FLIGHT EVALUATION OF ADVANCED FLIGHT CONTROL SYSTEMS AND COCKPIT DISPLAYS FOR POWERED-LIFT STOL AIRCRAFT

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SUMMARY

A flight research program was conducted to assess the improvements, in longitudinal path control during a STOL approach and landing, that can be achieved with manual and automatic control system concepts and cockpit displays with various degrees of complexity. NASA-Ames powered-lift Augmentor Wing Research Aircraft was used in the research program. Satisfactory flying qualities were demonstrated for selected stabilization and command augmentation systems and flight director combinations. The ability of the pilot to perform precise landings at low touchdown sink rates with a gentle flare maneuver was also achieved. Flight research is in progress to demonstrate fully automatic approach and landing to Category IIIa minimums.

INTRODUCTION

Demands which are anticipated to be placed on the operation of STOL transport aircraft due to requirements for precise glide-slope tracking, short field landing performance, acceptable landing sink rates, and adequate safety margins, are expected to dictate a precision of control during the transition, approach, and landing exceeding that which is realized by current-generation jet transport aircraft. The ability of STOL aircraft, particularly those utilizing substantial amounts of powered-lift, to meet these demands may be impeded by tendencies toward sluggish and highly coupled response associated with the low-speed operation, high wing-loading, and substantial thrust turning representative of these designs. For example, pitch attitude control is compromised by poor static stability, by substantial trim changes due to thrust and flaps, by turbulence disturbances, and by an easily excited phugoid mode. Left unattended, the phugoid substantially upsets flight-path and airspeed and degrades glide-slope tracking during the approach. Even if precise attitude control is achieved, the aircraft's response to pitch attitude is adversely influenced by operation at low speed and on the backside of the drag curve (at speeds where induced drag exceeds profile drag). Sluggish initial flight-path response to pitch attitude and the inability to sustain long-term path corrections with a change in attitude make path control with attitude unsuitable. While thrust is a very powerful path control, coupling of flight-path and airspeed (as a consequence of large effective thrust turning angles) and thrust response lags make thrust control of flight path unsatisfactory or even unacceptable. Consequently, it may be necessary to develop flight control and display concepts that improve the inherent control characteristics of this type of aircraft if the operational requirements are to be met.

The Ames Research Center's Augmentor Wing Research Aircraft is a propulsive-lift jet STOL transport that, because of its configuration and operational flight conditions, exhibits some of the control characteristics noted in the foregoing discussion. The aircraft was developed for the purpose of demonstrating the augmented jet flap concept for powered-lift STOL operation and to provide a powered-lift STOL transport aircraft for flight dynamics, navigation, guidance and control, and STOL operations flight research. It was initially procured with flying qualities sufficient to permit the exploration of its flight envelope and to demonstrate the performance, stability and control characteristics associated with the augmented jet flap. Following the proof-of-concept flight tests, a versatile digital avionics system and an array of cockpit displays were installed in the aircraft to extend its capability to support the research program noted above. Two major efforts have been under way to

- define and evaluate stabilization and command augmentation systems (SCAS) and displays for improving flying qualities associated with a manually flown IFR approach and landing

- define and determine the approach and landing performance and pilot acceptance of fully automatic flight control systems and associated displays for visibility conditions down to Category IIIa.

Among the more challenging tasks for either the pilot or an automatic system to perform with these aircraft is glide-slope tracking and flare to a precise touchdown. The following sections describe the results to date of flight research conducted to assess the improvement, in longitudinal path control during the approach and landing, which can be achieved for a given degree of control system and display complexity. Although these control systems and displays have been demonstrated on a specific powered-lift concept, the nature of the path-control improvement is considered to be applicable to other powered-lift aircraft configurations.

SYMBOLS

IFR	instrument flight rules
MLS	microwave landing system
VFR	visual flight rules
Z_{δ_T}	vertical acceleration derivative with respect to the throttle control
$\Delta u_{ss}/\Delta\gamma_{ss}$	ratio of change of steady-state airspeed to flight path due to a change in thrust at constant pitch attitude

$d\gamma/du$	gradient of flight with airspeed at the stabilized approach condition - constant thrust
$\Delta\gamma_{MAX}/\Delta\gamma_{ss}$	ratio of the peak to steady-state change in flight path due to a change in thrust at constant pitch attitude
$\Delta\gamma_{MAX}/\Delta\theta_{ss}$	ratio of the peak change in flight path to the steady-state change in pitch attitude
$\Delta\gamma_{ss}/\Delta\theta_{ss}$	ratio of the steady-state changes in flight path to pitch attitude

