Boeing/Sperry Automatic Landing System 727 Airplane

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A milestone in the history of American commercial aviation was reached on the night of February 27, 1967. A Pan American Boeing 727 jetliner made a fully automatic landing at JFK International Airport in New York. This was a scheduled flight with 98 fare-paying passengers onboard. With visibility restricted by snow flurries, and despite crosswinds gusting to 12 knots, the touchdown was smoothly executed within 4 ft of runway centerline. This relatively unheralded feat was the culmination of years of effort by many related groups in the field of aviation. This paper considers the changing role of the automatic flight control system in commercial aviation relative to function and safety. It describes the evolution of the 727 system with respect to its use in obtaining progressively lower operational weather minimums for the airlines. The over-all landing system is then described, explaining details of the dual-pitch channels of the automatic pilot, and the unique methods used to implement a system that is both safe and dependable. Following a discussion of the 727 automatic landing certification program, touchdown dispersions are shown to meet tentative FAA criteria.

Introduction

THE role of the automatic flight control system (AFCS) in commercial aviation had not, until recently, changed very dramatically since the first automatic pilot was introduced into fleet operation nearly 35 years ago. The early models of AFCS did nothing more than maintain a fixed air plane attitude for the pilot. The typical AFCS found in commercial transports today provides most of the functions listed in Table 1. However, the role of the AFCS did not change; it was not a dispatch item, but served primarily to reduce pilot workload and add to the comfort of the passengers. The safety aspects of the AFCS were passive in nature. It was necessary to demonstrate only that the AFCS could not in any way compromise the safety of the airplane. The interface between the automatic and manual control systems was designed so that the automatic system could be readily and positively disconnected from the manual controls in the event of a malfunction of the automatic controls.

Table 1 AFCS modes/functions

Lateral/directional control	Longitudinal control
Yaw damping	Pitch attitude hold
Roll attitude hold	Barometric altitude hold
Heading hold	Pitch knob maneuvering
Turn knob maneuvering	Airspeed hold
Preset heading control	ILS glide slope tracking
VHF omnidirectional range (VOR) radial tracking	Autothrottle control
Instrumental landing system (ILS) localizer tracking	

With the development of the commercial jet transport, the AFCS was called upon to perform some new functions, and for the first time its role began to change (Table 2). The swept-back wing of the jet transport accentuated the lateral directional instability known as "Dutch roll." The safety of an airplane is directly related to its handling qualities, and less than satisfactory handling qualities resulted from the Dutch roll instability. It was highly desirable to augment the characteristics of the basic airplane with a means for damping the Dutch roll. In some commercial jet transports, this damper is mandatory for safe operation in some portions of the altitude/airspeed flight envelope. In effect then, a portion of the AFCS has become a dispatch item.

Another phenomenon demonstrated by the high-speed jet transport is that known as Mach tuck-under. This effect manifests itself as a divergent mode whereby an incremental increase in speed (Mach number) causes a nose-down pitching moment on the airplane, which in turn causes a further increase in speed. Although the amount of Mach tuck-under, and the particular range of Mach number over which it occurs, will vary from one model of airplane to another, it typically occurs in the region of Mach 0.8–0.9. This phenomenon again represents a compromise of handling qualities and is of such a magnitude in some models as to be considered unsafe. The AFCS was again called upon to come to the rescue and to provide automatically a compensating pitching moment that would eliminate the divergent mode. This is typically accomplished by programming elevator deflection as a precise function of Mach number over the critical Mach range. Again, a subsystem of the AFCS was required to provide the margin of safety deemed necessary for high-speed operation of commercial jet transports.

Thus, we find that the role of the AFCS relative to safety is changing from passive to active, and two of its subsystems

Table 2 Evolution of AFCS role

Provide pilot relief and passenger comfort.
Enhance safety by improving handling qualities.
Allow operation at lower weather minimum.

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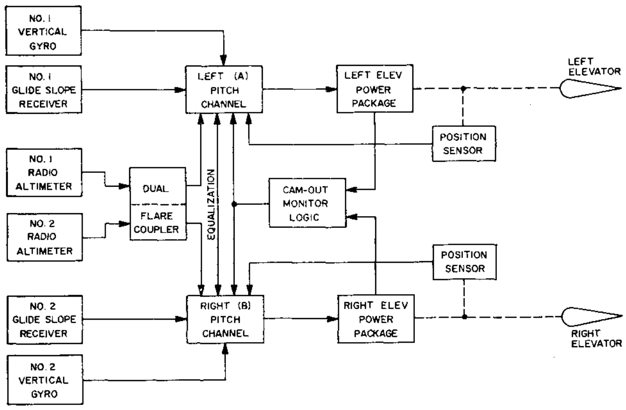

Fig. 1 Dual-pitch axis control systems.

have already become dispatch items. It is not only the handling qualities of the jet transport that have acted as stimuli in changing the role of the AFCS. Rapidly increasing density of air traffic in major terminal areas has provided the incentive to find the means by which it will be possible to operate into and out of these terminal areas in spite of adverse weather conditions. Economic penalties and personal inconveniences resulting from delayed arrivals and diversions to alternate airports are becoming intolerable.

