Automatic Rollout Control of the 747 Airplane

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An automatic rollout control system has been developed for the Boeing 747 airplane. The rollout control system consists of three independent channels that control the rudders and nose gear steering mechanism. The action of the rudders and nose gear steering provides control of the lateral path of the airplane along the runaway from touchdown to a safe taxi speed. With the addition of this system, the capability of the airplane eventually will be extended to operate in category IIIb conditions (less than 700 ft RVR, but not less than 150 ft RVR). The system requirements, developing of the control law, simulator results, and flight testing of the rollout control system, are described.

Introduction

A TRIPLE-CHANNEL fail-operational autopilot is offered as 747 equipment. This system has been operational since 1971 and provides control of the airplane in the pitch and roll axes from initial approach through flare to touchdown. The system is certified for use in category IIIa weather condition (700 ft RVR). A further development of this system has been the addition of a lateral rollout control mode.[1] This mode controls the lateral path of the airplane along the runway from touchdown to a safe taxi speed. The addition of this mode is a step toward achieving airplane operation in category IIIb weather conditions. Provisions that may be required to establish the longitudinal performance for category IIIb operation are not considered in this paper.

General Description

The system uses three independent control channels. Independence of the channels is insured through separate actuators, isolation of the power supplies, sensors, computers, airplane wire bundles, and shelf wire harnesses. The rollout mode becomes operational at an altitude of 5 ft. The control law uses localizer beam error, lateral acceleration, and yaw rate as inputs to provide rudder and nose wheel response to steer the airplane on the runway. The rollout control signals are the same as the signals used in the fail-operational approach control law from 1500 ft to touchdown (except yaw rate, which is used in the former system). Appropriate confidence testing of the approach mode system therefore insures the integrity of the rollout system inputs prior to touchdown. Decrab of the airplane occurs through reaction to the main gear at touchdown, causing a lateral acceleration signal to drive the rudder in a sense to align the airplane with localizer null.

The rollout command signals drive three independent rollout control servos of equal authority connected in parallel to the rudder feel-centering unit, as shown in Fig. 1. The output of the servos provides an input in parallel with the pilot's rudder pedals to the main dual tandem control actuators, which drive the upper and lower rudders. The rudders provide the directional control at high speed. Nose wheel steering, which is connected to the rudder pedals, becomes increasingly effective as the speed decreases below 70 knots. The nose wheel/rudder pedal interconnect occurs automatically through electromechanical actuators signaled from squat switches at nose gear touchdown. The rollout control servo can command a full rudder travel of ±26 deg. An override mechanism is installed between the rollout control servos and the rudder pedals to provide the pilot with override capability. This mechanism is sized to require an override force of 150 lbs to insure that normal pilot differential braking does not overpower the control system.

The control law implementation, monitoring, and warning circuitry for each channel are contained in a landing and rollout control unit (LRCU). The monitoring of each channel, shown in Fig. 2, consists of a servo system monitor, which compares computed rollout commands with the rollout control servo output, and a camout monitor, which detects disagreement between the rollout control servo and the surface position. Logic circuits provide warning of sensor failure, power failure, and autopilot disengagement. The arrangement of the rollout control system was developed to allow 1) normal performance after any single failure, and 2) isolation of a failed channel through automatic disengagement in case of first-channel failure.

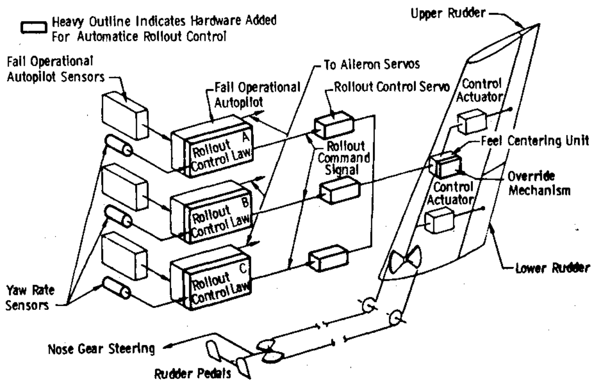

Fig. 1 Rollout mechanization.