DESCRIPTION OF THE BASIC AIRCRAFT

The Augmentor Wing Research Aircraft (fig. 1) a de Havilland C-8A Buffalo, modified by The Boeing Company, de Havilland of Canada, and Rolls Royce of Canada to incorporate a propulsive-lift system. It has a maximum gross weight of 21,792 kg (48,000 lb) and a range of operational wing loadings of 215-272 kg/m^2 (44-55 lb/ft^2). The propulsive-lift system utilizes an augmentor jet flap designed for deflections up to 75°. Rolls Royce Spey MK 801-SF engines power the aircraft with fan air, used to blow the augmentor flap, and with hot thrust which can be deflected over a range of 98° through two conical nozzles on each engine. Primary flight controls consist of a single-segment elevator for pitch maneuvering and trim; ailerons, spoilers, and outboard augmentor flap chokes used in combination for roll control; a two-segment rudder for yaw control; vectored hot thrust for path and speed control; and inboard augmentor flap chokes for lift control. A more detailed physical description of the aircraft and its characteristics is given in reference 1.

Before describing the SCAS, display, and autopilot concepts investigated in this research program, it is useful to review the flight-path control characteristics of the basic aircraft and to identify the objectives for improving flying qualities. Longitudinal path control can be accomplished during the approach and landing by either modulating thrust or deflecting the hot thrust component; however, neither the throttle nor nozzle controls are satisfactory for approach or flare control. Since the approach is conducted on the backside of the drag curve, pitch attitude is primarily used for speed control. Sufficient, short-term path control in response to attitude exists to provide at least marginally acceptable flare and landing precision.

Figure 2 illustrates the aircraft's stabilized path control capability using either throttle or nozzle controls. Throttle control characteristics are shown at the left for the approach flap setting, a nominal approach thrust vector angle of 80°, and for thrust levels corresponding to engine speeds from 90 percent rpm to a maximum setting of 100 percent. A typical approach would be conducted on a 7.5° glide slope at a speed of 65 knots. At the approach speed, the aircraft is only capable of achieving flight-path angles from -4° to -11° for this range of thrust settings. If pitch attitude is maintained constant by the pilot or by an attitude stabilization system, this path control capability is reduced to a range from -4.8° to -9.9° as a consequence of flight-path/airspeed coupling ($\Delta u_{ss}/\Delta\gamma_{ss}$ = -2.2 knots/deg) and the operation on the backside of the drag curve. The steady flight-path/speed relationship at constant thrust for the backside condition is $d\gamma/du = 0.15°/\text{knot}$ and it degrades climb and descent performance when speed is allowed to vary about the approach reference.

Flight-path control capability that can be achieved by deflecting the nozzles at a nominal approach thrust setting of 94 percent rpm is illustrated at the right. The flight-path envelope is expanded over that available using thrust control, with capability of achieving path angles of 2.7° to −13.3° for the maximum range of nozzle angles from 6° to 104°. The relationship of path and speed response to the nozzle control at constant attitude is conventional in that positive path increments are accompanied by increased airspeed and vice versa.

The transient response of flight-path and airspeed to thrust for constant attitude is shown in the time histories of figure 3. Flight-path initially responds quickly to the change in thrust and with an acceptable throttle sensitivity ($Z_{\delta_T} = -0.04$ g/cm or -0.1 g/in.). The equivalent first-order thrust time constant is approximately 0.75 sec. However, the initial path response washes out to a lower value ($\Delta\gamma_{MAX}/\Delta\gamma_{ss} = 2.1$). Airspeed response is decidedly unconventional in that speed decays following an increase in thrust and is in turn reflected in the constant attitude path-speed coupling noted previously.

Time histories of path and speed response to the nozzle control at constant attitude are also presented in figure 3 for comparison with thrust control characteristics. The initial path response to nozzle deflection is sluggish compared to the response to a thrust increment and the response may not be sufficient for tight glide-slope tracking in turbulence. If quicker path response is desired, the pilot must initiate the correction with pitch attitude and follow-up with the nozzle control to sustain the long-term correction. Coupling between flight path and airspeed at constant attitude is conventional as was previously noted. Some pitch control may be coordinated with the nozzle control if the pilot desires to maintain airspeed.

