Military and Civil All Weather Landing Systems for C-141

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The landing function without dependence on ground base systems is accomplished through the vertical navigation computer. A two step programed let-down to a predetermined longitude and latitude is a concept of the system. In favorable terrain the let-downs and approaches are planned to 200 ft alt. The computer outputs can be used by the flight director for manual pilot control and by the automatic flight control system (AFCS) for automatic modes. The system is designed for future improvements so that when precision radar systems are developed, utilizing ground reflectors, landings to touch-down can be accomplished. Automatic throttles provide air speed control, and the AFCS relieves the pilot of flight path control. Radar altimeter indicates precise altitudes to the pilot to within ± 1 ft. Automatic landing utilizing instrument landing system (ILS) ground based system is accomplished through the auto pilot coupled to glide slope and localizer. At 100 ft alt the radar altimeter gives the signal to the landing flare computer and programs let-down, flare, and touch-down. Commands are presented to the pilot through the flight director system for manual control. The go-around computer determines optimum path if the pilot determines to abort.

Introduction

THE Air Force C-141A has been designed as a jet cargo transport. It will be used by Military Air Transport Service (MATS) to transport cargo and personnel to military bases throughout the world. Because of the importance of completing missions, the airplane must be capable of landing under conditions of limited visibility. The C-141 also has been designed as a commercial air freighter and the airplane received its FAA Type Certificate on January 29, 1965. The all weather landing system, therefore, is being designed to meet both military and civil requirements. In some cases the military and civil all weather landing system is identical. This is the system concept that relies on ILS and other ground landing aids that are in existence at the major commercial airports throughout the world, and also at many military air fields. The C-141 has an additional all weather landing system (AWLS) concept that does not rely on these ground facilities because of the requirement for world-wide operations and of the necessity for flying in military troops and supplies to various non-ILS equipped air fields in areas where world conflicts may arise. This concept utilizes a vertical navigation computer for programed let-down and approach to a given latitude and longitude point of a runway. This paper describes the basic design aspects of these two concepts.

General Arrangement

The following is a description of some of the airplane basic characteristics considered important for automatic landing: a high wing swept 25° at the quarter chord, the wing area is 3228 sq ft^2, and the maximum take-off weight is 316,600 lb. Normal landing weight is 257,500 lb. The low wing loading of 78 psf at landing weight allows approach speeds as low as 131 knots and touch-down speeds of 126.5. The airplane, at this landing weight, can land under FAA rules in 5750 ft. These low speeds for this large transport are beneficial for landing under limited visibility. The moderate wing sweep provides for good stability and control characteristics. The airplane has a "T" tail and the movable stabilizer for trim and the elevators for pitch control operate above the wing wake and afford excellent stability and control.

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Flight Control System

The flight control system (FCS) and its characteristics is another essential element. Lateral control is by conventional ailerons operated by dual full power units at each aileron. Artificial feel is through a spring cartridge mounted on the rear beam at the center of the airplane. Yaw control is through a conventional rudder operated by dual full power units located on the rudder torque tube. Artificial feel is provided through a spring cartridge assembly. Pitch control is by elevators operated by triple full power units mounted at the top of the vertical stabilizer. Artificial feel is provided through a three step spring cartridge and by a "Q" system that receives its inputs from dual central air data computers. Pitch trim is accomplished by positioning the stabilizer by an actuator that can be powered hydraulically or electrically. Rudder and aileron trim is through actuators incorporated with the feel mechanisms and positions the control surfaces for trim. Pilot control forces have been tailored carefully; they are essentially light and provide responsible reactions to pilot inputs.

Automatic Flight Control System

The AFCS was designed from the beginning to have some provisions for all weather landing. The auto pilot is an Eclipse Pioneer PB-60 system with the following features: control wheel steering, altitude hold, Mach hold, split axis control and coupling for localizer, glide slope, and radio navigation modes. The yaw channel can be considered separate from the rest of the auto pilot as it is used also as the dual yaw damper system.