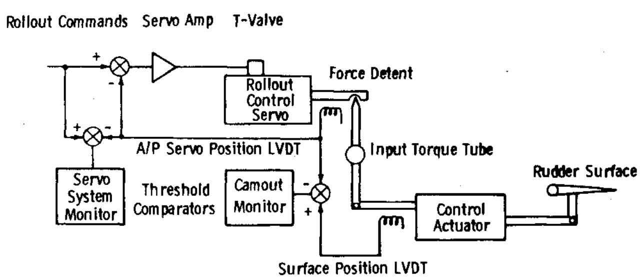

Fig. 2 Monitoring control logic.

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System Operation

Rollout control is divided into two submodes: rollout arm, which normally occurs at 1500 ft alt, and rollout engage, which occurs at 5 ft alt. At rollout arm, the rollout control servos are pressurized, which allows a check to be made of the servo operation before touchdown without interferring with normal rudder control. To insure transient free engagement, synchronization of the servos, surface position LVDT signals, and rollout command signals are maintained down to the point of rollout engagement.

When rollout engagement occurs at 5 ft alt, the localizer component of the rollout signal is clamped to its existing value. At touchdown the clamping circuit is removed. The action of the clamping circuit prevents localizer beam anomalies from producing large yaw and roll rates prior to touchdown. In addition, to reduce the effect of beam anomalies during the rollout maneuver, the localizer signal rate limit is reduced at rollout engagement.

If the airplane lands with zero heading error but displaced from the localizer null, the command signal is dependent on localizer proportional and integral signals to control the airplane toward the localizer null. When landing in a crosswind, the airplane is flown crabbed into the wind, wings level, by the roll axis autopilot down to touchdown. At touchdown, the lateral accelerometer used by the rollout control law provides a signal to align the airplane with the runway centerline. The use of the accelerometer to align the airplane with the runway centerline at touchdown avoids flying with a wing down in crosswind conditions and thus minimizes the possibility of having large roll attitudes during the touchdown maneuver.

Design Objectives

The primary design objectives are summarized: 1) System operation in flight to touchdown. The category IIIb autopilot system must meet the airworthiness requirements for a category IIIa system. These requirements are contained in Advisory Circulars issued by the Federal Aviation Authority.[2,3]

2) System operation after touchdown. a) The maximum distance from the aircraft centerline at the main body landing gear to the runway centerline should not exceed 27 ft on a 2σ basis. b) The probability that an outboard landing gear will come closer than 5 ft to the lateral edge of a 150-ft-wide runway for normal operation shall be improbable (less than once for 10^6 rollout operations). c) The probability of the outboard landing gear exceeding the confines of a 150-ft-wide runway considering any failures or failure combinations of the ground rollout system shall be extremely improbable (less than once for 10^9 rollout operations). d) The system must be capable of providing fail-operational lateral rollout control to permit the flight crew to slow the airplane to a safe taxi speed without reliance on external visual reference.

These objectives are incorporated in a Proposed Special Condition submitted to the Federal Aviation Administration for a category IIIb autopilot system, including criteria for automatic ground rollout control.

Rollout Control Law Description

A block diagram of a single-channel rollout control system is shown in Fig. 3. The four signals used to generate the steering command are localizer deviation, lateral acceleration, roll attitude, and yaw rate. The localizer path is a proportional plus integral control law. The accelerometer path is used to decrab the airplane at touchdown and to provide damping of the airplane ground track. The roll attitude signal is used to correct the output of the lateral accelerometer for small angles of roll attitude. The yaw rate path is used to increase the ground track damping signal as the airplane approaches the end of the runway.

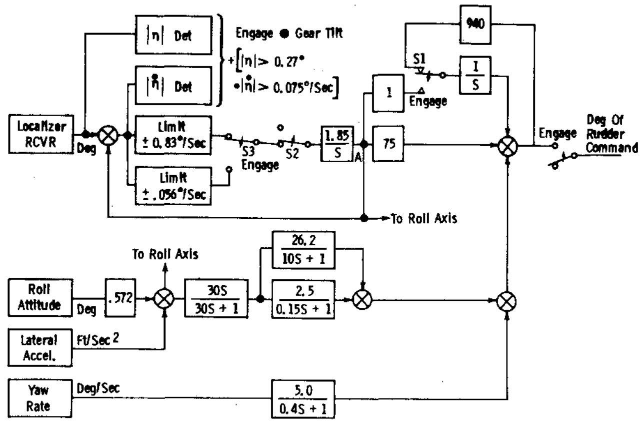

Fig. 3 Landing rollout computer block diagram.