These characteristics of flight-path and airspeed response to the throttle and nozzle controls dictate that the throttles be used for precise glide-slope tracking and that the nozzles be used to augment thrust control for gross path corrections. Due to the amount of flight-path overshoot and path-speed coupling associated with thrust control, it is difficult for the pilot to anticipate the amount of thrust required to initiate and stabilize a path correction. As a consequence, he must devote considerable attention to path and speed control. Attitude control may be used to reduce path-speed coupling by coordinating attitude changes with the thrust control to minimize the speed excursions. However, this requirement for continuous control in the pitch axis increases the pilot's control workload for glide-slope tracking. Furthermore, the control technique is unfamiliar in that nose-down attitude changes are required to maintain speed when the pilot increases thrust to reduce the descent rate, and vice versa.

Raw data IFR glide-slope control down to a decision height of 60 m (200 ft) with the throttles alone was given pilot ratings of 5 to 6. These ratings were based on the Cooper-Harper scale of reference 2 and were due to large path-speed coupling and unpredictable flight-path response. Path-control authority was also considered insufficient for glide-slope tracking in turbulence. As a consequence, glide-slope control required coordinated use of the throttles and nozzle controls and still was given pilot ratings of 5 to 6 due to the sluggish path response to changes in the nozzle deflection and the workload associated with manipulation of the various controls.

The landing flare was routinely performed by pitching the aircraft to a touchdown attitude with some adjustment in thrust to offset high angles of attack or high sink rates at flare entry or to compensate for any floating tendency. Response of the aircraft to the pitch rotation develops adequate normal acceleration to check the sink rate to an acceptable level ($\Delta\gamma_{MAX}/\Delta\theta_{ss} \approx 0.55$). However, a pitch rotation on the order of 10° at a rate of 2 to 3°/sec is required to check the sink rate to 1.8 m/sec (6 ft/sec) and this is considered unsatisfactory for commercial operation. Flare and landing accomplished primarily using pitch with an assist as required from thrust was given ratings from 3-1/2 to 5.

In summary, the requirement to coordinate the use of three controls for precise tracking and to establish the proper flare conditions presented the pilot with an unsatisfactory workload. As a consequence, it is desirable to improve approach path control by eliminating the path-speed coupling, by reducing the number of controls required for path control, by quickening path response for glide-slope tracking and flare, by desensitizing response to winds and turbulence, and by providing better tracking commands to the pilot.

DESCRIPTION OF THE FLIGHT RESEARCH PROGRAM

To achieve desired improvements in control and reductions in pilot workload, combinations of experimental SCAS, display, and autopilot configurations were chosen for evaluation in the flight research program. The SCAS configurations that were evaluated are described in table I. The program proceeded with a buildup in complexity of the control system for improving manual path control, including a throttle-nozzle interconnect to reduce the number of path controllers and to provide path-speed decoupling; speed stabilization to eliminate the back-side of the drag curve operation and to reduce the requirement for thrust modulation; and flight-path SCAS to allow the pilot to control the flight-path vector with pitch attitude so as to reduce the path-tracking requirement to a single control. A fully automatic system was also mechanized for glide-slope capture, tracking, and flare. Evaluations of various displays were obtained for selected SCAS options and for the autopilot mode. Raw data glide-slope tracking was assessed for all the SCAS configurations. A flight director was evaluated for straight-in approaches with the throttle-nozzle interconnect and with the flight-path SCAS, and as an approach monitor for the automatic flight mode. Detailed descriptions of the flight control and display modes are subsequently provided with the discussion of results obtained during the flight experiments. Pitch, roll, and yaw SCAS was provided with all configurations.

Landing approaches were flown on a 7.5° glide slope at airspeeds from 65 to 70 knots to landings on a 30 m by 518 m (100 ft by 1700 ft) STOL runway at NASA Ames' experimental flight facility at the Crows Landing Naval Airfield. Landing approach guidance was provided by a prototype microwave landing system

(MODILS). Research pilots from NASA Ames, the Canadian Department of Transport and National Aeronautical Establishment conducted the flight evaluations in this program. Both VFR and IFR approaches were flown in calm to light wind conditions. Additional evaluations were obtained when possible with surface conditions ranging from strong headwinds to light tailwinds and in light to moderate turbulence. Pilot commentary and opinion ratings based on the Cooper-Harper scale were obtained for all configurations. The pilots' assessments of the acceptability of the manually controlled flare and touchdown were based on the consistency of landing performance (touchdown point and sink rate) which could be achieved for a particular configuration rather than on the ability to land at a specific point within a prespecified sink rate. Flared landings were performed to reduce the approach sink rate (4.3 m/sec or 14 ft/sec) to levels well within the aircraft's landing gear limits (3.8 m/sec or 12.6 ft/sec).