The task of defining acceptable means by which operational weather minimums may be safely reduced has proven to be monumental. Notwithstanding the massive effort already put forth, there is still much to be done before "zero-zero" or all-weather operation can be realized. One thing has become apparent, i.e., the lowering of operational weather minimums must be accomplished in realistic steps. The steps have been defined by the FAA, with the help of the aviation industry, in terms of weather minimums categories. The equipment requirements and the associated performance and safety criteria for each of these categories have been only partly defined. Briefly, the weather minimums categories are as shown in Table 3.

One of the major deterrents to defining the equipment and facility requirements for lower operational weather minimums is the lack of operational experience in those environments. It was decided that in taking each of the steps toward lower minimums we would impose design objectives that, in our best judgment, would provide capability for operating to the next lower weather category. We felt that only by doing this would the pilots be able to gain the operational experience so vital to defining the associated performance and safety criteria for that next category. Let us trace this progression to date, with reference to Table 4.

The AFCS originally certified in the 727 was designed to meet the safety and performance requirements for Category I, but with sufficient margin to provide stable and accurate path control on the instrument landing systems (ILS) localizer and glide slope beams down to altitudes below 100 ft. Furthermore, its elevator authority was limited so that a malfunction would not result in significant altitude loss which would otherwise limit its use to some altitude above 100 ft. As a result, in October 1963, the 727 AFCS was certified for clear-weather operation down to an altitude of 78 ft. By demonstrating performance and pilot proficiency, the airlines soon obtained FAA authorization to operate under Category I weather minimum conditions and, having established visual contact at the 200-ft minimum decision altitude (MDA), to continue under automatic control down to 78 ft. Operational experience gained through this and other programs led to the formulation of criteria for Category II operation. These new accuracy criteria required that certain improvements be made to the 727 AFCS, primarily in the glide slope control circuits of the automatic pilot. This improvement program led to a recertification of the 727 AFCS in October 1965 for Category II operation, and these improvements were delivered to the airlines. By early 1966, through demonstrations of system performance and pilot proficiency, the airlines began obtaining FAA approval to operate in Category II weather minimum conditions.

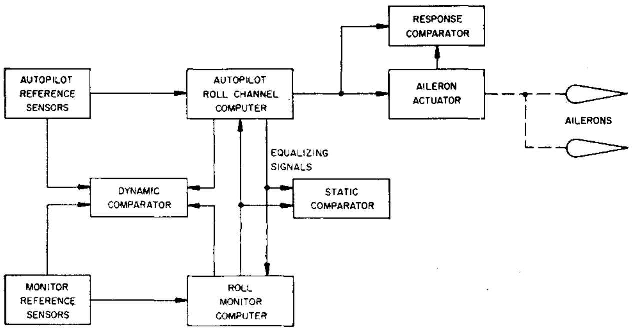

Fig. 2 Roll control and monitor system.

The step to Category IIIA operation is not as simple. First of all, performance and accuracy criteria are not defined, to say nothing of safety requirements. However, one hurdle that was defined and had to be overcome was the so-called 50-ft rule. That is, the autopilot could not be used below an altitude corresponding to 50 ft plus the amount of altitude lost during manual recovery from a nose-down, hard-over malfunction of the autopilot. Since the manual recovery must allow for a 1-sec fault recognition time by the pilot, it was obvious that the autopilot had to be made "fail-passive." This, and other practical considerations, led to self-imposed design criteria that can be rather simply stated as follows: the pilot shall be immediately warned of a malfunction, and no malfunction shall disturb the flight path of the airplane to the extent that the pilot cannot take over manually and complete the landing safely or execute a go-around. Furthermore, consistent with the philosophy of providing operational margin below the Category IIIA objective, it was deemed necessary to provide automatic flight path control throughout the flare maneuver to touchdown. By certification of such a system, we would again be in a position to obtain airline operational experience that would aid in defining the criteria for a further reduction in operational weather minimums.

727 Automatic Landing System Description

Equipment added to the 727 to enable certification of the airplane for automatic approach in Category II weather minimums consists of improved ILS receivers, a radio altimeter and indicator for minimum decision altitude (MDA) determination, an improved rain-repellant system, and autopilot modifications to provide tight ILS beam tracking. Additional equipment necessary for the 727 automatic landing system includes 1) a second radio altimeter, 2) a second autopilot pitch channel, 3) an autopilot flare coupler (dual), 4) an autopilot roll monitor channel, and 5) autopilot approach progress display modifications.

In pitch axis control, two pitch control channels are used to independently drive separate elevator hydraulic actuators.

