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Flight-Test Results of Propulsion-Only Emergency Control System on MD-11 Airplane

John J. Burken* and Frank W. Burcham Jr.†
NASA Dryden Flight Research Center, Edwards, California 93523-0273

A large, civilian, multiengine transport MD-11 airplane control system was recently modified to perform as an emergency backup controller using engine thrust only. The emergency backup system, referred to as the propulsion-controlled aircraft (PCA) system, would be used if a major primary flight control system fails. To allow for longitudinal- and lateral-directional control, the PCA system requires at least two engines and is implemented through software modifications. A flight-test program was conducted to evaluate the PCA system high-altitude flying characteristics and to demonstrate its capacity to perform safe landings. The cruise flight conditions, several low approaches, and four landings without any aerodynamic flight control surface movement were demonstrated; however, only one landing is presented. Results that show satisfactory performance of the PCA system in the longitudinal axis are presented. Test results indicate that the lateral-directional axis of the system performed well at high altitude but was sluggish and prone to thermal upsets during landing approaches. Flight-test experiences and test techniques are also discussed, with emphasis on the lateral-directional axis because of the difficulties encountered in flight test.

Nomenclature

$C_{l\beta}$ = roll caused by dihedral term
H = altitude, ft
K_{lat} = lateral feedforward gain, lb/deg
K_{lc} = heading error feedforward gain, deg
K_{phid} = bank angle rate feedback gain, deg/s
K_{pr} = turn coordination feedback gain, deg/s
K_{vm} = tail engine gain, lbf
p = roll rate, deg/s
q = pitch rate, deg/s
r = yaw rate, deg/s
s = Laplace transform
t = time, s
V = airspeed, kn
v_{err} = velocity error, kn
W = takeoff gross weight, lb
α = angle of attack, deg
γ = flight-path angle, deg
γ_{cmd} = flight-path-angle command, deg
γ_{err} = flight-path-angle error, deg
ζ = damping ratio
θ = pitch attitude angle, deg
$\dot{\theta}$ = pitch attitude angle rate, deg/s
λ = eigenvalues
λ_{cl} = closed-loop propulsion-controlled aircraft eigenvalues
Φ = bank angle, deg
Φ_{cmd} = bank angle command, deg
$\dot{\phi}$ = bank angle rate, deg/s
Ψ = heading angle, deg
Ψ_{cmd} = heading angle command, deg
Ψ_{step} = heading step
ω = frequency, rad/s

Introduction

AIRCRAFT flight control systems are designed with extensive redundancy to ensure a low probability of failure. During recent years, however, several aircraft have experienced major flight control system failures, leaving engine thrust as the only usable control effector. In some of these emergency situations, the engines were used open loop to maintain control of the flight-path and bank angle of the airplane. Perhaps the best known use of manual-throttles-only control occurred in July 1989 on United Airlines flight 232. At cruise conditions, a DC-10 (McDonnell–Douglas, Long Beach, California) suffered an uncontained tail engine failure that caused the loss of all hydraulics. After the failure, the airplane trimmed at approximately 210 kn with a significant yaw angle because of damage to the center engine nacelle. Under extremely difficult circumstances, the crew used wing engine throttles for control and was able to crash land at the Sioux City, Iowa, airport, and over one-half of the people onboard were saved.[1] In the majority of cases surveyed, major flight control system failures (because of loss of all hydraulic power) have resulted in crashes, with a total of over 1200 fatalities.[2] The aircraft involved in these crashes were a B-747, a DC-10, a C-5A, and a B-52.

The challenge was to create a sufficient degree of control through thrust modulation to control and safely land an airplane with severely damaged or inoperative control surfaces. The objective of the propulsion-controlled aircraft (PCA) emergency backup system is to command the engines to maneuver the airplane to a safe landing without moving the normal aerodynamic control surfaces. NASA Dryden Flight Research Center has conceived, developed, and tested closed-loop, propulsion-controlled aircraft systems using only engine thrust. The PCA system was first flown on an F-15 airplane and more recently on the MD-11 airplane. This paper discusses the MD-11 PCA system in detail. This system requires that the airplane have at least two engines, preferably two wing engines, functioning.

To investigate the PCA concept, NASA performed analytical studies and conducted several flight-test programs. Gross control can be obtained by using the throttles in the open-loop sense (manual throttles only), but making a safe runway landing is exceedingly difficult because of low phugoid and Dutch roll damping coupled with the high pilot workload near the ground.[2–6] To improve performance and reduce the pilot workload, the PCA program was developed.

Test Vehicle Description

Figure 1 shows the MD-11 airplane, a large, long-range, three-engine, wide-body transport. This airplane is 202 ft long and has a wing span of 170 ft and a maximum takeoff gross weight W of 618,000 lb.

Flight Control Systems

The MD-11 airplane is equipped with a conventional mechanical control system. Digital flight control computers (FCCs) provide

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*Aerospace Engineer, Controls and Dynamics Branch.
†Aerospace Engineer, Propulsion Branch Chief. Associate Fellow AIAA.