DESCRIPTION OF THE EXPERIMENTAL FLIGHT CONTROL SYSTEM AND DISPLAYS

The aircraft's primary flight controls described previously can be driven through servos commanded by an experimental digital avionics system (STOLAND). This system was developed for NASA Ames by Sperry Flight Systems and is described in reference 3. The major components of the system are a Sperry 1819A general-purpose digital computer and a data adapter to interface the aircraft's sensors, controls, displays, and navigation aids. The controls used for longitudinal path tracking are the elevator for pitch attitude stabilization and the inboard augmentor chokes, throttles, and nozzles for vertical path and airspeed control. The pitch stabilization system is driven by an electro-hydraulic series servo actuator limited to 38.5 percent of total elevator authority. The inboard augmentor flap chokes are full authority controls which are also driven by electro-hydraulic servos. The Spey engines' throttles and hot thrust nozzles are driven by electro-mechanical parallel servos with full control authority. Commands to these controls appropriate for the various SCAS or automatic modes of interest are generated through suitable combinations of sensor information processed when necessary by complementary filters to retain high frequency content while removing undesirable noise or gust disturbances.

The primary instrument displays and system mode controls available to the pilot are an electronic attitude director indicator (EADI), which presents pitch and roll attitude; aerodyanmic flight path; raw glide-slope and localizer deviation; and calibrated airspeed, vertical speed, and radar altitude in digital readout. Flight director command bars can be called up on the display if desired. A multifunction display provides a moving map presentation of the aircraft's position with respect to the desired flight path, as well as heading and altitude status information. A mechanical horizontal situation indicator (HSI) presents aircraft heading and bearing to the navigational aid as well as glide-slope and localizer deviation. A mode select panel provides switches for engaging SCAS modes, the flight director, and various autopilot modes. A keyboard and status display on the center console permits manual entry and readout of instructions to the digital computer.

DISCUSSION OF RESULTS

Results of manual control for raw data IFR approaches with the various SCAS modes will be reviewed first. Contribution of these modes to control of the flare and landing will be noted where appropriate. Next, the influence of improved displays on manually flown approaches will be discussed. Finally, experience to date with fully automatic glide-slope tracking modes will be reviewed. A summary of pilot ratings for the manual SCAS modes for raw data IFR and flight director displays is provided in table II. The results shown encompass the range of pilot ratings obtained in the flight evaluations for each experimental configuration.

Contribution of Manual SCAS Modes

Throttle-nozzle interconnect — A simple means for reducing the flight path-airspeed coupling and improving closed-loop flight-path control for the basic aircraft can be provided by interconnecting the aircraft's throttle and nozzle controls. This interconnect is mechanized by a constant-gain linear crossfeed from the throttle to the nozzle control servo. The sense of this interconnect is to reduce the hot thrust deflection for an increase in thrust, and vice versa. An illustration of the influence of this interconnect on the aircraft's performance envelope is presented in figure 4 for a value of the interconnect gain which essentially eliminates path-speed coupling at constant attitude for the approach condition. The contours on the diagram are for constant throttle position and nozzle angles. In comparison to the performance envelope of the basic aircraft, which is reproduced on the figure, this control configuration provides a substantial increase in path-control capability. A positive climb angle of 1.7° can now be generated at 100 percent rpm, while a quite steep descent of -14.5° can be obtained at 90 percent rpm. Improvements in dynamic path response can also be recognized in the time histories for a step thrust application shown in the figure. Flight-path responds quickly with no overshoot, and very little change in airspeed is noted. This behavior would permit the pilot to track the glide slope with the throttle alone and not require significant pitch control to improve path response or maintain speed.

Pilot ratings from 4-1/2 to 5 for raw data IFR operation to a 60 m (200 ft) decision height represented some improvement over the basic aircraft and were a consequence of the improved path response and reduced workload for speed control. The requirement to modulate both the throttles and nozzle controls for glide-slope tracking is relieved and with the disturbances to speed reduced substantially, the approach can be flown with a single control, the throttle. Increased path-control authority provides better capability for coping with disturbances due to turbulence and wind shears. The primary remaining deficiency in path tracking and one that accounts for the unsatisfactory pilot rating is the instrument scan workload for lateral path tracking associated with the raw data display. No modification of flare control characteristics or technique is associated with this configuration.

Airspeed stabilization — Another means of eliminating the flight-path/airspeed coupling induced by thrust control is to stabilize airspeed at the selected approach condition. By prohibiting significant variation in airspeed response to thrust, the dynamics of flight-path response to thrust can be improved to the same extent as that provided by the throttle/nozzle interconnect. Speed stabilization also inhibits the backside of the drag curve characteristics associated with the aircraft's response to pitch attitude variations thus permitting attitude to be used for flight-path control. This system also reduces variations of speed and flight-path in response to longitudinal gust components.