Prior to automatic rollout engagement, switches S1, S2, and S3 are in the positions shown in Fig. 3. The closed loop on the localizer integral path (via S1) is used to synchronize initial conditions, thus precluding any transient rudder movement at rollout engage. Switch S2 is used to clamp the localizer signal (point A) from rollout engage to touchdown and at any time thereafter if the localizer deviation attains a magnitude of 0.27 deg or a rate greater than 0.075 deg/s. The rate capability of the localizer circuitry is changed via S3.

Because of beam convergence, the localizer path loop gain increases as the airplane approaches the localizer transmitter so that additional damping is required for the control law. The localizer path could have been gain-programmed, but this would have presented a mechanization problem inasmuch as the gain programmer would have to vary as a function of time or distance down the runway, making monitoring prior to system engage difficult. To avoid localizer programming, the accelerometer path gain was increased in the vicinity of the 0.2-rad region. (The dominating ground track time constant at high speed is approximately 30 s.)

At low speeds toward the end of the rollout maneuver, the dominating time constant of the ground track changes from 30 s to approximately 8 s (Dutch roll region). In addition, the localizer intensity increases significantly toward the localizer transmitter and can vary from airport to airport over a range of approximately 60 to 100 μA/deg (nominal 75 μA/deg). At Dutch roll frequencies, the accelerometer path contributes only 50% of the necessary damping. To compensate for all of these effects, increased damping in the Dutch roll region is provided from the yaw rate gyro signal.

The accelerometer filter path is shown in Bode form in Fig. 4. To eliminate offsets from the acclerometer, the low frequencies are washed out. The high frequencies are rolled off to decouple the rollout path frequencies from the airplane flexible modes. The reason for the shape of the filter in the bandpass region is to increase the gain of the filter in the 0.2-rad region without lagging the phase in the 8-s. period region. If, for example, the asymptote AB were moved higher in frequency by a factor of 4, the Dutch roll mode would become unstable.

The pitch axis control law to touchdown is identical to that used in the fail-operational autopilot. At touchdown, a nose-lowering command of ½ deg/s pitch attitude is applied to the pitch autopilot servo to force the nose gear onto the runway. This change was made for rollout control because it was found during flight testing that, without this command, the airplane remained in a nose-high attitude for up to 15 s after main gear touchdown.

To adapt to the rollout control system, the lateral axis approach control law is modified at rollout engage to incorporate a wings-level command. This is accomplished by disengaging the approach command to the aileron and using a roll attitude signal to level the wings.

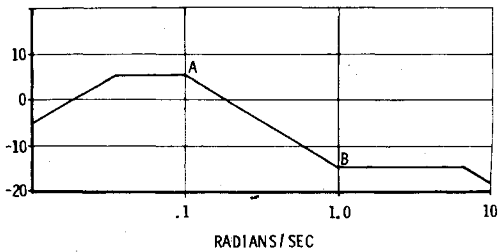

Fig. 4 Accelerometer path filter characteristic.

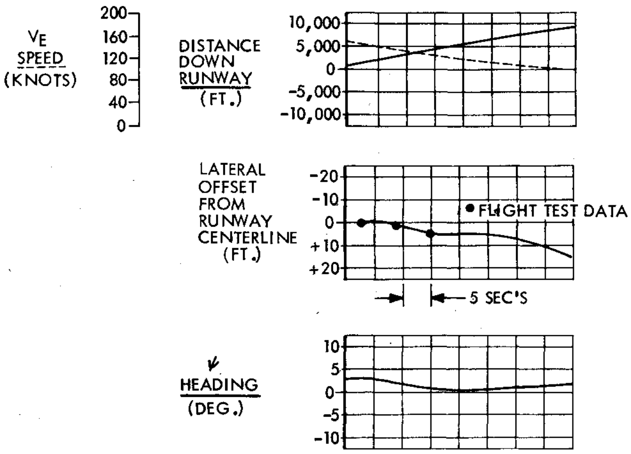

Fig. 5 Comparison of simulated and flight-test data: fail-operational autopilot disengaged at touchdown.