Based on flight tests of the pilot factors program on the T-39, the concept of force wheel sensors and split-axis control is considered essential for control by the pilot on flying the AWLS commands on the manual mode. Tests on the C-141 have proven to pilots also, the advantages of these features. The pilots report the control wheel steering mode is very beneficial as automatic trim always is applied through the auto pilot, and during configuration changes (such as lowering flaps or landing gear) trim is automatic and pilot control is easy to maintain. This also is very important in the case of decision to make a go-around.

Basic AFCS Operation

The auto pilot engages on the localizer and captures the glide slope and makes the approach to the runway. The FAA

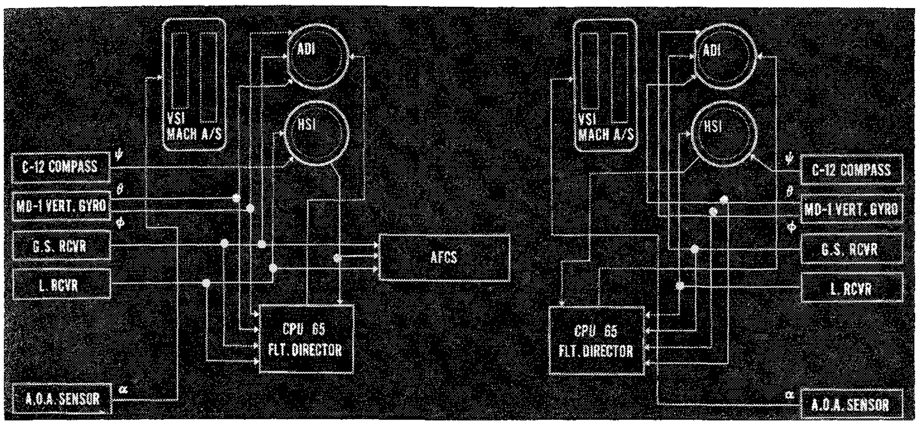

Fig. 1 AFCS-basic.

rules on auto pilot operation specify that the minimum altitudes for operation are based on the loss of altitude on auto pilot hardovers with a 1-sec delay before initiation of recovery. This varies for different aircraft and somewhat on the test procedure, but the flight test on the C-141 has shown altitude losses of less than 45 ft to recover from hardovers. The pilot then must disengage the auto pilot and take over at the FAA designated altitude and continue the approach, initiate flare, decrab for cross-winds, touch-down, and roll-out.

Block Diagram Basic

Figure 1 is a block diagram of the present auto pilot and flight director system. The pilot's system is shown on the left and the co-pilot's on the right. Practically everything is dual. The AFCS receives inputs from the pilot's horizontal situation indicator (HSI), glide slope receiver, and localizer and commands yaw; and receives roll and pitch attitude of the airplane through the elevator and aileron servos and the dual rudder yaw damper servos.

Category II Landing Concept

The lower minima landing system for the C-141 consists of two different configurations. For production, a system for category II operation is being programed. This system is being designed to meet the category II requirements as specified in the FAA advisory circular (AC No. AC 20-31). The production configured airplane will be demonstrated to meet FAA category II criteria with automatic touch-down. The system is configured such that the prototype aircraft then will be equipped with additional components as required to meet category III B requirements, as now known. This will involve duality of equipment in certain key areas. The production category II system is described first and the category III B development system will be described later. Essentially, the two are similar in many respects and the category II is planned as a base for adding additional equipments or features believed necessary for category III B operations.

On category II landings the system automatically engages glide slope, landing monitors are armed, flight path on glide slope is maintained by the auto pilot, the flare computers are armed on glide slope engage, and the rate of descent is controlled from flare engage to touch-down. Flare engage occurs at approximately 60 ft, and then the throttles are retarded slowly to accomplish touch-down. The pilot manually removes any crab angle that may exist and controls the roll-out.

A monitor is added to the automatic pilot so that it will disengage on failure automatically and thus preclude loss of altitude from hardovers and permit automatic pilot operation to touch-down. The concept maintains the pilot in the automatic control loop as an active element and with complete control of the system through the use of the force wheel steering concept. The pilot serves as the reliable element in the system, providing the redundancy necessary for fail safe operation. An optimum climb out computer is installed which presents commands the pilot can use if he decides to discontinue the landing and climb out.