The system operates by driving the nozzles in proportion to speed error. In the approach condition with the hot thrust deflected 80°, incremental changes in nozzle deflection provide essentially longitudinal force control and can produce up to ±0.1 g of longitudinal acceleration within the nozzle control limits. With this authority, it is possible to counteract longitudinal force perturbations of a magnitude associated with 6° changes in pitch attitude or 1.9 knot/sec horizontal wind gradients.

Figure 5 illustrates the aircraft's dynamic response to pitch attitude at constant thrust with the speed stabilization system operating. It is apparent in the figure that, within the authority of the nozzles the aircraft is very markedly operating on the frontside of the drag curve. Substantial changes in flight path can be obtained with little change in airspeed. Capability exists to achieve level flight with no throttle adjustments although large attitude changes may be required. The dynamic response of flight path to the change in attitude occurs with no overshoot. Consequently, the pilot may use a control technique for the landing approach that relies primarily on pitch attitude corrections for glide-slope tracking and requires only infrequent adjustments in thrust for sustaining gross changes in rate of descent. When nozzle limits are reached, the aircraft's response will, of course, revert to the backside characteristics associated with the basic aircraft, and thrust modulation will be required for glide-slope corrections.

The speed stabilization system also has capability to suppress flight-path disturbances due to horizontal wind shear. When the system is engaged, it drives the nozzles to counteract the accelerations associated with the shear gradient, thereby reducing the magnitude of the change of airspeed, and consequently suppressing the source of the flight-path disturbance. As indicated previously, the nozzle authority is equivalent to a 1.9 knot/sec horizontal gradient, which, for the nominal approach sink rate (4.3 m/sec or 14 ft/sec at 65 knots on a 7.5° glide slope) at which this aircraft is operated, corresponds to a spatial gradient of 13.3 knots/30 m (13.3 knots/100 ft). When the nozzles reach an authority limit, the pilot still has substantial capability to counteract subsequent path disturbances with an application of thrust.

Stabilization of airspeed at this selected approach reference permitted the pilot to track the glide slope with the pitch control with only occasional adjustments of thrust for large path angle changes. The flare could also be performed with pitch as it could for the basic aircraft, although some thrust reduction was required to inhibit a tendency to float. These characteristics were the basis for pilot ratings in the 3-1/2 to 4-1/2 category for raw data approaches. The pilots expressed a desire for a more authoritative path control, and quicker heave responses for flight path changes on short final and for the flare maneuver. Hence, they were unwilling to give the system clearly satisfactory ratings. Speed excursions during maneuvers and in the presence of turbulence were substantially reduced by the system and hence path distrubances which would ordinarily be induced were largely suppressed.

Flight-path command and stabilization— Improvements in flight-path response for glide-slope tracking and flare can be achieved by quickening the initial path response to pitch attitude control, by providing increased steady-state path control authority with pitch attitude, and by reducing path disturbances due to winds and turbulence. To obtain these improvements, capability must be incorporated in the flight control system for quickly generating increments in lift on the order of ±0.1 to 0.2 g. This capability in the Augmentor Wing Aircraft is provided by the inboard augmentor flap chokes. In the approach configuration, the chokes have an authority of ±0.12 g. Flight-path stabilization is achieved by driving the chokes in proportion to flight-path angle error based on a reference established at the time of system engagement. Changes in flight-path can be commanded by the pilot through changes in pitch attitude which drive the chokes through the feedforward path. Additional path command quickening could be obtained through a feedforward of column force (the attitude command input); however, simulation studies indicated this additional command quickening did not produce significant improvement in path tracking.

The speed stabilization system described previously was used in conjunction with the flight-path SCAS to permit a frontside control technique to be adopted for glide-slope tracking. An indication of the quickened response and increased path control authority is shown in comparison with the basic aircraft and the speed stabilization system in figure 5. The incremental changes in path angle in response to attitude are essentially equal ($\Delta\gamma_{ss}/\Delta\theta_{ss} = 1.0$); hence, it is possible to effectively point the flight path vector in the desired direction with the aircraft's pitch attitude. With this path quickening and path-control authority, glide-slope tracking can be accomplished through attitude control alone, thus considerably simplifying the pilot's longitudinal control workload.

This system also provides a flare capability that permits a less dramatic flare maneuver than that required for the basic aircraft to arrest the sink rate prior to touchdown. It can be seen in figure 6 that the landing sink rate for the basic aircraft is approximately 2 m/sec (6 ft/sec) as compared to 1 m/sec (3 ft/sec) with the flight path SCAS. Furthermore, where a pitch rotation in excess of 10° is required for the basic aircraft, this maneuver is reduced to approximately 5° with this SCAS configuration.