Table 3 FAA weather minimums categories

Category	Minimum decision altitude, ft	Runway visual range, ft
I	200	2600
II	100	1200
IIIA	0	700
IIIB	0	150
IIIC	0	0

Figure 1 is a simplified block diagram of the dual pitch system. Complete duality is maintained in the pitch axis system from the input sensors to the elevator control servos, inclusive. The only inter-tie between the two pitch control channels is an equalization signal path. The equalization signal has limited authority, and enables the two channels to track within system accuracy requirements in the presence of normal component tolerances. A dual flare coupler provides flight path computation between the glide slope control phase and touchdown. The flare coupler commands an exponential flare profile as a function of altitude rate and displacement, and is programmed to control the touchdown rate of descent to $2\frac{1}{2}$ fps. The radio altimeter signal is used in the glide slope mode to program the glide slope gain as a function of altitude above the terrain, with the unique feature that depressions in the terrain which appear as an increase in altitude are ignored. In the flare mode, the radio altimeter signal is the primary source for the flare coupler command computation.

Tracking of the two pitch channels is continuously monitored by fail-safe amplifiers. If a malfunction causes the tracking error to exceed a predetermined amount, the pitch channels disconnect automatically.

Roll axis control is based upon a different dual concept. In this case, the second channel is a roll monitor that duplicates the computations of the roll channel, but it does not drive a separate aileron control servo (Fig. 2). Fundamentally, the roll monitor is a comparison monitor. It receives signal information from a separate set of sensors, operates on these signals to compute aileron command, and compares these commands with the corresponding command signals in the roll channel to verify their integrity. Having validated the command signals, it also computes the required response of the aileron servo, and compares this computed response with that of the actual servo. The various signal comparisons are monitored by a fail-safe amplifier; if static or dynamic errors exceed prescribed thresholds, automatic disengagement occurs, with pilot warning. This system also utilizes an equalization technique to minimize the effect of tolerances.

The autothrottle system (Fig. 3) used on the 727 airplane was developed specifically to enhance the performance of the automatic approach and landing system. It reduces the pilot's workload and allows more time for his role as the master monitor of the automatic approach progress. However, it is not a required subsystem of the 727 automatic landing system. Upon engagement, the autothrottle system operates the thrust levers to control the airplane indicated airspeed to coincide with the airspeed indicator speed command "bug" which is manually set by the pilot. The airspeed error signal is combined with a longitudinal accelerometer signal through a low-pass filter to minimize throttle activity in gusty air conditions. A pitch attitude signal is used to augment the airspeed error computation to reduce transient airspeed errors during normal airplane maneuvers. The autothrottle system complements the automatic flare maneuver by retarding the throttle levers at a fixed rate during the flare mode of autopilot operation.

The approach progress display is an array of annunciators used to inform the pilot of the autopilot mode of operation. Figure 4 illustrates the sequence of events during an automatic approach to touchdown and the associated indication displayed to the pilot. Six cues are given by amber and green indications from three light annunciators. An automatic approach to touchdown begins with the autopilot engaged and the airplane course set to intercept the localizer. When the automatic coupling mode is selected, the following occurs:

Table 4 Certification history of 727 AFCS

Category	Certification date	Minimum altitude, ft: Visual contact required	Minimum altitude, ft: Manual takeover required
I	Oct. 1963	200	78
II	Oct. 1965	100	78
II with automatic landing	June 1966	100	0

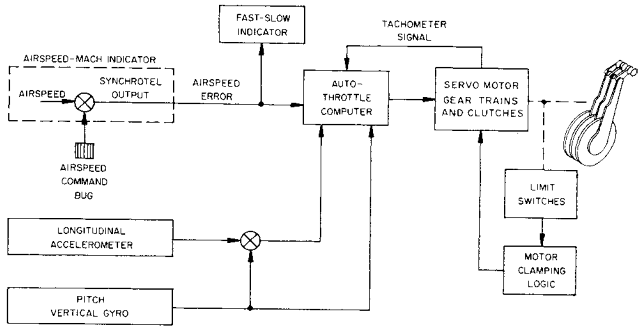

Fig. 3 727 autothrottle system.

1) The localizer annunciator will be amber, indicating that the roll axis control system is in an armed state for automatic acquisition of the localizer beam.

2) The glide slope annunciator will be amber, indicating that the pitch axis control system is armed for automatic acquisition of the glide slope beam.

3) Upon intercepting the localizer beam, the localizer annunciator turns green, and the roll control system initiates capture of the localizer beam.

4) Upon intercepting the glide slope beam, the glide slope annunciator turns green, and the pitch control system initiates capture of the glide slope beam. Up to this point in the approach, only one pitch channel has been engaged. Upon intercepting the glide slope beam, the second pitch channel is engaged automatically, and fail-safe monitoring begins.

5) At approximately 1500 ft of altitude, the autopilot initiates localizer and glide slope gain programming in response to radio altimeter signals. Simultaneously, the roll monitor is activated, which in turn arms the autopilot flare mode. This is indicated to the pilot by the flare annunciator turing amber. The approach is now, and will remain, fully monitored to touchdown.

6) At approximately 50 ft of altitude, the pitch axis control system switches from the glide slope mode to the flare mode, indicated by the flare annunciator turning green. Normal time between flare initiation and touchdown is approximately 8 sec.