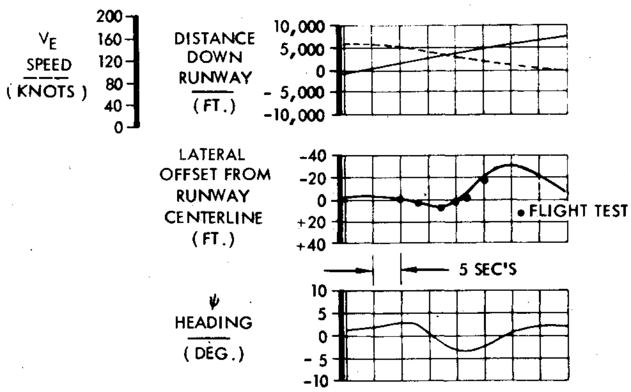

Fig. 6 Comparison of simulated and flight-test data: fail-operational autopilot engaged through rollout.

Simulation

A simulation of the airplane and rollout control system was made on a digital computer. The simulation was used to optimize the control law, examine failure conditions, and determine system performance. Initially the simulator parameters were based on theoretical values, with a subsequent update of the dynamics based on flight-test results. This update of the simulation was based on data obtained from 15 approaches and landings of the airplane with the rollout control disengaged. The landings used to verify the simulation were made on both wet and dry runways for various airplane weights and center-of-gravity positions. The following parameters were of special interest because they essentially determined the gain on the rollout control steering law: 1) $C_{n\beta}$ (yawing moment due to sideslip); 2) tire/runway coefficent of friction; 3) gear deflections; and 4) nose wheel steering effects.

The tests were conducted in the following manner:

1) A triple channel autoland appraoch was initiated.

2) At approximately 1000 ft, the pilot inserted 2-3 deg of rudder to induce a sideslip that was maintained until touchdown.

3) At touchdown, the pilot released the rudder and disengaged the autoland autopilot.

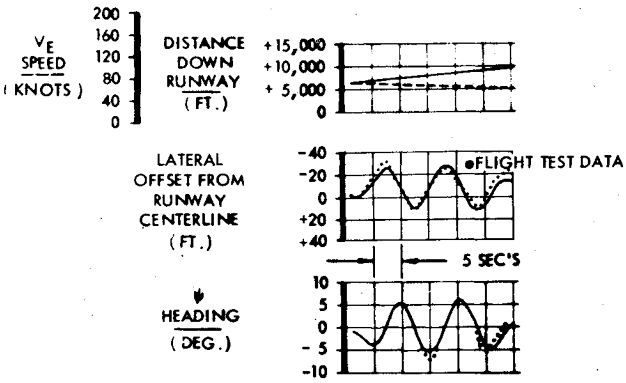

Fig. 7 Comparison of simulated and flight-test data: low-speed forced steering.

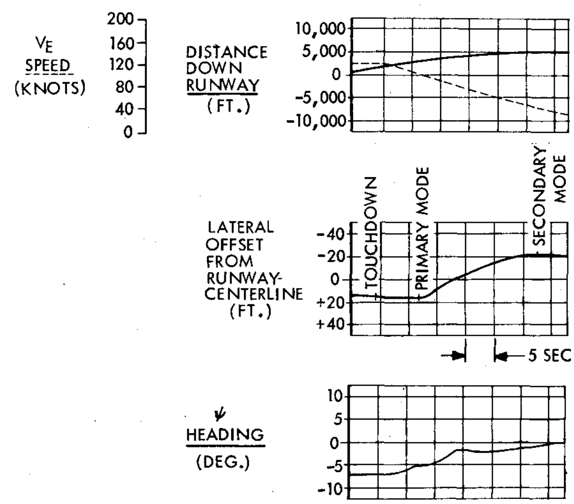

Fig. 8 Definition of primary and secondary modes.

A typical ground roll that occurred during these tests is shown in Fig. 5. The lateral offset shown is the distance from the airplane centerline at the main body landing gear to the runway centerline. It can be seen that the forward slip condition results in a large deviation from the runway centerline after touchdown due to the initial heading angle. Adjustments were made to the simulator parameters $C_{n\beta}$ and μ (tire/runway) to match the test results. Similar tests were performed leaving the fail-operational autopilot engaged after touchdown and during the ensuing ground maneuver. Data from these tests were used primarily to correct the aileron derivatives for ground effects (Fig. 6).