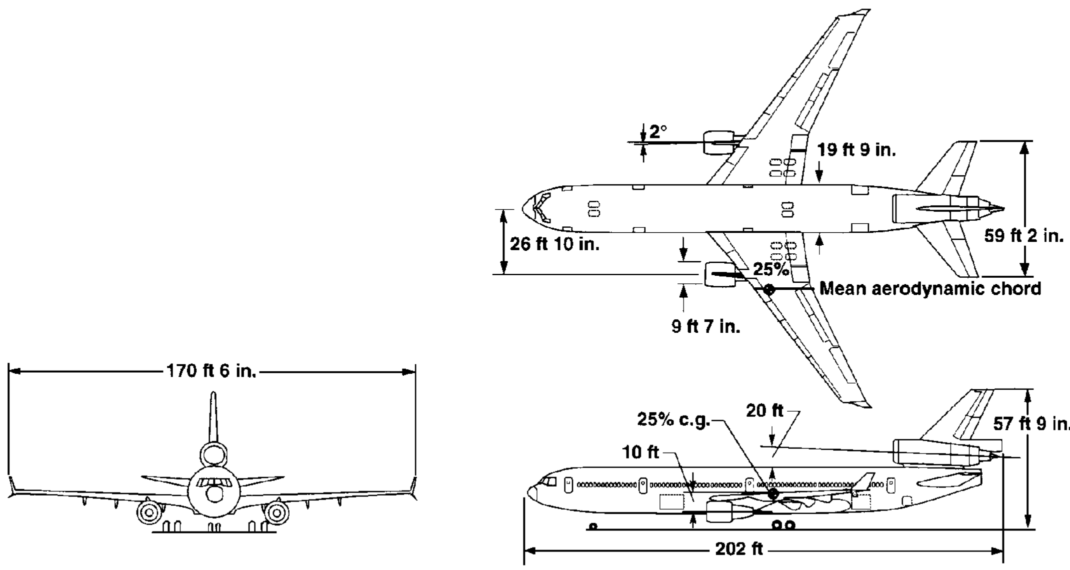

Fig. 1 MD-11 airplane.

autopilot, autothrottle, navigator, and longitudinal- and lateral-directional damping. The autopilot control includes a thumbwheel for commanding flight-path angle γ_{cmd} and a heading knob for commanding the desired heading Ψ_{cmd}.

Engines

Three PW4460 (Pratt and Whitney, Palm Beach, Florida) high-bypass-ratio turbofan engines in the 60,000-lb thrust class power the MD-11 airplane. Two engines are mounted in underwing pods. The third engine is located at the base of the vertical stabilizer. Each engine has a full-authority digital engine control (FADEC) system in which the software was modified for the PCA program. The modification allows for an increased range of engine pressure ratio (EPR) commands to be sent from the FCC. The range was increased from 5% of the trimmed EPR to approximately 0.9–1.50 EPR. The wing engines are 121 in. below the nominal vertical c.g., and the tail engine is 240 in. above the vertical c.g., with its thrust axis inclined 2.5 deg (nozzle pointing down).

As is typical for high-bypass turbofan engines, thrust response at low-power settings is initially slow. Once thrust levels exceed 20%, the engine response improves dramatically. An approach idle setting when the flaps are extended beyond 27 deg maintains the idle revolutions per minute at a sufficiently high level so that the 8 s from idle to full power requirement can be met. A cruise idle or minimum idle setting can require as much as 12 s to go from idle to full power.[2] If PCA were engaged with minimum idle setting, a pilot-induced oscillation could occur because of the large time lags; therefore, another modification to the FADEC system included setting the approach idle when the PCA system was engaged.

PCA Control System Design

The design of the longitudinal- and lateral-directional control laws assumes that the normal control surfaces are not functioning and are not in a hardover position. Given the limited engine bandwidth, PCA control requires a relatively stable open-loop plant or slightly unstable poles. As a transport airplane, the MD-11 easily meets this criterion. The phugoid mode was slightly unstable for the worst cases investigated, and the Dutch roll mode was lightly damped. The MD-11 engine bandwidth is limited to approximately 2 rad/s. The PCA system uses engine thrust modulation driven by a closed-loop controller to increase the damping and allow the pilot to land safely. An instrument landing system (ILS)-coupled mode was designed and flight tested, with results presented in Refs. 2 and 7.

The initial PCA system was designed to have minimal impact on existing hardware and software. The resulting system only required software changes. The flight control panel was used for the pilot input paths. The heading control knob was used for the lateral-directional controller, and the flight-path-angle thumbwheel was used for the longitudinal axis. Collective thrust commands to the wing engines provided pitch or longitudinal control, and differential thrust commands provided lateral-directional control.

Large civil transports have at least two engines; therefore, the design philosophy was to make the MD-11 PCA independent of the control system and to work primarily with the two wing engines. If the aircraft has more engines, however, the control engineer should modify the design to take advantage of this feature, assuming the engines are operational. If the aircraft has four engines, such as the B-747, and one engine has failed, the remaining engine on that side can be used in conjunction with the remaining operational engines on the other side for control. In the case of the MD-11 with three engines, we had the option to use the tail engine by changing the tail control logic to on or off.[7] The Sioux City, Iowa, crash was caused by tail engine failure.

Longitudinal Control

The longitudinal control law commands γ and augments phugoid damping (Fig. 2). The feedback signals selected were pitch attitude θ, pitch attitude rate $\dot{\theta}$, velocity error v_{err}, and flight-path angle. These signals were already available to the primary stability augmentation system. Flight-path-angle error γ_{err} is passed through a proportional-plus-limited-integral compensator to maintain an acceptable tracking task for the pilots. Washed-out pitch attitude and attitude rate are summed after the integrator for improved damping. The PCA system was primarily designed for the generic two-engine aircraft. However, the triengine MD-11 PCA system had the option to take advantage of the third engine control effectiveness. As shown in Fig. 2, the tail engine command had a negative washout filter with a time constant of 4 s. To control γ more precisely, the tail engine command was designed to initially go the opposite direction from the wing engines command because the tail engine is above the vertical c.g. ($\approx +20$ ft) and the wing engines are below the vertical c.g. (≈ -10 ft). Therefore, as the wing engine spooled up to track a positive γ_{cmd}, the tail engine would reduce thrust. Another tail engine PCA option was the speed control mode. The MD-11 trim speed could be reduced by as much as 40 kn by reducing the tail engine thrust. Reference 7 gives detailed information regarding the longitudinal controller.