Dual-Pitch Channel Description

In order to implement a fail-passive system, it is necessary to employ a means for reliably detecting both active and pas-

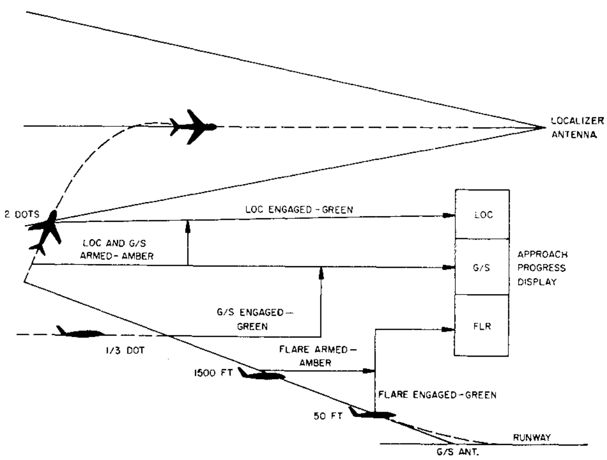

Fig. 4 Approach progress display.

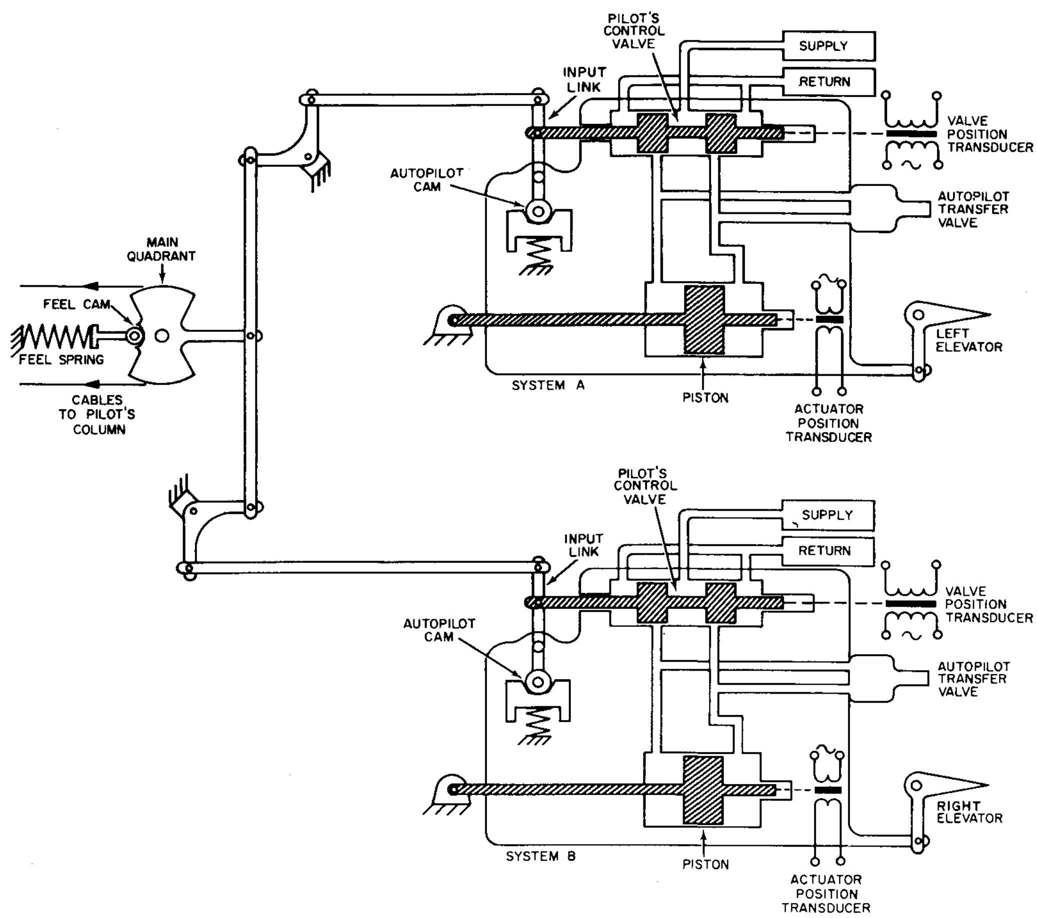

Fig. 5 Elevator control system.

sive failures, and a certain amount of duality is required, particularly at the sensor level.‡ Once the sensor signals are validated, the response of the remaining components to the signals can be validated by comparison monitoring techniques. Alternatively, the system can be completely dualized so that a failure of one channel is counteracted by the opposing channel. As indicated by the previous description of the system, the 727 AFCS autopilot uses both techniques. The simultaneously operating dual pitch channels are considered unique and are explored in more detail.