To complete the program, one low-speed and two high-speed steering tests along the runway were made. The low-speed results (Fig. 7) were used to check the nose gear steering simulation, and the high speed allowed a check of the main gear and rudder simulations. Figures 5-7 also show the simulation results of the respective maneuvers after the simulation had been updated from the flight-test data.

In the following sections, the term "dispersion" is used to describe the statistical distribution of the airplane lateral offsets at a specified position on the runway. The calculated dispersion values are used to show that items 2a and 2b of the "Design Objectives" section are satisfied.

Simulation: Rollout Control

The rollout control system performance was evaluated using a six-degree-of-freedom simulation starting at 1500 ft and continuing through touchdown and rollout to 20 knots ground speed. The simulation allowed inclusion of autothrottle, automatic braking, and thrust reverser systems. The runs all were begun at 1500 ft to show that the touchdown dispersions were exactly the same as the certified autoland touchdown dispersions, although the localizer is clamped from 5-ft alt to touchdown.

A typical simulated rollout maneuver is shown in Fig. 8. Note that the airplane has a lateral offset prior to touchdown because the localizer antennae are at the nose of the airplane and the airplane is flying in a 13-knot crosswind. During the maneuver, two peak excursions from the runway centerline occur, and these have been defined as primary and secondary modes. The magnitude of these peaks is dependent on runway conditions, airplane configuration, and crosswind. The primary mode is a skid in that the airplane slides away from the runway centerline with the heading angle slowly being brought to zero. It is the primary-mode displacement that sets the maximum crosswind limitation on the system. The displacement due to the primary mode cannot be reduced because of the difficulty of producing direct side force in an airplane. Worst-case performance occurs with a lightweight airplane landing with standing water on the runway.

Rollout Performance

A. Factors Affecting Performance

The lateral offset of the airplane during rollout is effected by the following:

1) Course alignment accuracy. The International Civil Air Organization (ICAO) category II requirements state that the localizer shall be maintained to within ±10 ft; AC 20-57A[2] recommends that this be used on a 2σ basis.

2) Beam bends. The magnitude of the beam bend is stated in AC 20-57A[2] to be $\pm 5\mu A$ on a 2σ basis. This results in a dispersion of 11.6 ft at a point 10,000 ft from the transmitter.

3) Airborne receiver centering error. To comply with an ICAO category II system, the receiver must be centered to within 5 μA on a 2σ basis. Assuming single-channel operation, the dispersion is 11.6 ft at a distance of 10,000 ft from the localizer transmitter.

4) Autopilot system tolerances. Offsets from sensors and autopilot, tolerances in sensor gradients and autopilot gains, and drift on integrators result in a dispersion that is less than 0.5 ft (2σ). This contribution is negligible.

5) Lateral wind plus turbulence. Appendix A describes the wind model used in determining the system response to crosswinds and turbulence. (Figure 16 shows the probability of mean wind speeds at tower height for the crosswind component. The curve has been divided into sections as indicated to yield a mean probability for discrete winds.)

6) Maneuvering. The performance of the system is dependent on maneuvering prior to localizer capture and on the distance at which localizer capture occurs. A dispersion of 10 ft on a 2σ basis is used to cover these effects. This value was determined originally during development of the fail-operational autopilot from simulator results for various capture conditions.

Table 1 Lateral dispersion at the primary mode

	Total displacement	
1) Course alignment	10.0 ft	2σ
2) Beam bends	8.7	2σ
3) Airborne rec. centering error	6.15	2σ
4) Autopilot system tolerances	0.5	2σ
5) Lateral wind + turbulence	15.2	2σ
6) Maneuvering	10.0	2σ
rss of foregoing	23.33	2σ

B. Wet Runway Dispersion: Primary Mode

The performance described is based on a worst-case analysis of the following: airplane weight, 400,000-500,000 lb; center of gravity, 30%; approach speed, $V_{ref} + 10$ knots; runway condition, wet; and crosswind, 0 to 13 knots. Braking action equivalent to the use of medium autobrakes is assumed.