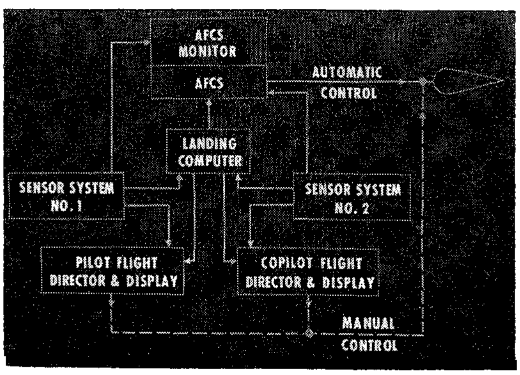

Fig. 2 Manual-automatic concept.

Manual/Auto Concept

Figure 2 depicts the manual/auto basic concept. In the center the landing computer system generates the signals for automatic landing functions. A signal is sent to the AFCS to control automatically the aircraft through the aileron, elevator, and rudder servos. The AFCS is self-monitored and disengages on malfunction. Concurrent with this, the computer sends signals to the pilot-co-pilot flight directors, and the commands are displayed for the pilots on the flight director displays. The landing computer is dual and will be described in detail later. Separate systems provide the inputs to the dual systems, and the sensors systems 1 and 2 contain all elements for providing the automatic landing functions and the pilot presentations.

Category II Monitor Concept

The category II system has dual landing computers and essentially is two systems—the pilot's manual system and the automatic system. The pilot's sensors feed the pilot's landing computer and the pilot's flight director and attitude direction indicator (ADI). The automatic system receives its inputs from the co-pilot's sensors and provides signals to the landing computer and this output is fed to a comparator. The resulting signal is sent to the co-pilot's flight director and ADI and feeds the auto pilot system. Although the system is not completely monitored, the monitoring is provided on the more sensitive elements such as the sensors, flare computer, and auto pilot. Detectable faults result in the disengagement of the axis of the automatic system affected and alert the pilot to failures through fault lights. The landing computer con-

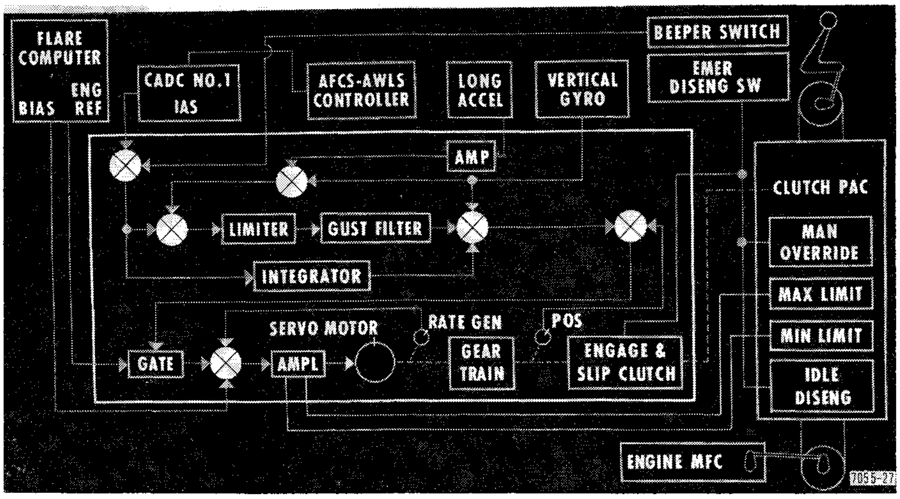

Fig. 3 Auto throttle system.

tains a flare computer commanding rate of descent exponentially which will approach $2\frac{1}{2}$ fps at 0 alt.