The 727 basic elevator control system contains dual electrohydraulic actuators. To appreciate fully the fail-safe protection of the 727 dual pitch channels, it is necessary to investigate the elevator actuators, control system linkages, and associated artificial feel system. This is most clearly done with reference to the mechanical schematic diagram of Fig. 5. For simplicity, the actuators are shown as single-stage devices driven by a pilot's control valve (manual operation). The feel system is shown as a simple mechanical spring. The 727 elevator actuators are actually two-stage devices, and the feel system varies the effective feel spring gradient as a function of flight condition.

It can be seen that the right and left elevators are not bussed together, but they are connected together through the actuator input linkages of the control system. Each elevator is powered from a separate actuator. In manual operation, when the pilot moves the control column, the control cables rotate the main quadrant. The feel spring provides an opposing force consisting of an initial preload plus an additional force proportional to quadrant rotation as it compresses the feel spring. The quadrant rotation is transmitted through the bell cranks and linkages, and displaces the pilot's control valves with respect to the actuator housings. As a result, hydraulic pressure is ported to the main pistons, causing motion of the actuator housings and corresponding deflection of the elevators. Motion of the actuator housings recenters the pilot's control valves.

In single-channel autopilot operation, hydraulic supply pressure is connected to one autopilot transfer valve. Also, the input link that drives the pilot's control valve of the same actuator is caged by a spring-loaded cam (autopilot cam); this prevents movement of the pilot's control valve with respect to the actuator housing. When the autopilot amplifier supplies d.c. current to the transfer valve, the valve ports hydraulic pressure to the main piston, causing motion of the actuator housing and a corresponding elevator deflection. As the actuator moves, it forces the control system linkages to follow it, thus rotating the main quadrant and compressing the feel spring. Note that the pilot's column follows the movement of the actuator, and the linkages of the opposite actuator cause the pilot's control valve of that actuator to move; that is, the opposite actuator is "slaved" to the autopilot-driven actuator, and both elevators deflect an equal amount. The actuator position transducer provides a feedback signal to the autopilot amplifier that cancels the command signal at the amplifier input and rebalances the transfer valve when the elevator has reached the commanded position. If a large command signal is present at the amplifier input, the actuators will move and deflect the elevators up to the point where the reaction force of the feel spring is greater than the spring preload force at the autopilot cam. Then a small increase in actuator displacement will cause the input link to rotate (since the autopilot cam spring compresses), and the pilot's control valve will move. The mechanical advantage and relative valve authorities are such that a small motion of the pilot's control valve will completely cancel the hydraulic input from the autopilot transfer valve, and further actuator

‡ In some cases, equivalent reliability may be obtained by in-line monitoring of a single sensor, but some sensors have failure modes that cannot be practically covered by this technique.

displacement is prohibited. Thus, it is seen that autopilot elevator authority is determined by the feel spring gradient relative to the autopilot cam spring preload.

During dual-pitch channel operation, both actuator input links are caged by their respective autopilot cams, and each autopilot transfer valve is driven from a separate autopilot channel. As long as the two autopilot commands agree, both actuators (and elevators) will respond together. Also, since the reaction force of the feel spring is distributed equally between the autopilot cams, the autopilot authority is doubled.

Assume now that the two autopilot commands do not agree. In a typical case both systems are initially balanced, with the elevators faired. If a command is transmitted to system A transfer valve only, then actuator A will start to move, and in so doing, it will attempt to rotate the main quadrant as well as the input link to system B actuator. However, to do so it would have to overcome the preload force of the feel spring plus the preload force at B autopilot cam. Since the sum of these preload forces is greater than the preload force on A autopilot cam, that cam spring will yield, allowing the input link of actuator A to rotate and move its pilot control valve. This control valve input cancels the transfer valve input for a very small elevator deflection. The airplane will start to respond to the small elevator deflection, but as it does so, the sensors of the autopilot B supply an opposing command to transfer valve B. As actuator B tries to move and rotate the main quadrant, the preload forces of the main quadrant and A autopilot cam must be overcome. Again, the sum of these forces is greater than the preload force on B autopilot cam, and its cam spring yields. This allows the input link to the actuator B to rotate and move its pilot control valve. Now the input from the transfer valve B is cancelled; the two elevators are deflected slightly in opposing directions, and the airplane continues on its path undisturbed. Therefore, the dual system is inherently fail-passive.

In the following discussion the phrase "cam-out" will be used with reference to an actuator, when its autopilot cam spring preload has been overridden and its transfer valve flow is cancelled by flow from the pilot's control valve. Also, it will be seen in Fig. 5 that linear transducers are connected to the pilot's control valves. The polarity and magnitude of their signal outputs are indicative of pilot valve travels, and supply intelligence when cam-out occurs, as well as the direction of commanded surface which caused the cam-out. These transducers will be referred to as "cam-out sensors."