Primary-mode dispersion for each discrete wind when applied to the worst-case wet runway condition is plotted in Fig. 9, along with the cumulative distribution (approximately 200 runs per crosswind). Table 1 shows the lateral dispersion of the airplane at the primary mode. Items 2 and 3 have been modified to account for the convergence of the localizer beam (see Appendix B). The dispersion is with respect to the runway centerline. Item 5 is derived from the simulation results of the system and is taken from Fig. 9. The 2σ dispersion is 23.33 ft, and the requirement is 27 feet (2σ).

C. Wet Runway Dispersion: Secondary Mode

The secondary-mode dispersion for each discrete wind and the cumulative distribution is shown in Fig. 10. Table 2 shows the lateral dispersion of the airplane at the secondary mode. Item 5 is derived from the simulation results and is taken from Fig. 10. The 2σ dispersion is 23.97 ft, with a requirement of 27 ft (2σ). The calculated dispersion values for the rollout control system are therefore within the design requirements.

Flight-Test Performance Correlation

Twenty-five rollout test conditions (nonfailure) were used to correlate system performance with simulator results. Because the simulator results are all run with crosswinds from one direction, the flight-test conditions were selected with the significant crosswind from the same direction.

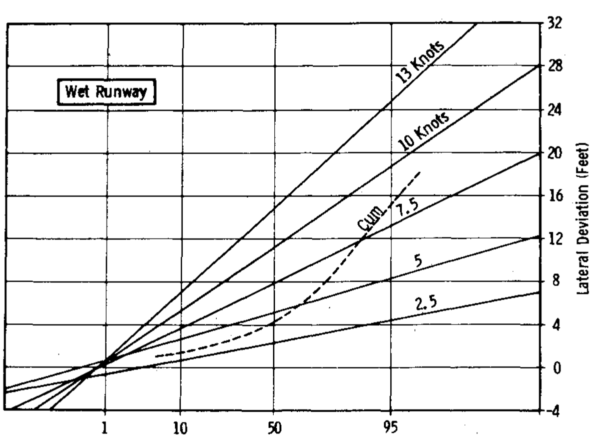

Fig. 9 Lateral dispersion due to discrete winds: primary mode.

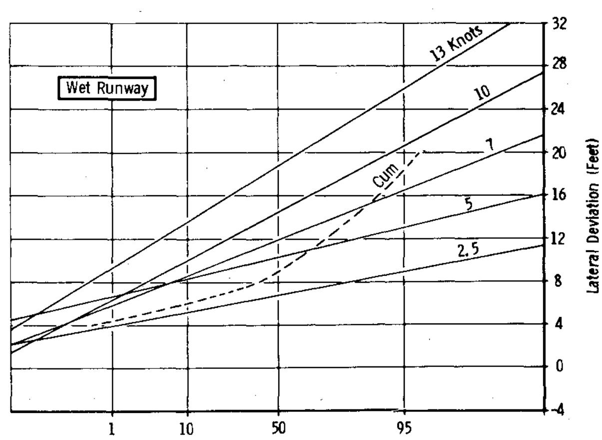

Fig. 10 Lateral dispersion due to discrete winds: secondary mode.

Table 2 Lateral dispersion at the secondary mode

	Total displacement	
1) Course alignment accuracy	10.0 ft	2σ
2) Beam bends	5.8	2σ
3) Airborne rec. centering error	4.1	2σ
4) Autopilot system tolerances	0.5	2σ
5) Lateral wind + tubulence	18.0	2σ
6) Maneuvering	10.0	2σ
rss of foregoing	23.97	2σ

Table 3 Statistical correlation

	Simulator	Flight test
Touchdown	$2\sigma = 23.21$ ft	$2\sigma = 19.76$ ft
Primary mode	$2\sigma = 23.33$ ft	$2\sigma = 26.53$ ft
Secondary mode	$2\sigma = 23.97$ ft	$2\sigma = 20.67$ ft

The statistical correlation between flight-test data and simulator results is shown in Table 3. The simulator results in Table 3 are based on aprroximately 1000 runs using the airplane configuration, wind, and runway conditions given in the "Rollout Performance" section. The corresponding flight-test results are based on 25 approaches and rollout operations with parameters similar to those used in the simulation. Agreement between the simulator and flight-test dispersion values confirms that the simulator model, with its larger statistical base, can be used to predict normal performance and investigate the effect of possible failures during rollout operation.

Flight-Test Failure Demonstrations

In addition to the 25 rollout performance conditions, flight test demonstrations of airplane system failures that could affect rollout performance were made to show safe operation in the event of these failures occurring. A few typical conditions are illustrated below.