Auto Throttle

The automatic throttle system (ATS) is utilized to control automatically the airspeed of the aircraft during approach and flare. When the system is engaged, the throttles are positioned automatically to maintain the proper airspeed. The system features the capability of individual retrimming or shutting down of any throttle without affecting the position of the remaining throttles, and without disengaging the auto throttle system. Disengagement of the automatic throttle system alone is achieved by operating the auto throttle engage-disengage switch located on the outboard throttle lever. System design is such that under all conditions of engagement the pilot can override physically the automatic system.

A block diagram of the ATS system is shown in Fig. 3. The airspeed error command is generated in the central air data computer (CADC). The output of the sensor is sent to a limiter, gust filter, and integrator. The error signal is filtered to minimize the effects of gusts on the motion of the throttles without degrading the airspeed capability of the system. The error signal from the gust filter is summed with a lagged pitch attitude signal to improve the damping of the system and to minimize errors during maneuvers such as turns and glide path capture. Airspeed error and pitch attitude signals are supplied to an integrator that eliminates long term errors in the control system. This final signal is sent to the throttle servo to position the throttles to maintain the selected airspeed. A single servo is used with a drum and clutch pack assembly to drive the aircraft throttles.

A constant bias signal is applied to the throttle servo in series with the servorate feedback. Normally, the throttle follow-up signal, which operates through the static gate, synchronizes the bias signal. After the static gate has been opened by the flare-engage signal from the flare logic-circuit, the bias signal drives the throttles at a constant rate from the approach setting to flight idle. The servoloop of the airspeed computer also is monitored. If a signal from the comparators or the power monitors is received, the ATS system will be disengaged and proper annunciator light identification mad to the pilot.

Go-Around System

A go-around computer system provides the pilot optimum climb-out in the event he decides to abort the landing. This system is shown in schematic in Fig. 4. Angle of attack signals are fed to the go-around computer from an angle attack vane.

During engagement of the go-around mode a longitudinal accelerometer furnishes the go-around computer with an indication of the longitudinal acceleration of the airplane to permit derivation of the optimum climb-out path. Flap position sensors are included to account for lift variations due to flap settings.

Rotation, takeoff, climb-out, and go-around computations are accomplished in the go-around computer. This system provides display of programed or command angle-of-attack $\alpha\ c$ on the ADI indicator. The pilot will fly by the steering pointer and the aircraft always will accomplish the optimum rotation at takeoff and climb-out. A timer function interconnected through the squat switch enables the inclusion of ground effect in the takeoff mode. A go-around switch is located on the pilot's control wheel and, when actuated, presents the go-around commands on the ADI and disengages the auto-land signals.

Pilot Presentation

Figure 5 is the revised instrument panel with the new features for AWLS. In the center the HSI is unchanged. The ADI is modified to provide a radar altimeter symbol operating over the final 200 ft of approach, and the pitch steering bar also is used for auto climb-out commands and automatic landing commands. The vertical scale instrument (VSI) airspeed Mach and altitude indicators are unchanged.

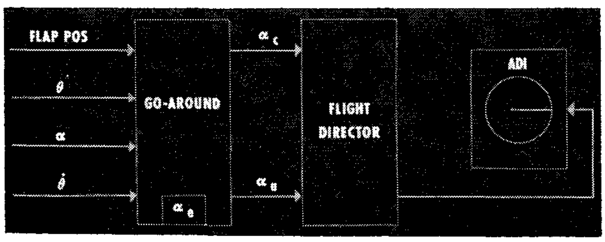

Fig. 4 Go-around computer system.

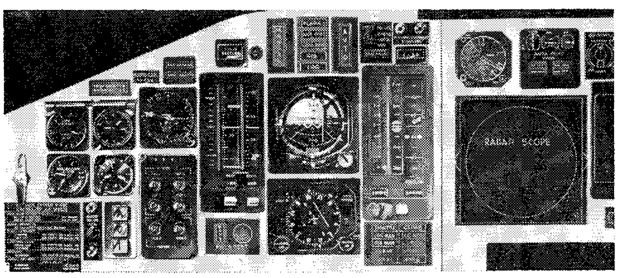

Fig. 5 Pilot presentation.