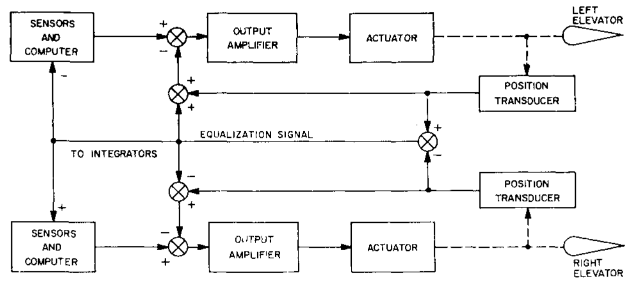

Fig. 6 Dual-pitch channel equalization.

Equalization

In operation of dual autopilots, it is to be expected that tolerances will be such as to result in unequal commands to the two transfer valves. This does not affect performance, as it can be shown that this system will respond to the smaller of the two commands, with one actuator controlling. The other actuator will be cammed-out and slaved to the controlling actuator. However, the cam-out transducers provide intelligence to a failure-warning system, and nuisance failure warnings cannot be tolerated. Therefore, means were devised for equalizing the commands from the two autopilot channels (Fig. 6). There is a certain amount of compliance in the control system linkages, so that relative elevator positions can disagree by approximately 1° before the force unbalance of the system is enough to initiate cam-out of an actuator. An equalization reference signal is obtained by subtracting the two actuator position transducer signals. This error signal is fed back to the two autopilot channels in a sense to increase the command to the elevator of least deflection, and decrease the command to the elevator of greatest deflection. The equalization signal is fed back to the output amplifier of each channel for short-term correction, and to an integrator in each computer signal path for long-term correction. The "authority" of the equalization signal is very important since it tends to propagate a failure from one autopilot channel to the other channel. With the implementation chosen for the 727, the equalization signal authority is inherently limited at the sensor level by the mechanical compliance of the system. (The elevators can never disagree in excess of the compliance range without causing actuator cam-out.) Gain authority is controlled by using redundant passive circuit elements whose failure modes cannot result in a gain increase. Hot-wire fault protection is inherent in that a fault at any point in the signal chain will cause dual opposing actuator cam-outs, shown previously to be a passive failure. The authority of the equalizer signal is restricted then to only that required to compensate for tolerance build-up in the two pitch channels, and thus keeps the elevators tracking within the compliance range below the cam-out threshold. For example, in the 727 a hardover failure at one autopilot output amplifier will result in dual opposing cam outs of the actuators for a pitch attitude transient of less than 1 deg, and automatic disconnect will occur in less than 1 sec, warning the pilot and leaving the flight path essentially undisturbed.

A most desirable goal has been achieved through the previously described implementation: the components of the system can be maintained within practical tolerances and will provide dependable performance that is both safe and free from nuisance disengagements. It is not enough for a system to be reliable in terms of the probability of detail part failures, and safe in terms of fault detection. If it is necessary to maintain the components to unreasonably close tolerances in order to preclude nuisance disengagements, then such a system will not be dependable and will not contribute to lowering the operational weather minimums.

Monitoring of the Dual-Pitch Channels

An exhaustive failure analysis has indicated that all active and passive modes of failure are manifested by the relative states of only four signals in the dual channel system. The signals of significance are the two cam-out transducer signals and the two signal outputs from the autopilot output amplifiers. Certain relative states of these signals are indicative of malfunctions, whereas other relative states are indicative of normal performance. Fail-safe monitoring, with automatic disengagement and pilot warning, required the transposition of the states of these four signals into corresponding states of redundant relays, in a fail-safe manner. The mechanism for achieving this transposition has been referred to as a fail-safe amplifier. Under normal operation, the output of this amplifier energizes two pairs of relay coils. In order that these relay coils remain energized, it is necessary that the amplifier properly transmit an 800-cycle signal, applied at its input. In this way, the fail-safe amplifier is self-checking. A signal that is to be monitored is connected to the input of the fail-safe amplifier. If the level of the monitored signal exceeds a prescribed threshold, it will cancel alternate pulses of the 800-cycle reference signal and result in de-activating the associated pair of output relays. The pair of output relays which is de-activated corresponds to the phase of the monitored signal. The integrity of the monitored signal path is

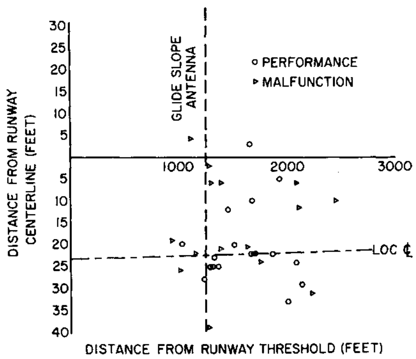

Fig. 7 Touchdown dispersions, Runway 29—Oakland.

established by tracer signal techniques. This is not intended to be a failure analysis of the monitoring system, but rather to indicate the basic philosophy used in monitoring the dual pitch channels. By transposing signal states into corresponding states of redundant relays, and then by interconnecting the contacts of these redundant relays in the proper fashion, the monitor provides automatic disengagement in the event of a malfunction in the system. At the same time, it ignores those conditions resulting from normal operation.