Trim Speed Control

Once the normal 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. Lowering flaps and stabilizer trim are ideal for reducing trim speed, but they require hydraulic power to change the position of the surface. However, assuming total hydraulic power loss, speed can be changed in several ways for acceptable landing speeds. Methods include moving the c.g. aft, reducing weight, and lowering the landing gear. In the case of the low- and high-mounted engine airplanes (such as the MD-11, mentioned earlier[2,7]), the trim speed can be reduced by increasing the thrust of the low-mounted engines and decreasing the thrust of the high-mounted engines. See Ref. 2 for more details on trim speed issues covered in the flight test.

Lateral-Directional Control

Lateral-directional control is obtained by using differential throttle inputs to generate yaw, resulting in roll caused by the dihedral term $C_{l\beta}$. The lateral-directional control law tracks heading angle commands Ψ_{cmd} (Fig. 3). The feedback signals selected to improve the damping and closed-loop performance consist of bank angle Φ, bank angle rate $\dot{\phi}$, yaw rate r, and heading angle Ψ. Bank angle rate was included for Dutch roll damping, and yaw rate and bank angle were included for turn coordination. The resulting output from the PCA lateral-directional controller is then used to modulate the thrust of each engine.

Linear Analysis

In the longitudinal- and lateral-directional axes, classical methods were initially used to design the controllers. The classical single input/single output methods included root locus and frequency analysis methods, such as Bode or Nyquist techniques. Classical linear design was used for acceptable rise time and damping characteristics. Later in the flight-test phase, a nonlinear time-domain method was employed for rapid control gain adjustments.[8] This design was also evaluated in a nonlinear piloted simulation, where the gains were adjusted to increase damping or performance.

From linear analysis, the longitudinal closed-loop PCA eigenvalues λ_{cl} are shown in Table 1 as a representative case, along with the damping ratio. Flight conditions were $H = 12{,}000$ ft, $V = 175$ kn, flaps at 28 deg, slats extended, c.g. = 23% mean aerodynamic chord (MAC), $W = 360{,}000$ lb, and gear down. The phugoid damping increased from barely stable to highly damped (0.657) when the PCA system closed the loop. The stability margins for flight-path loop

Table 1 MD-11 airplane longitudinal PCA closed-loop eigenvalues

	Closed loop	
	Eigenvalue	Damping ratio
Phugoid	$-0.168 \pm 0.193j$	0.657
Short period	$-0.440 \pm 1.13j$	0.368
Engine	-2.15	1.0
Control and integrator	-0.069	1.0
Control and washout	-0.375	1.0

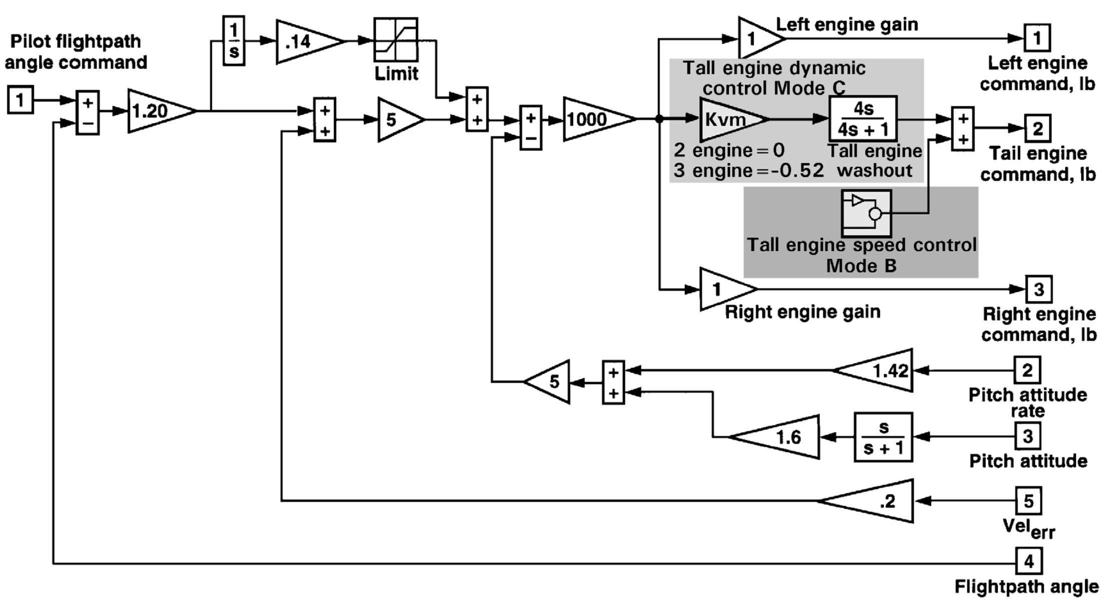

Fig. 2 Longitudinal MD-11 PCA control law, two- and three-engine modes.