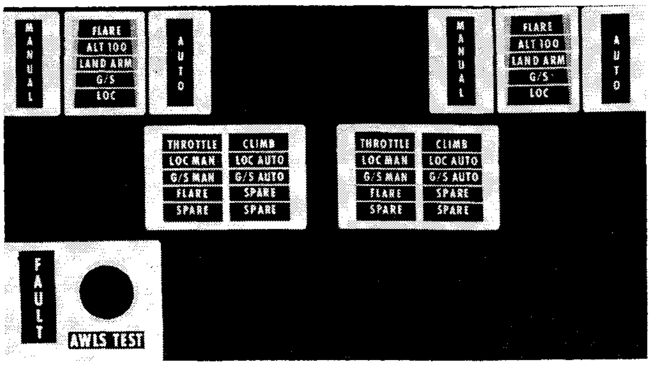

Fig. 6 AWLS information display.

Above the radar scope is a new indicator for radar altitude. The scale reads in feet and its range is 0 to 2500 ft. Above the ADI is a new progress display panel. This panel was placed in close proximity to the flight director instruments so the pilot can monitor the progress of the indicators on auto landing while also monitoring the flight instruments. The airway marker light panel has been moved down below the clock. To the left of the clock is the accelerometer. The co-pilot also has the new ADI and the new progress display panel. Other new additions in the flight station are a new AWLS test panel and new fault identification annunciator light panels located on the instrument panel.

AWLS Displays and Test Panel

Figure 6 is the AWLS information display elements. Two progress display panels are provided: one for the pilot's panel and one for the co-pilot's. Two fault panels are provided also. A single AWLS test panel is located on the pilot's instrument panel next to the HSI.

The progress display panel is located above the ADI. It has been placed and planned to be read from the bottom to top following the auto-land progress. These lights illuminate green to indicate operational sequence. Reading up the first is localizer engage; next glide slope engage; next indicates land arm, which indicates performance monitoring now is operative; next is altitude 100 ft indication, which is an important progress step and may be used as a decision point; and next is flare engage, indicating throttles begin to retard and nose of airplane eases up. There also are provided two master warning lights. The light marked "auto" comes on red if elements of the auto pilot and other elements necessary for the automatic mode are inoperative. Next is a light reading manual and this illuminates when the instrument system is inoperative and consequently no valid commands for landing in manual AWLS mode are available.

The philosophy of the fault warning system is based on presenting to the pilot the status of two separate modes: auto and manual. Although some of the systems are based on single system plus a monitor concept, provisions have been made that in case of this single malfunction, failsafe operation of the airplane can be maintained. For instance, a failure of any one of the elements in the automatic system will cause that system to be inoperative; however, the pilot still can have the commands presented on his instruments and he can take over manual control and accomplish the landing. In case there is a single failure that renders the manual system inoperative, he can continue his auto landing, or, if he so desires he can initiate a go-around. A single failure in the throttle system will render this system inoperative; however, when the warning light conveys this to the pilot he can manually take over the airspeed functions and the automatic landing system will still land the airplane. Other elements that are monitored and fault indications that are provided to the pilot or co-pilot are localizer, manual and auto; glide slope, manual and auto; climb or go-around system; and throttle system.

Test of the systems is based on the concept of "faulting" and then "resetting" of the monitors. The test button is pushed and the comparator and functions of each system are checked. The test "faults" and "resets" individual monitors and proceeds through all the elements of the system. When the test is complete the test button snaps out and the master warning light illuminates; the depression of the switch extinguishes the light and resets the system. If, however, there is a failure or fault, the fault light will illuminate and the test will stop.