The combination of flight-path SCAS with the speed stabilization system allowed the pilot to fly the approach and to perform the landing using attitude control alone. No throttle manipulation was required other than a conventional reduction of thrust during the latter stages of the flare to counteract any tendency to float (as noted in the previous discussion). As indicated in table II, pilot ratings from 2 to 4 were given to this configuration for approach path-tracking and ratings of 2-1/2 to 3 for the flare. Favorable comments were expressed with regard to the reduced workload, the improved heave response, and more docile flare requirements. Although path disturbances due to winds and

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turbulence were noticeably suppressed, this configuration offered very little better performance than the speed stabilized configuration in this regard. The pilot rating of 4 for glide-slope tracking was based on the workload associated with the instrument scan for a raw data IFR approach. Improvements in this evaluation that can be obtained with a flight director will be discussed subsequently.

Influence of Displays

Raw data — The raw data information was provided by a conventional cross pointer display located on the HSI. In comparison to a conventional ILS, the glide slope and localizer cross-pointer needles were desensitized in proportion to the approach path angle and the range from the runway landing zone to the localizer transmitter. Sensitivity was set at approximately 1°/dot for both indicators. A cross bar representing aerodynamic flight-path angle in the vertical plane was available on the EADI, superimposed on the pitch attitude scale. This display was useful in providing lead information for glide-slope acquisition and tracking, and for alerting the pilot to incipient glide-slope deviations caused by variation in horizontal and vertical winds and turbulence. An MLS box, superimposed on the EADI, offered a more integrated display for MLS tracking and a potentially reduced scanning workload for the pilot. The EADI and HSI displays are illustrated in figure 7.

Pilot evaluations for the SCAS modes noted in the previous section were performed with the raw data information. Objections were registered concerning the instrument scan workload between the EADI and HSI and one pilot could not justify a rating better than 4 for glide-slope tracking with the best SCAS configuration; this was because of the overall task workload contributed by the instrument scan. Favorable comments were given to use of the flight-path angle bar for glide-slope tracking. In some instances, the pilots felt this information improved their ability to control glide slope enough to warrant a one-half to one unit improvement in pilot rating. Although the presentation of raw MLS deviation on the EADI provided a more integrated display, the pilots felt this offered little improvement for the task because it was still necessary to refer to the HSI to get heading information for localizer tracking.

Flight director — The three-axis flight director consisted of commands for the pilot's throttle, column, and wheel controls for glide-slope and localizer tracking, maintaining the desired airspeed, and safe angle-of-attack margins. This flight director was designed for the Augmentor Wing Aircraft under contract by Systems Technology, Inc. and is described in detail in reference 4. Complementary filtered vertical velocity, vertical beam deviations and deviation rate are generated for use in holding altitude, and capturing and tracking the glide slope. When in level flight, the inputs to the pitch bar present commands to the pilot to maintain the altitude at the time the flight director was engaged. Glide-slope capture is initiated when the aircraft is within 30 m (100 ft) of the glide-slope beam. Subsequent glide-slope tracking may either be done with throttles or pitch control, depending on the flight control system configuration. Schedule changes in thrust and pitch attitude are commanded as a function of flap angle and initiation of glide-slope capture. Angle-of-attack margins are protected through commands for increased thrust introduced to the throttles when the angle of attack exceeds 10°. A limit on the thrust command corresponding to maximum authorized thrust (rpm = 98.5 percent) is included in the throttle logic. Commands to maintain the reference airspeed are introduced to the pitch bar in the event a speed stabilization system is not utilized during the approach. Complementary filtered lateral beam deviation and deviation rate are generated for lateral path capture and tracking.

The flight director provided a significant reduction in scanning workload and a reduction in vertical and lateral excursions during the approach. The aircraft generally arrived at a 30 m (100 ft) decision height better established for a precise flare and landing when the flight director was used, and in these cases improvements in pilot ratings from one to two units were obtained. As indicated in table II, evaluation of the throttle/nozzle interconnect configuration was improved from pilot ratings of 4-1/2 to 5 with raw data to 2 to 3 with the director for operation to 30 m (100 ft) minimums. In this case, the director logic was structured to command vertical path control through the throttles. The flight-path SCAS configuration was given ratings of 1-1/2 to 2-1/2 with the director. For this configuration, path tracking commands were oriented to the attitude control. The throttle and choke controls were integrated by the SCAS for flight path command and stabilization.