A. Engine Failure Conditions

This condition demonstrated rollout control with an outboard engine failure simulated 4 s after touchdown at the time of thrust reverser application. When reverse thrust was applied, engine 1 (outboard) remained at idle reverse, and the remaining engines had maximum reverse thrust applied. Asymmetrical reverse thrust was applied until pilot recognition of the failure (approximately 4 s), and then engine 4 (opposite outboard) was brought back to idle reverse, with engines 2 and 3 remaining in reverse thrust and retarded according to the normal speed schedule. Figure 11 is a time history of lateral offset for this condition.

A second engine failure condition was performed in the following manner. After touchdown, engine 1 remained at idle forward with reverse thrust applied to the other engines. With asymmetrical reverse thrust applied during rollout, performance of the rollout control system was satisfactory, with a maximum lateral offset of 18 ft being recorded.

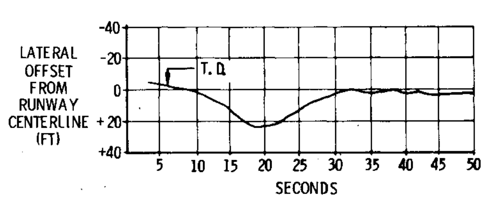

Fig. 11 Outboard engine failure.

B. Yaw Damper Hardover

An upper yaw damper hardover at an altitude of approximately 5 ft was made with a crosswind component of 13 knots from the right, with the failure introduced such that the trailing edge of the rudder moved to the left. The yaw damper hardover caused no detectable difference in rollout control performance.

C. Rollout Command Hardover

This condition was conducted to demonstrate operation of rollout control with a rollout command hardover introduced into a single channel at rollout engage. The performance during the rollout maneuver was identical to the triple-channel system.

D. Failed Nose Gear Steering

A nose gear steering failure was introduced by engaging the rudder pedal steering so that the nose gear was free to caster. Figure 12 is a time history of the lateral offset. This figure shows that the failure effect was insignificant.

A nose gear steering failure corresponding to the nose gear steering being in a faired position also was evaluated. In this case, the nose gear remained within ± 1 deg throughout the condition. Prior to touchdown, the airplane was offset to the right to develop a steering error intentionally. The data for this condition are shown in Fig. 13

E. Autobrake Failures

The 747 autobrake system controls the braking of the 16 main gear wheels to achieve selected braking action. A failure in this system can lead to the loss of eight brakes on one side of the airplane, with the remaining eight wheels providing braking action. Tests were conducted to show the effect of

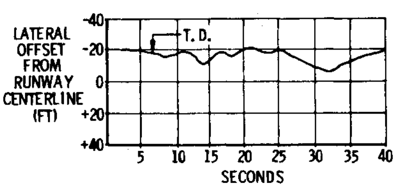

Fig. 12 Nose gear steering disengaged ($\pm$70-deg free caster).

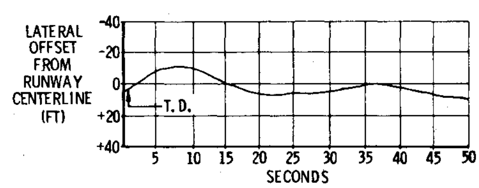

Fig. 13 Nose gear faired ($\pm$1-deg free caster).

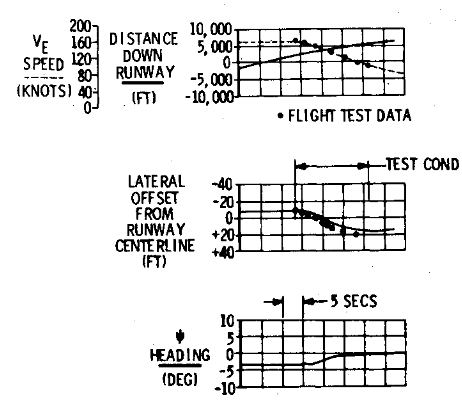

Fig. 14 Comparison of simulator and flight-test data: right brakes inoperative, high-speed case.