The redundant relay contacts of the fail-safe monitor are interconnected to perform the following functions:

1) Disengage the system if a single cam-out is indicated unless the cam-out agrees with the command from the autopilot output amplifier. This protects against a failure in the actuator which would cause it to revert to the slaved mode, or a failure of the transfer valve (active or passive).

2) Disengage the system if dual opposing cam-outs are indicated. This protects against any active or passive failure in the sensors and electronics or an active failure of the actuator.

It is significant to note that the monitor ignores a single cam-out when it agrees with the sense of the autopilot command, as well as a dual cam-out if the cam-outs are in the same direction. Neither of these conditions reflects a fault. Thus, the monitor has met the objective of detecting true failures and eliminating nuisance disengagements, thereby providing both the safety and dependability required for lower weather minimums.

Certification Program—Laboratory Phase

Prior to flight testing the fail-passive automatic landing system, laboratory tests were carried out with the autopilot hardware in a simulated airplane environment. The test setup consisted of coupling the preproduction autopilot hardware to the 727 Flight Controls Test Rig and an analog computer simulation of the 727 airframe equations of motion. The objectives of the laboratory tests were to evaluate the effect of system tolerances on both performance (including safety) and dependability (susceptibility to nuisance failure alarms) and to verify the monitor responsiveness to simulated malfunctions.

System failure modes investigated in previous autopilot programs involved only passive or instantaneously saturated malfunctions of signal paths. Since the automatic landing system is operating in one of the most critical phases of flight, the failure detection monitor was required to detect time dependent failures (ramp-type malfunctions), e.g., a slowly changing vertical gyro reference caused by a failure in its erection circuit. The failure mode investigation included taking into account those tolerance distributions that would be most significant in reducing the monitor sensitivity for detecting each failure condition.

The laboratory test results were combined with a detailed description of the monitoring techniques to form a "failure analysis" document of the automatic landing system. This document was submitted to the FAA along with a proposed flight test demonstration specification document in request for an FAA Type Inspection Authorization (TIA). The flight test specification called for demonstrating the failure modes which the laboratory study showed to be most critical, as well as demonstrating the system automatic touchdown performance.

A TIA for the Model 727 Automatic Approach and Landing System was issued by the FAA, dated December 28, 1965. Basically, the TIA approved testing of an automatic approach and landing system configuration to meet performance requirements of Category II and automatically land the airplane under visual flying rules (VFR) conditions below the Category II weather minimums. The automatic landing performance was to be evaluated using best known criteria at that time without benefit of established approved criteria by the FAA.

FAA Flight Test Evaluation

In order to demonstrate the automatic landing system to the FAA, the autopilot had to be in a production configuration, and the test airplane had to reflect production standards for all equipment that interfaced with the autopilot. The TIA required that specific ground checks be made and witnessed by FAA personnel, to substantiate that the automatic landing system installed on the test airplane conformed to the drawings and diagrams presented to the FAA in request for a TIA. Bench and airplane ground tests also substantiated that the monitor threshold levels were at their least sensitive values with respect to malfunction detection, and that the control system power packages reflected the worst case tolerance situation established by the system failure analysis for the most critical system failures.

In-flight demonstration of the system to the FAA began on March 15, 1966. All simulated malfunction testing and the majority of performance testing was conducted at the Oakland International Airport in California, a Category II ILS facility. Performance testing was also conducted at Portland International Airport in Oregon, Seattle-Tacoma International Airport in Washington, and Boeing Field in Seattle to provide cross-comparison data of the system operation at different ILS ground facilities. FAA demonstration flight tests, involving 72 approaches, were 90% complete after 3 days of flying. The FAA required that satisfactory system performance be demonstrated under moderate turbulent, windshear, and crosswind air conditions. These air conditions were finally found at Stapleton International Airport, Denver, Colo., where the flight tests were completed on April 29, 1966.

Thirty-four approaches were conducted at Oakland with simulated malfunctions. All malfunctons were inserted at altitudes below 100 ft (Category II MDA). At no time was the FAA pilot made aware whether a given approach was to demonstrate performance or to demonstrate the system responsiveness to a failure. The types of malfunctions demonstrated were as follows: 1) autothrottle advance and retard hardovers during flare, 2) elevator nose-down and nose-up hardovers at approximately 80, 50, and 30 ft of altitude, 3) elevator nose-down and nose-up ramp fault commands at approximately 80, 50, and 30 ft of altitude, 4) failure of the system to provide a flare command, 5) aileron hardover at flare, 6) roll vertical gyro ramp fault at approximately 80 and 50 ft of altitude, and 7) both yaw dampers inoperative and one operative with a hardover at flare.