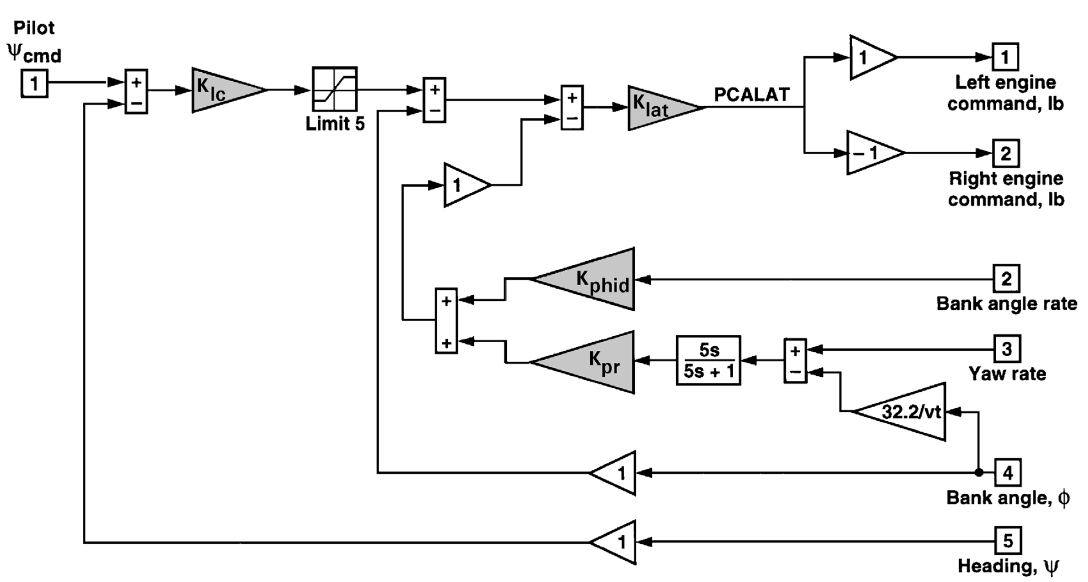

Fig. 3 Lateral-directional control law; note that shaded boxes (K_{lc}, K_{lat}, K_{pr}, K_{phid}) were modified gains during flight test.

are gain margin equal to 13 dB at $\omega = 1.02$ rad/s and phase margin equal to 47 deg at $\omega = 0.28$ rad/s. These margins are acceptable for the stability criteria of 6 dB and 45 deg.

From linear analysis, Table 2 lists the lateral-directional closed-loop PCA eigenvalues and damping ratios. Flight conditions were $H = 12{,}000$ ft, $V = 175$ kn, flaps at 28 deg, slats extended, c.g. = 23% MAC, $W = 360{,}000$ lb, gear down, and default gains. The Dutch roll damping was 0.61 with the closed-loop system, allowing for good airplane response characteristics. In addition, the stability margins for the heading angle loop are gain margin equal to 26 dB at $\omega = 1.47$ rad/s and phase margin equal to 69 deg at $\omega = 0.43$ rad/s. The closed-loop analysis is for the default gains used in the initial flight-test phase; however, the sluggish response of the airplane required a different set of gains to improve the roll rate.

Table 2 MD-11 lateral-directional PCA closed-loop eigenvalues

	Default closed loop	
	Eigenvalue	Damping ratio
Dutch roll	$-0.291 \pm 0.379j$	0.61
Spiral mode	$-0.134 + 0.085j$	0.85
Rolling mode	$-0.134 - 0.085j$	0.85
Engine	$-0.970 \pm 1.15j$	0.64
Control and washout	-0.350	1.0

Simulation

Flight control system design and analysis for aircraft rely on mathematical models of the vehicle dynamics. These models are brought together to form a linear or nonlinear simulation for design and evaluation.

For linear analysis and simulation, the engines were modeled as a first-order Laplace transform:

$$\text{eng}(s) = \frac{1}{0.5s + 1} \tag{1}$$

with a rate limit of one-half the engine thrust output in pounds per second:

$$\text{eng}_{\text{rate}} = \text{trim}_{\text{thrust}/2} \tag{2}$$

Evaluation of this simple model is shown in the Results and Discussion section through time history matching of flight and simulation aircraft angular position and rates.

Flight-Test Maneuvers

A series of evaluation maneuvers were flown at a condition of 12,000 ft, 175V, gear down, flaps extended to 28 deg, slats extended, c.g. at 23% MAC, and 360,000 lb. The pilot stabilized the airplane at this flight condition with the PCA system turned on and completed a series of step inputs. During PCA flight-test operations, the

