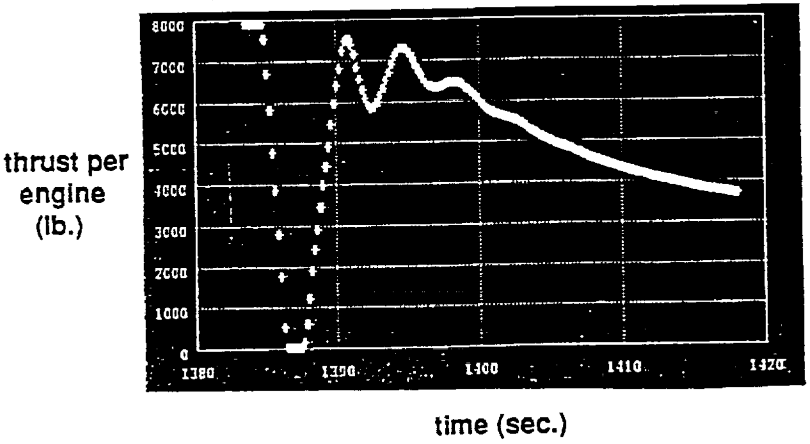
Trimmed EPRic vs Stabilator Failed Position

Gross Weight = 180,000 lbs, cg = 27.8%

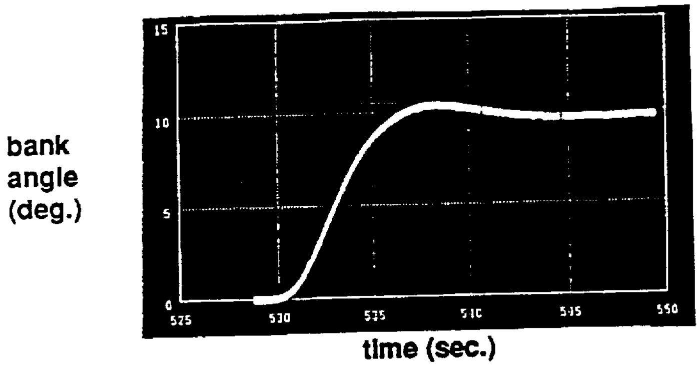
Appendix F – PCA Step Responses to –3 Degree Flightpath Angle Step Command (no flaps; lg down; 2000 ft altitude)

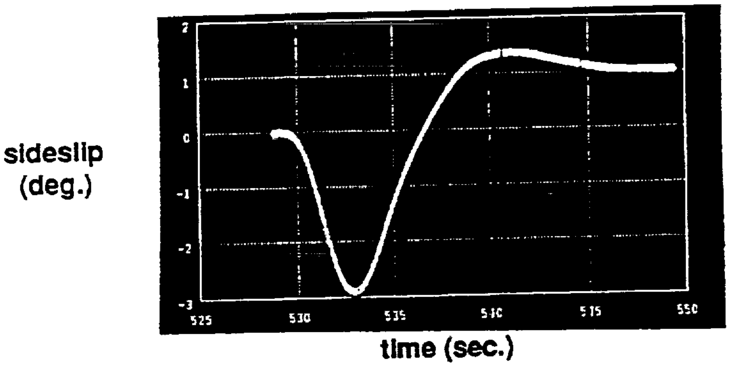


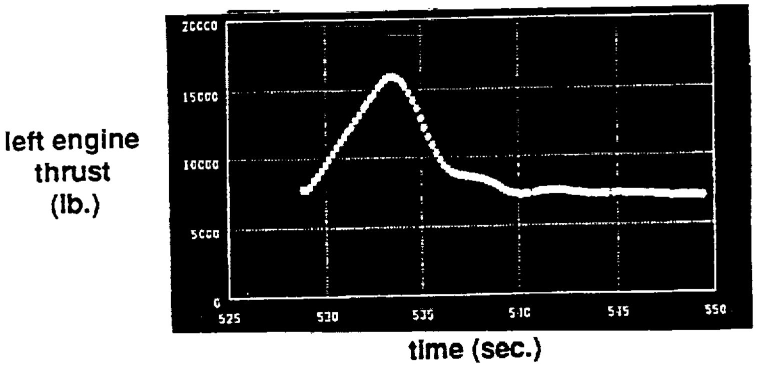


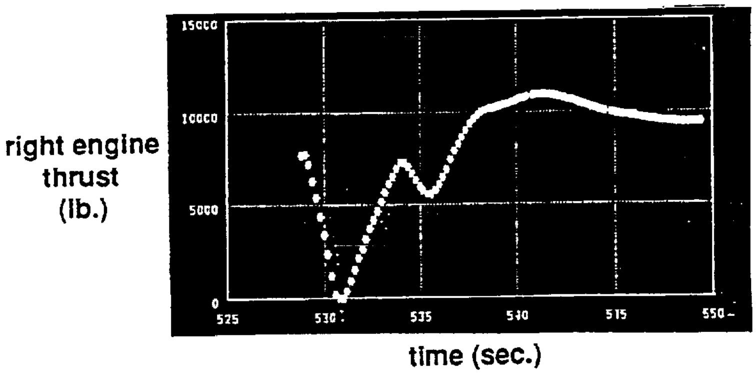


Appendix G – PCA Responses to 10 Degree Bank Angle Step Command (no flaps; lg down; 2000 ft altitude)









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13. ABSTRACT ***(Maximum 200 words)***

Failures of aircraft primary flight-control systems to aircraft during flight have led to catastrophic accidents with subsequent loss of lives (e.g., DC-10 crash, B-747 crash, C-5 crash, B-52 crash, and others). Dryden Flight Research Center (DFRC) investigated the use of engine thrust for emergency flight control of several airplanes, including the B-720, Lear 24, F-15, C-402, and B-747.

A series of three piloted simulation tests have been conducted at Ames Research Center to investigate propulsion control for safely landing a medium size jet transport which has experienced a total primary flight-control failure. The first series of tests was completed in July 1992 and defined the best interface for the pilot commands to drive the engines. The second series of tests was completed in August 1994 and investigated propulsion controlled aircraft (PCA) display requirements and various command modes. The third series of tests was completed in May 1995 and investigated PCA full-flight envelope capabilities.

This report describes the concept of a PCA, discusses pilot controls, displays, and procedures; and presents the results of piloted simulation evaluations of the concept by a cross-section of air transport pilots.

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