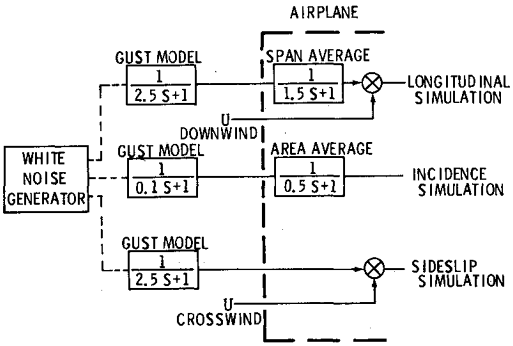

Fig. 15 Wind model.

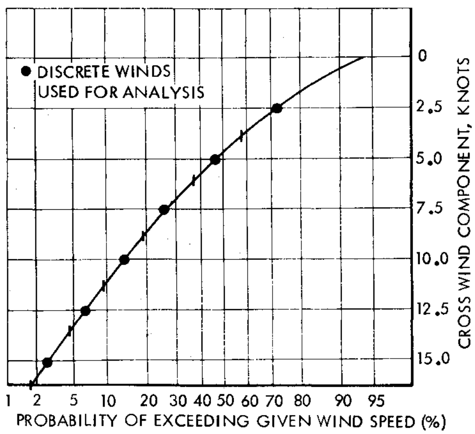

Fig. 16 Mean wind speeds at tower height.

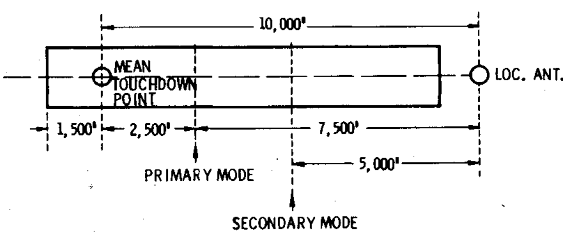

Fig. 17 Runway model.

this failure on the rollout control system performance. A comparison of the flight-test and simulator data for the case of all right brakes failing at high speed is shown in Fig. 14. The maximum offset was 20 ft, showing that this failure is not hazardous.

Conclusion

The control law used in the rollout control system is a minor modification of that used during the approach phase of the flight. All of the essential sensors and actuators are used and/or checked during the approach phase, thus insuring a high degree of reliability for the rollout control system. Simulation and flight-test data show that the performance of the rollout control system meets the design objectives with a crosswind limitation of 13 knots and that the introduction of possible failures does not present a hazard to safe operation. Under the state conditions, the rollout control system provides lateral control for category IIIb operation. The problem of longitudinal performance requires a technical or operational solution before full category IIIb operation can be achieved.

It has been shown that the simulation of the airplane and control systems compares well with flight-test results, for both normal and failure conditions. Consequently, the simulator can be used to provide certification data, thus limiting the amount of flight testing required.

The rollout control system is currently in production and is certified for operation in category IIIa conditions on a no-hazard basis. At this time, the system is installed and operational with two airlines.

Table 4 Localizer convergence factors

Perturbation disturbances	Touch-down, ft	Primary mode, ft	Secondary mode, ft
1) Course align.	10	10	.10
2) Beam bends	11.6	11.6×0.75 = 8.7	11.6×0.50 = 5.8
3) Rec. centering	8.2	8.2×0.75 = 6.15	8.2×0.50 = 4.1
4) System tol.	0.5	0.5	0.5
5) Maneuvering	10	10	10

Appendix A: Wind Model

The wind model is as follows: $T_{\text{long}} = 2.5$ s, $T_{\text{vert}} = 0.1$ s, $T_{\text{lat}} = 2.5$ s; span averaging: lag of $\tau = 1.5$s; area averaging: lag of $\tau = 0.5$ s. The block diagram of Fig. 15 shows how the wind model is incorporated into the simulation of the system. Figure 16 shows the probability of mean wind speeds at tower height for the crosswind component.

Appendix B

The runway model used for simulation purposes and the approximate position of the primary and secondary modes are shown in Fig. 17. The appropriate convergence factors for items 2 and 3 are given in Table 4.

References

[1] "Boone, J. H. and Simpson, R. D., "Self-Aligning Rollout Guidance System," U. S. Patent 4,006,70, Feb. 8, 1977.

[2] Dept. of Transportation Advisory Circular AC 20-57A, Jan. 12, 1971.

[3] Dept. of Transportation Advisory Circular AC 120-28A, Dec. 14, 1971.