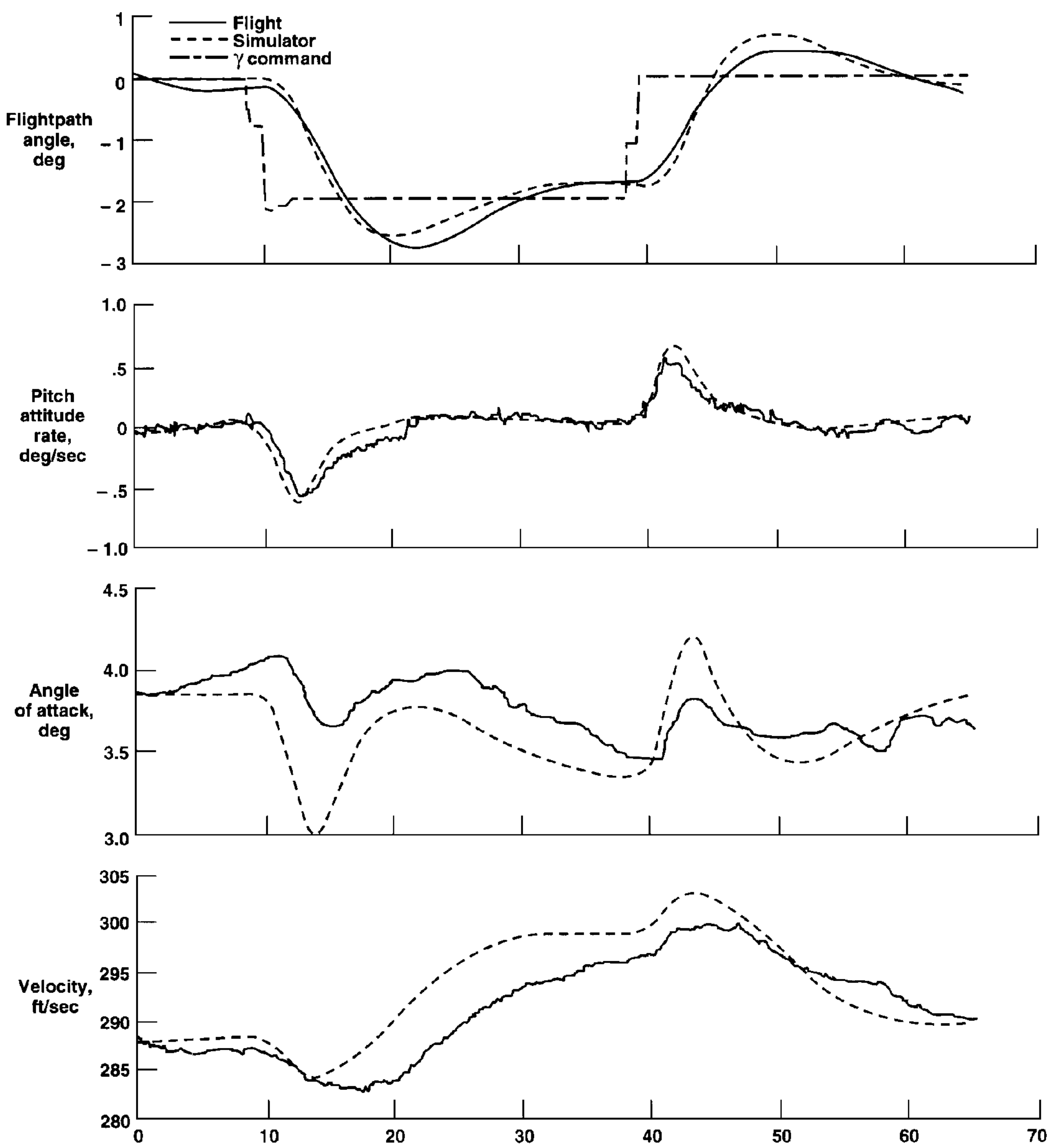

Fig. 4 Comparison of flight and linear simulation flight-path-angle step response; two-engine PCA mode for γ control.

hydraulic system was powered with the control surfaces fixed. The PCA system incorporated a safety disengage capability, which was accomplished by the pilot through moving the throttle lever or by pressing a cockpit FCC switch. These features provided pilots with normal throttle and conventional control surface response if needed.

To increase confidence in the system, low approaches were performed in a graduated series of decreasing altitudes until a landing was accomplished. Note that the flaps were set at 28 deg (takeoff flap position) to obtain low landing speeds. Other flight conditions were flown, such as 0.0-deg flaps and a range of c.g. positions (23–31% MAC), altitudes, and speeds.[2] Low approaches to 50 ft above ground were flown with 0.0-deg flaps, gear down, and an airspeed of approximately 195 kn. These cases were not allowed to touch down because of programmatic decisions. Although the 0.0-deg-flap approach speeds would have been pushing the upper limitations of a normal MD-11 landing (204-kn tire speed), during an emergency these conditions would be acceptable. The PCA flying qualities with the flaps at 0.0 deg were well behaved. No noticeable stability or performance degradation occurred.

There were 19 PCA flights on the MD-11, with a total of 4 PCA landings accomplished; 2 landings by the pilot and 2 with the ILS-coupled system. The operating envelope of the PCA system tested during these flights ranged from an altitude of 35,000 ft to sea level. The PCA system was demonstrated to 16 pilots and several observers representing airlines, the U.S. Air Force, the U.S. Navy, industry, and the Federal Aviation Agency. For the purpose of brevity, only one PCA landing is shown in this report (see Ref. 2 for more details).

Results and Discussion

This section describes the linear simulation to flight result comparison for the longitudinal- and lateral-directional axes. In addition, results are presented for the improved lateral-directional controller and one MD-11 PCA landing.

Comparison of Simulation to Flight Evaluation

Figure 4 shows a longitudinal axis comparison of flight and linear simulator results for a series of flight-path-angle step inputs at a flight condition of 175 kn, 12,000 ft, 28-deg flaps, and gear down for the two-engine PCA mode. There is an overshoot of the response compared to command of approximately 30% for both the simulator and flight-test results. This overshoot did not concern the pilots even at low altitudes. In general, the linear model represents the flight dynamics reasonably well and is adequate for control design. Reference 7 provides additional information regarding the different longitudinal modes flown, such as the speed control mode and the three-engine γ_{cmd} mode.

Figure 5 shows a lateral-directional axis comparison of flight and linear simulation results for a heading angle command, step input using the default gains at the preceding flight condition. The time history traces of the simulator model matched the flight data