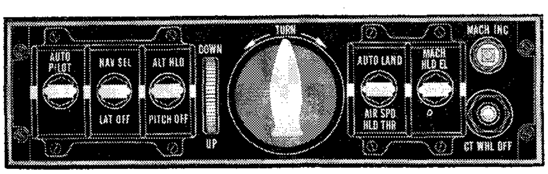

Fig. 7 AFCS-AWLS control panel

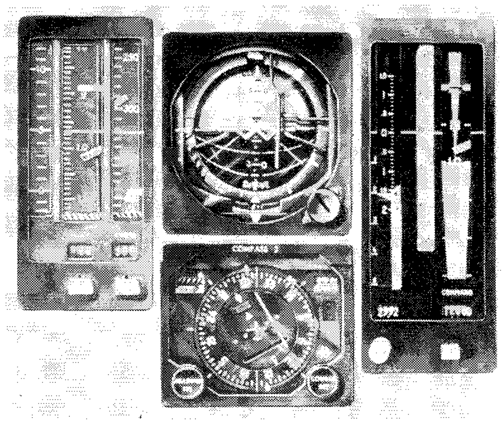

Fig. 8 Integrated flight instrument systems.

AFCS Control Panel

Figure 7 shows the modified AFCS panel. There are nine function switches that are auto pilot on/off, navigation select and lateral axis, altitude hold or pitch axis, pitch control, turn control, auto land/airspeed hold throttles, Mach hold elevator, a Mach increase button, and control wheel steering on/off.

Integrated Flight Instruments

The CPU-65 flight director system is replaced with a new system that has greater accuracy and the transfer functions of the system are made compatible with all other elements of the AWLS. The changes to the ADI are the addition of the radar altimeter tape to be used for accurate closure to the runway, as shown in Fig. 8. This tape is in addition to the radar altimeter instrument that reads from 0 to 2500 ft. This tape on the ADI has a range of 0 to 175 ft. It first appears on the instrument at approximately 175 ft alt and continues to move up to the airplane reference on the instrument. The other

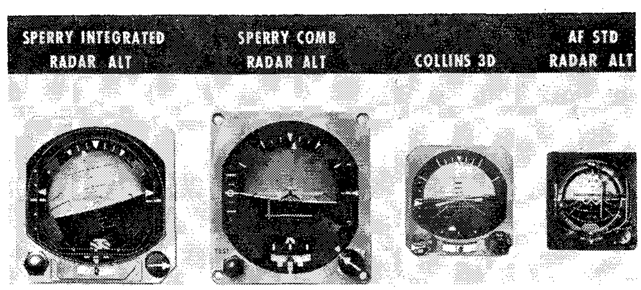

Fig. 9 Flight directors.

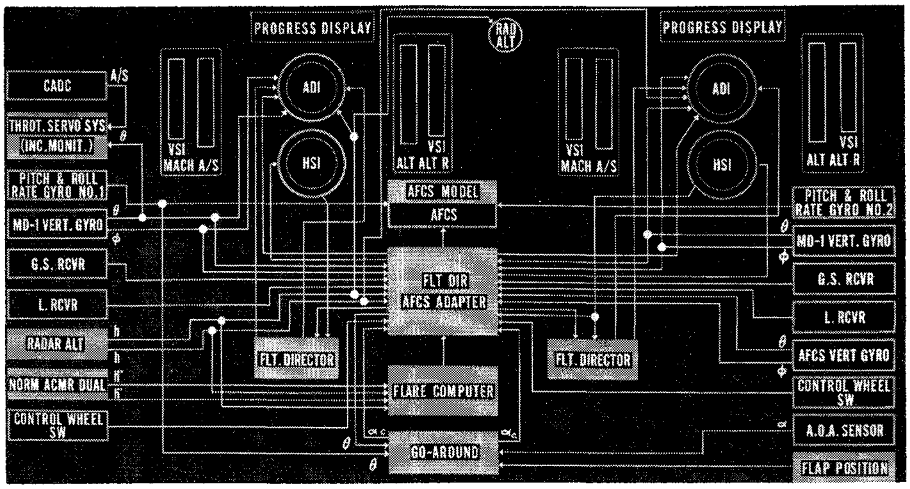

Fig. 10 AWLS.

addition to the ADI is to incorporate the command for automatic go-around on the pitch command bar.