Although very good results have been obtained with the flight director, it should not be inferred that this is the only acceptable means of improving the pilot's IFR landing guidance information. A well-integrated situation display has potential for producing similar results. However, display system limitations and the time available for further experiments did not permit these concepts to be explored in flight.

Moving map display — A simulation evaluation of the coordinated use of a moving map presentation on the electronic multifunction display (MFD) in conjunction with the HSI and EADI was carried out to define the best use of the MFD during manual approach and landing operation (ref. 5). The operation included acquisition of reference terminal area flight paths leading to the final landing approach, the approach itself, and go-arounds to and including holding patterns. These operations were flown on raw data with either the map or HSI or using the flight director for guidance with the MFD and HSI available to provide status information. An indication of the display content is provided in figure 7. While there appeared to be no consistent differences in tracking errors using the map or HSI, the pilots had more confidence in their ability to maintain geographical orientation during curved path tracking and establishing holding patterns when using the map. Course predictor and history dots permitted the pilots to better anticipate control requirements to capture the reference path, acquire and maintain the curved track, and to enter a holding pattern. The HSI provided better capability for localizer tracking during the final approach segment. Pilot evaluations of task controlability and precision, utility of status information, display clutter, and attentional workload indicated a preferance for the map although it was felt that improvements could be made on this display as well as on the HSI or EADI displays. One suggested improvement was to include a heading scale on the EADI; in combination with the MLS deviation data on this instrument the heading scale could eliminate the need to refer to the HSI during the final approach.

Automatic Glide-Slope Tracking Modes

To date, approximately 105 automatic approaches and 25 automatic landings have been made using the STOLAND flight control system. The early results have been characterized by glide-slope deviations of ±8 m (±25 ft) accompanied by significant fluctuations in rate of climb and engine rpm with resulting inconsistent flare entries. Steps have been taken to improve the glide-slope tracking performance and to make the flare entries consistent. The results to be presented demonstrate some of the problems related to providing good glide-slope tracking for STOL aircraft and one solution to these problems.

In normal cruise flight the STOLAND automatic control system uses pitch attitude to maintain path tracking and the throttles to control airspeed. When the aircraft is in the STOL approach mode the control functions are reversed such that throttles are used for vertical path tracking and pitch attitude is used to maintain airspeed.

Figure 8 indicates that with the original automatic system design, the aircraft oscillates about the nominal -7.5° glide slope with a 10- to 12-sec period and engine rpm varies from 92 to 98 percent. Gain optimization studies carried out in flight and on the simulator showed that little improvement could be achieved using the existing autothrottle system. Due to hysteresis in the throttle-fuel control, the automatic system apparently has inadequate bandwidth for good glide-slope tracking. Consequently, the augmentor chokes were introduced to quicken and improve the precision of path control. Figure 8 shows the significant improvement in the glide-slope tracking resulting from the use of direct lift control through chokes. The glide-slope error has been reduced to less than ±3 m (±10 ft), path excursions are less than 1° and overall rpm variations reduced to 3 percent. On other STOL airplanes the thrust control may provide the required bandwidth for good tracking but if it does not, direct lift control devices are likely to be required.

The poor path tracking evident in figure 8 did not greatly concern the pilots monitoring the approach. They were much more aware of the elevator activity, pitch oscillations, and normal acceleration levels. The source of the elevator activity was a noisy airspeed signal that substantially reduced the elevator activity when smoothed.

Two solutions to the pitch activity problem were evaluated. First, the velocity control gains were reduced; this proved unsatisfactory because velocity transients that occurred during glide-slope capture persisted for an objectionable duration. Second, the cutoff frequency on the airspeed component in the complementary filter was lowered; this reduced pitch activity without compromising velocity tracking performance. The reduced control column and normal acceleration activity did not greatly affect the path tracking but did make the system more acceptable to the pilots.

CONCLUSIONS

A flight research program was conducted to assess the improvements, in longitudinal path control during a STOL approach and landing, that can be achieved with manual and automatic control system concepts and with cockpit displays with various degrees of complexity.

Substantial improvements in manually flown IFR approaches can be obtained with stabilization and command augmentation systems ranging in complexity from simple thrust-thrust deflection interconnects to sophisticated path-speed stabilization and command configurations. With the augmented aircraft given pilot ratings in the 5-6 range for raw data IFR approaches to a 60 m (200 ft) decision height, ultimate improvement to the 2-1/2 to 4 range can be achieved with the most complex SCAS. The addition of a flight director to overcome deficiencies of the raw data instrument scan permit the rating to be improved to the 1-1/2 to 2-1/2 category for operation to a 30 m (100 ft) decision height. Thus it is apparent that fully satisfactory capability to manually perform IFR approaches to current instrument flight minimums can be obtained for an aircraft of this class. The ability to accomplish a gentle flare maneuver to a low touchdown sink rate can also be achieved with systems which augment the basic aircraft's heave response. Improvements in pilot ratings for the flare from the 4-5 to the 2-3 category can be obtained.