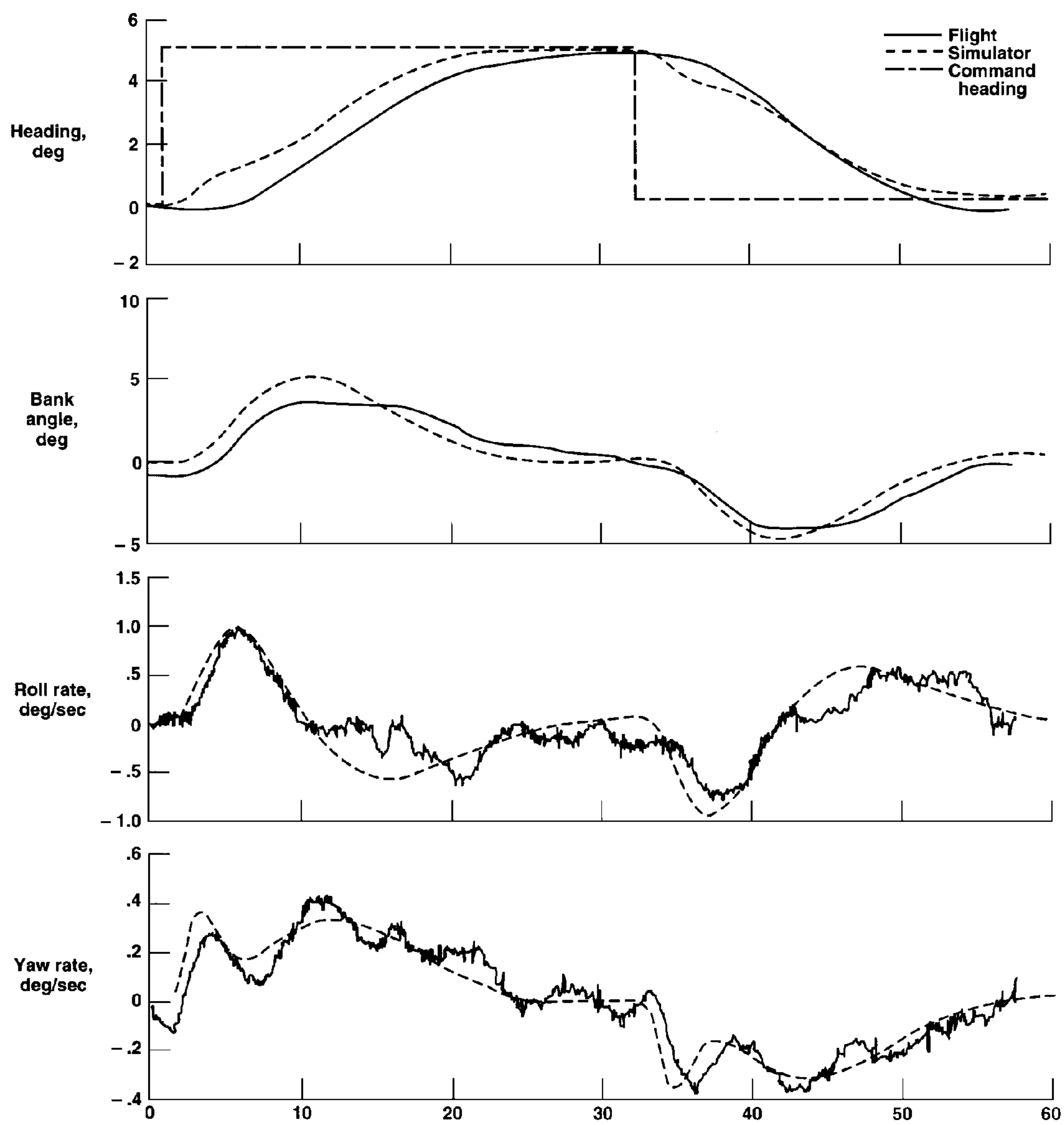

Fig. 5 Comparison of flight and linear simulation heading step response using the default gain set.

reasonably well. However, the pilots rated the lateral-directional response poor near the ground, and modifications to improve the sluggish response were needed.

The piloted simulations did indicate some lateral-directional challenges but not to the extent of the flight-test evaluations. Matching a pilot's workload, or gain, in a simulator to flight is a difficult task, especially during a turbulent day with a low-bandwidth control system. The level of turbulence has a large impact on the PCA controller performance and pilot ratings, especially in the roll axis. These approaches and landing occurred on a hot August day with light turbulence. Although the winds were light (approximately 9-kn head wind), high thermal disturbances caused roll upsets.

Lateral-Directional Axis Modification

The major controls challenge of the MD-11 PCA system was to improve the lateral-directional axis response without a new control law release. The pilots rated the response marginal at best. Lateral-directional control gains were modified to improve the performance. The heading error feedforward, lateral feedforward, turn coordination feedback, and bank angle feedback (K_{lc}, K_{phid}, K_{lat}, and K_{pr}) gains were selected for modification (Fig. 3). The K_{phid} and K_{pr} gains were used as damping adjustment parameters, whereas the K_{lc} and K_{lat} gains affected the initial response. Six gain sets were flight tested, but only two are presented here: the default set and T6 gain set. Gain set T6 gave the largest roll rates per degree of commanded input and was the gain set used for the PCA landing.

Using linear root locus analysis, a nonlinear control design technique,[8] and relying on nonlinear simulation runs, the gains were modified (Table 3). The control system with these gains was then tested in flight. Table 4 lists the closed-loop eigenvalues of the default gain set and the T6 gain set. Flight conditions were $H = 12{,}000$ ft, $V = 175$ kn, flaps at 28 deg, slats extended, c.g. = 23% MAC, $W = 360{,}000$ lb, gear down, and default gains.

Figure 6 shows the flight comparison between the default gains and T6 gains at a flight condition of 175 kn, 12,000 ft, 28-deg flaps, and gear down. A heading change of 5 deg was commanded, and the time to reach 90% of the final value (rise time) was calculated. The rise time for the default gain set was 19.5 s, and the T6 gain set was 12 s. The heading performance was improved by 38% using the T6 gain set. The maximum body axis roll rate p in Fig. 6 increased 77% using T6 gains but at the cost of reduced Dutch roll damping. Note the roll and yaw rate traces (see also Table 4).