Study of Flight Directors

A study has been made of the several new flight directors and ADI's that are under development by various manufacturers; shown in Fig. 9 are four of several being investigated. These four are misleading in the figure as they are not to the same scale. Actually, all four are the same case size. These four will be discussed reading from left to right in the figure. The first is a Sperry integrated display instrument with radar altimeter. Significant features of this instrument are a spherical horizon with a blue background and an integrated pitch and roll command bar. This has a servoed radar altimeter tape and expanded localizer indication. On the right-hand side, raw data for glide slope are presented; on the left is a slow/fast indicator. The second instrument is a Sperry unit also combining the radar altimeter indication. This instrument has the new colored horizon with standard pitch and roll bars. The raw glide slope is presented and also the slow/fast indicator. The principal difference is that the radar altimeter is a galvenometer bar type. The command presentation is conventional. The third instrument is a Collins 3D ADI. This has the new colored 3D curtain type horizon. Integrated command information is presented and glide slope information is on the left; the latter has a servoed radar altimeter tape. The fourth instrument is the Air Force standard ADI with a radar altimeter function added. The horizon is a spherical type with a black and white presentation. It has pitch and roll command bars; a glide slope deviation indicator is on the left-hand side. It has a servoed altimeter tape and the localizer indicator in the bottom center.

Block Diagram AWLS

Figure 10 is the block diagram of the original auto pilot and flight director system plus the additional items that comprise the AWLS. The display panels, modified instruments, auto throttles, go-around computer, and flight director have been described.

The auto pilot has a monitor added to this system. This monitor disengages the auto pilot on malfunction and a red warning light comes on the pilot's panel. In this case the pilot can continue the landing by manually taking over the flight controls. The throttle servo and flare computer are still operative. The flight director and AFCS adapter provides for display information on the instruments for the pilot to follow. Progress displays also will function. The functions of the flare computer will be described next. The flare computer generates signals to both the automatic and manual systems resulting in a touch-down at a nominal $2\frac{1}{2}$ fps rate of descent. The flare computer receives inputs from a monitored radar altimeter that furnishes altitude and fixed altitude switching information to the computer. Other inputs to the flare computers are from the two normal accelerometers. These furnish vertical acceleration signal ($\ddot{h}$) for integration in the flare computer.

The radar altitude signal is limited to an output signal comparable to the flare engage altitude. The output of this limiter is fed to the flare engage switch that operates to initiate flare. To the limited radar altitude signal a bias is added to provide touch-down at $2\frac{1}{2}$ fps. The altitude rate and altitude signals are added. During an approach, and prior to flare, when all conditions are static (wind, airspeed, glide path angle), the sum of these signals [the altitude error (h_e)] is zero. Since these perfect approach conditions never will be realized, a synchronizer will keep the signal nulled prior to flare engage. To prevent any nose down pitch changes after flare is initiated, the signal is passed through an unsymmetrical limiter.

At the initiation of the flare engage the synchronizer is converted to an integrator by the operation of the flare engage static reference. The resultant performance of the computer is more repeatable if the flare gain is kept reasonably low. To accomplish a low gain without excessive command errors, a ramp signal commanding nose up is added to the altitude error signal at the initiation of the flare maneuver.

Comparators between the main signal and monitor signal chains provide monitoring of the flare reference, altitude error, and flare output signals. During preland system test, test signals are inserted in the monitoring system. The test signals are interpreted as error by the comparators, causing them to alarm, thereby checking the operation of each comparator.

Vertical Navigation for Approach

The C-141 AWLS has a second mode that can be used for military operation at forward bases where there is no ILS or ground landing aids. This system utilizes a vertical navigation computer that will permit a two-step programed let-down to a predetermined aimpoint and altitude, as shown in Fig. 11. It is planned to use this concept, in favorable terrain, down to lower minimums than now attained, where a landing may be made if visibility is attained. The computer outputs can be used by the flight director for manual control and by the auto pilot for automatic control. It is planned to study the use of precision radar with ground reflectors to provide automatic guidance to touch-down independent of ILS or other ground based systems.