The ramp-type malfunctions were inserted both above and below the monitor threshold. At no time did the FAA pilot respond to an inserted malfunction by visual cues before the autopilot monitor disconnected the system. Most approaches were accomplished with the pilot remaining under the hood well below the Category II MDA, and in some cases, below 50 ft. Recognition of a system malfunction by a disconnect of the autopilot was followed by a manually con-

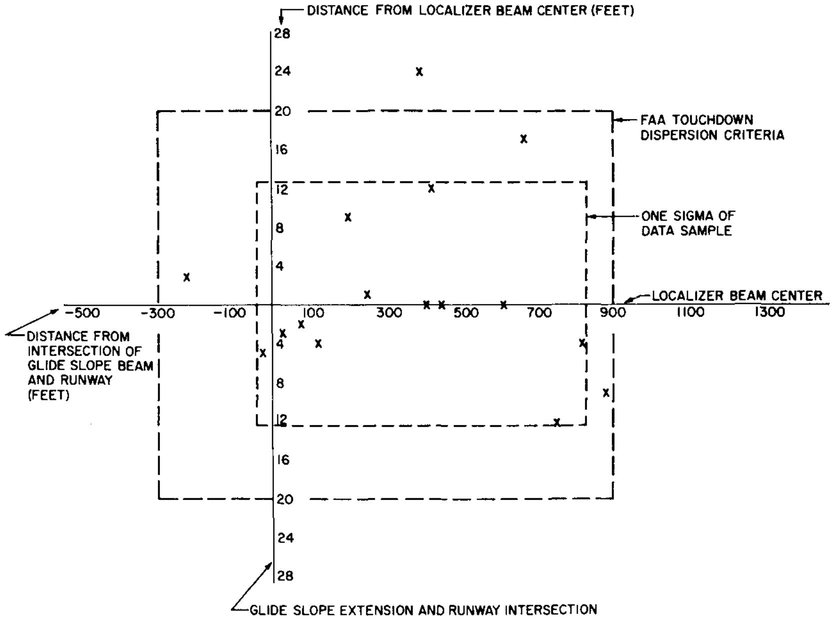

Fig. 8 727 automatic landing system certification touchdown dispersions compared to FAA criteria.

trolled go-around or landing at the discretion of the pilot. Failure of the flare mode was demonstrated at the request of the FAA to assure that the airplane remained in a nonhazardous attitude following fade-out of the glide slope control mode.

Sixteen approaches were conducted at Oakland to demonstrate the automatic approach and landing system performance to touchdown. All met the Category II performance criteria to 100 ft, and were continued to touchdown. Figure 7 illustrates the main gear longitudinal and lateral touchdown dispersion relative to a line on the runway designating the glide slope antenna location and the runway centerline. Included in Fig. 7 are the touchdown points for approaches where simulated malfunctions were undetected or were detected by the autopilot monitor just prior to touchdown. No specific FAA criteria existed with which to compare the performance results of the automatic landing system. However, the flight test results were compared with the results of laboratory studies, and all results agreed within 15% of predicted error values.

The approaches conducted at fields other than Oakland, to demonstrate system performance at several ILS facilities, exhibited touchdown dispersions comparable to those shown in Fig. 7. The Denver approaches satisfied the wind conditions of moderate turbulence, as classified by the FAA pilot, and were conducted with crosswind components between 13 and 26 knots as calculated from the airport tower reported winds. All approaches, whether for performance or malfunction detection, were considered by the FAA pilot to provide the controllability desired of an automatic approach and landing system, with an adequate margin of safety when the autopilot automatically disconnected upon recognition of a malfunction. Type certificaton for the 727 automatic approach and landing system was received from the Federal Aviation Agency in June 1966.

Conclusions

As far as Boeing and Sperry are concerned, the 727 automatic approach and landing system met the self-imposed design goals established at the outset of the program. Industry and the FAA have yet to detail an acceptable performance criteria for Category IIIA automatic landing systems.

However, an Agency Advisory Circular draft was issued last spring specifying tentative performance criteria for automatic landing under Category II weather minimums. In all probability this circular will, with some modifications, be the basis for performance criteria for Category IIIA automatic landing systems.

Let us now compare the results of the 727 performance testing at Oakland with the FAA first draft criteria for automatic landing under Category II weather minimums. The FAA circular states that the aircraft centerline and main gear touchdown dispersion should be shown on at least a one-sigma§ probability to lie 1) laterally, within ± 20 ft of the ILS localizer beam center, and 2) longitudinally, within -300 and $+900$ ft of the intersection of the glide slope beam center and the runway.

Figure 8 shows the performance touchdown data, presented in Fig. 7, replotted with respect to the Oakland ILS localizer beam center. For the sample shown, the one-sigma distribution falls well inside the FAA boundary. In fact, the FAA boundary can well represent a two-sigma distribution. However, note that this data reflects only a small sample of touchdowns, and an accumulation of in-service data must be gathered under normal operational environment in order to substantiate any conclusions drawn here.

The 727 automatic landing system represents the AFCS state-of-the-art as it exists today. The system has the capability both in performance and safety to extend the weather minimums to Category IIIA. As new techniques are developed in the area of "fail-operational" approach systems, whether the philosophy be complete automatic control or specific roles for both pilot and autopilot, the 727 system has the potential for growth to an all-weather blind-landing system.

§ These are likely to become two-sigma criteria.