Figure 6 also shows the EPR of the left and right engines for both gain sets. The T6 gain set commanded more engine activity than the default gains. The pilot's comments on the T6 gain set response were

Table 3 Lateral-directional modified control gains for improved roll response

	K_{lc}	K_{lat}	K_{pr}	K_{phid}
Default	1.0	1000.0	10.0	1.5
T6 gains	1.5	1500.0	6.7	1.0

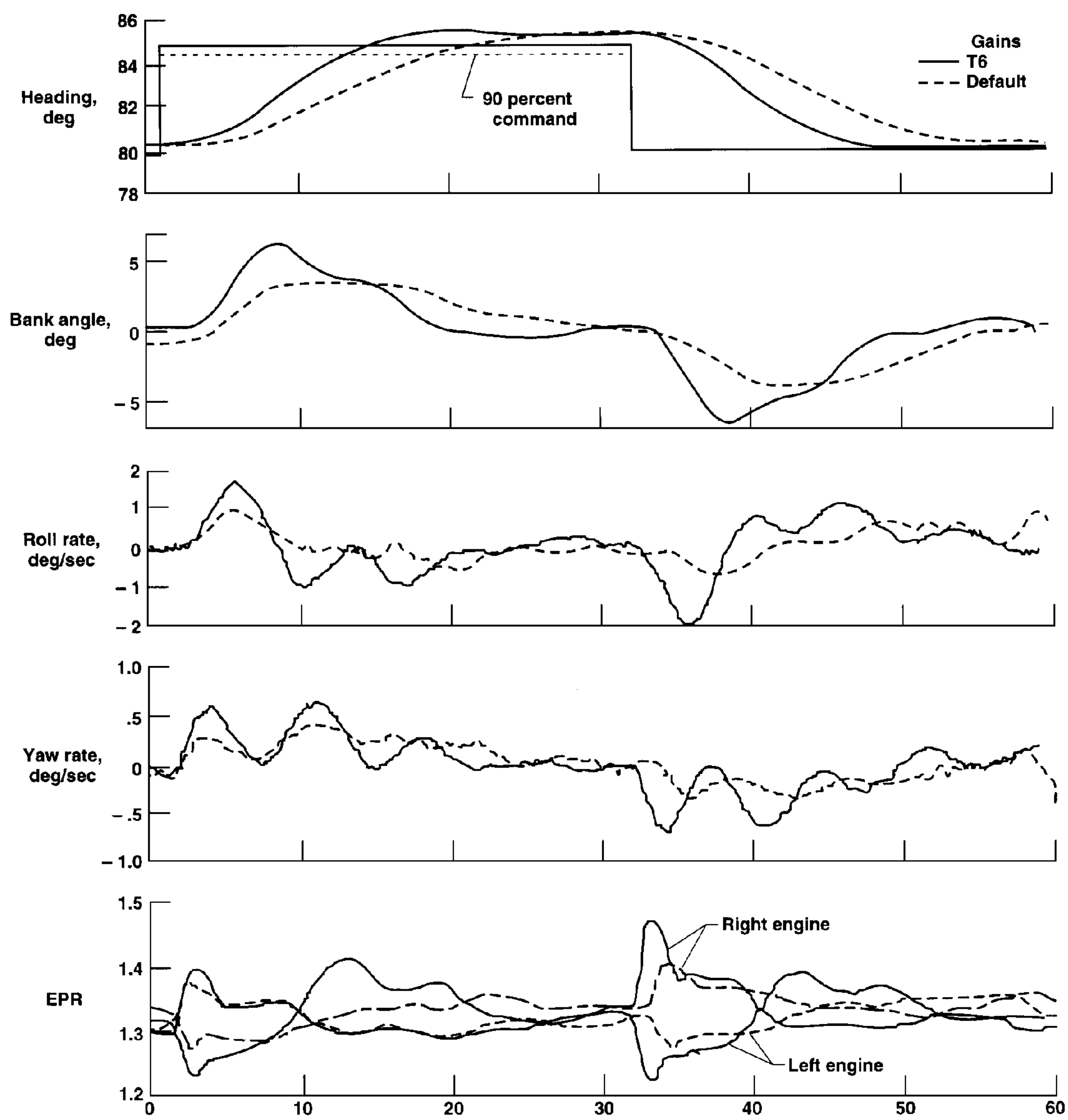

Fig. 6 Flight heading step response using the default and T6 gains.

much more favorable than those regarding the default gain response. The comments made were "I could feel the response 'kick-in' faster with T6 compared to the default set" and "I did not have to wait as long for the airplane to 'catch-up' to my input command." The T6 gain set was used for the PCA landing.

Landing Phase

After the lateral-directional axis response was improved, and without any longitudinal axis changes, a successful landing was performed using the PCA control system. In a trimmed 28-deg-flaps condition, a landing was performed without any control surface movement, simulating a total hydraulics pressure loss. The results are shown in Fig. 7, with the landing occurring at time = 83 s. During the approach, a large thermal upset caused the airplane to bank over to an angle of approximately 8 deg just after a lateral command change (time = 60 s). The lateral-directional axis controller commanded a restoring signal to remove the error, without pilot inputs. The 7-deg upset at time = 12 s was caused by the pilot's

Table 4 MD-11 lateral-directional PCA default and T6 gain set closed-loop eigenvalues

	Default closed loop		T6 gain set	
	Eigenvalue	Damping ratio	Eigenvalue	Damping ratio
Dutch roll	$-0.291 \pm 0.379j$	0.610	$-0.236 \pm 0.419j$	0.409
Spiral mode	$-0.134 + 0.085j$	0.85	$-0.204 + 0.081j$	0.93
Rolling mode	$-0.134 - 0.085j$	0.85	$-0.204 - 0.081j$	0.93
Engine	$-0.970 \pm 1.15j$	0.64	$-0.904 \pm 1.100j$	0.63
Control and washout	-0.350	1.0	-0.450	1.0