The requirement for low altitude accuracy dictates a tight control loop including the aerodynamic characteristics of the airplane. The vertical navigation system must sense aircraft maneuver with respect to the programed flight path, and delivery output signals which will enable the pilot or auto pilot

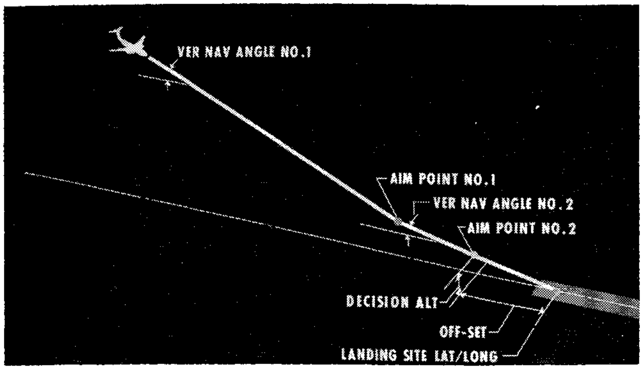

Fig. 11 Vertical navigation for approach.

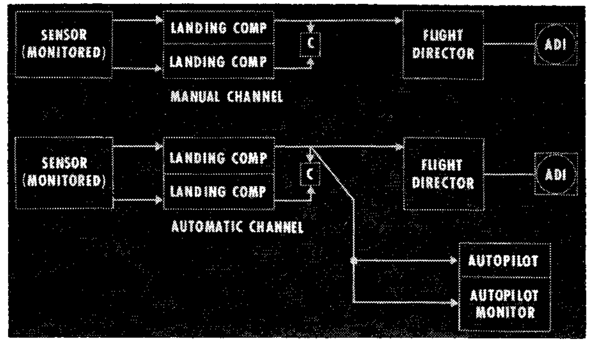

Fig. 12 Category III B monitor concept.

to fly the desired path without exceeding an allowable level of G-loading. Over-all loop response should be rapid but without appreciable overshoot at all altitudes and speeds, for all conditions of loading, with flaps and/or spoilers in normal flight positions. Transitions between different programed flight paths, including altitude hold, should be smooth and accurate. It should be possible to switch from vertical navigation control to normal ILS glide slope for the same aimpoint without noticeable transients.

A requirement that complicates the computer circuit implementation is that of the range of aimpoint distances over which operation may be required for any given programed flight path. Present ranges are between 0.1 and 60 naut miles for a corresponding dynamic range of 600:1. The range of flight path angles desired is from $\pm 15°$ to $\pm 1°$.

Category III B Landing Concept

As described before, a developmental system is being designed in addition to the category II production system just described. This system is called a category III B landing system. It is essentially the same as category II but more dual equipment and monitors have been added to provide for landing in zero visibility. A decrab computer has been added in the landing computer and the decrab function and roll-out are automatic. The category III B system additional equipment will be described in the following section.

Category III B Monitor Concept

Figure 12 is a block diagram showing the basic elements of the category III B system. The manual channel is independent of the automatic channel. The sensors of the pilot system feed to the dual landing computer and a comparator. The command signals go to the pilot's flight director and the landing command signals are presented on the pilot's ADI.

The automatic channel receives inputs from the co-pilot system sensors and these signals go to the dual landing computer and comparator of the automatic channel. Command signals are sent to the co-pilot's flight director and ADI. Control signals are transferred to the auto pilot and monitor for automatic landing.

Comparators between the main signal and monitor signal chains provide monitoring of the flare reference, altitude error, and flare output signals. During this preland system test, test signals are inserted in the monitoring system. The test signals are interpreted as error by the comparators, causing them to alarm, and thereby checking the operation of each comparator.

The operation of the category III B system is essentially as described for category II system in regard to the radar altimeter triggering the descent rates and other functions; but dual altimeters are used. Glide slope and localizer also are dual for the pilot system and the co-pilot or automatic system. The decrab function has been added. This development system has more duality, and more monitoring is required. As such, additional display and features are provided for the pilot for this more advanced system.

Conclusion

The category II system presently is installed in a flight aircraft, and a thorough flight test program is underway with joint Lockheed, Air Force, and FAA participation.