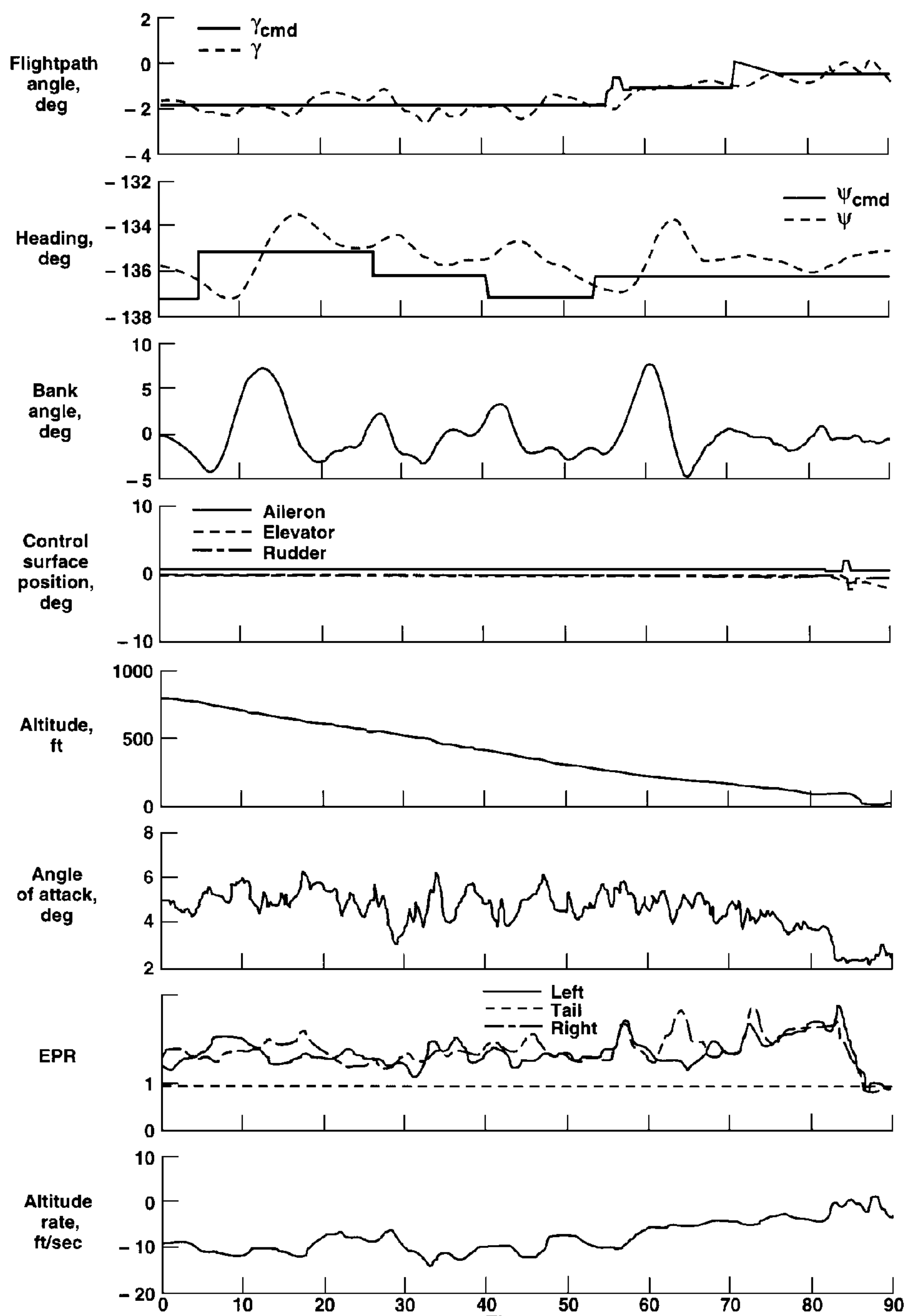

Fig. 7 Pilot-commanded landing with 28-deg flaps and an airspeed of 175 kn.

commanded input as shown in the heading trace (time = 5 s). Angle of attack α decreased just before landing because of ground effects, and the airplane landed with a sink rate of approximately 4 ft/s.

The MD-11 was stopped using reverse thrust and light braking but no spoilers or nosewheel steering. During an actual emergency PCA landing, the pilot would use the thrust reversers and limited braking available from the accumulators, which should be sufficient for stopping the airplane from a high-speed touchdown.

Concluding Remarks

An emergency backup control system using engine thrust only was designed and flight tested on a large, civil transport MD-11 airplane. This report describes the longitudinal- and lateral-directional PCA control system and compares simulation and flight-test results. Flight data comparisons with linear models were shown, with the emphasis on the lateral-directional sluggish response. The control system was designed from the onset with the flexibility to change several control gains in flight.

The pilots rated the longitudinal characteristics good, with minor pilot compensation needed. The performance was satisfactory; therefore, changes were not required during the first phase of flight test.

The original lateral-directional response was considered too sluggish near the ground because of wind gusts. Control law changes used to improve the response were shown and compared to the initial system. The roll response increased approximately 77% with a new gain set (T6), but the Dutch roll damping decreased. Allowing for gain changes in flight improved lateral-directional response without the need for time-consuming and expensive control law updates.

This backup control system could be used in the event of the airplane suffering a major primary flight control system failure, such as a total hydraulic pressure loss. The PCA system has limited control power, which may not be sufficient to handle surface hardovers or large mistrim configurations. However, in the absence of large mistrim configurations, the PCA system provides a method for returning the airplane to the airport and landing without the aid of aerodynamic control surfaces. The PCA system changes a flight situation where there is an extremely high workload (using manual throttle inputs) to a viable piloting task.

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