Flight research is in progress to demonstrate fully automatic approach and landing operation to Category IIIa minimum conditions. A substantial number of fully automatic approaches and landings have been performed and recent improvements in the glide-slope tracking logic have produced a satisfactory system concept. Fully automatic flares to touchdown have been performed and refinement of the automatic flare control is in progress. Once acceptable automatic glide slope and flare controls are established, operational evaluations will be conducted to explore operational procedures and approach path geometry.

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TABLE I.- COMPARISON OF SCAS CONCEPTS

SCAS concept	Mechanization	Effect on aircraft response	Pilot's control technique
Throttle-nozzle interconnect	Linear, constant gain command from throttles to nozzle servos	Decouples flight path and airspeed response for throttle control. Expands flight envelope.	Backside (flight-path with throttle, airspeed with pitch). Reduces pitch control activity.
Airspeed stabilization	Error between pilot selected reference and actual airspeed commands nozzle servos. Airspeed derived from complementary filter.	Eliminates path-speed coupling for throttle control. Eliminates path response decay for pitch control. Reduces path and speed excursions to horizontal gusts.	Frontside (flight-path with pitch). Throttle activity significantly reduced. Some thrust may be required to quicken path tracking and flare.
Flight-path airspeed command and stabilization	Airspeed error command nozzle servos.	Same as for speed stabilization.	Frontside
	Combination of flight-path and pitch attitude error drives throttle and choke servos (washout for chokes).	Quickens path response to attitude. Authoritative path control $\Delta\gamma_{ss}/\Delta\theta_{ss} \doteq 1.0$.	Only pitch control required for approach and flare.

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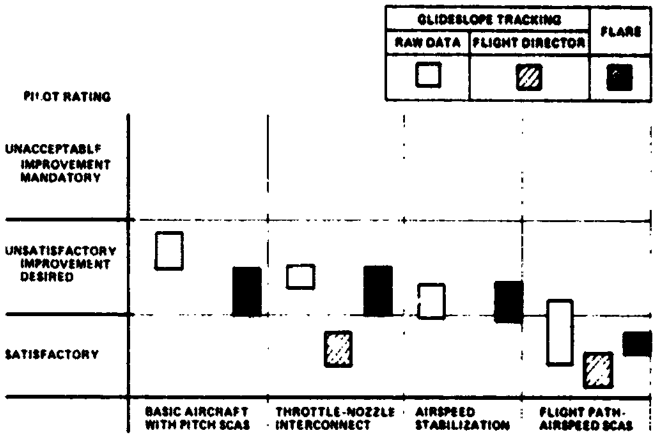
TABLE II

IFR GLIDESLOPE TRACKING AND FLARE



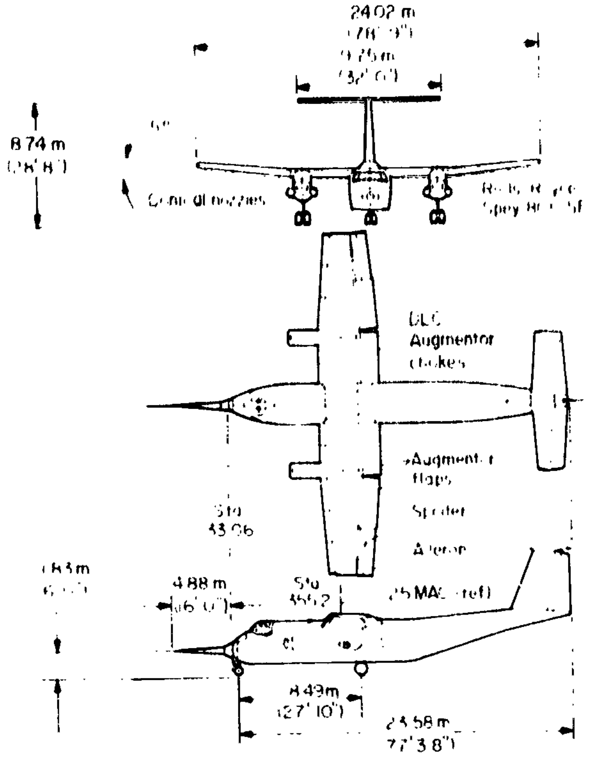


Figure 1.- The Augmentor Wing Research Aircraft.

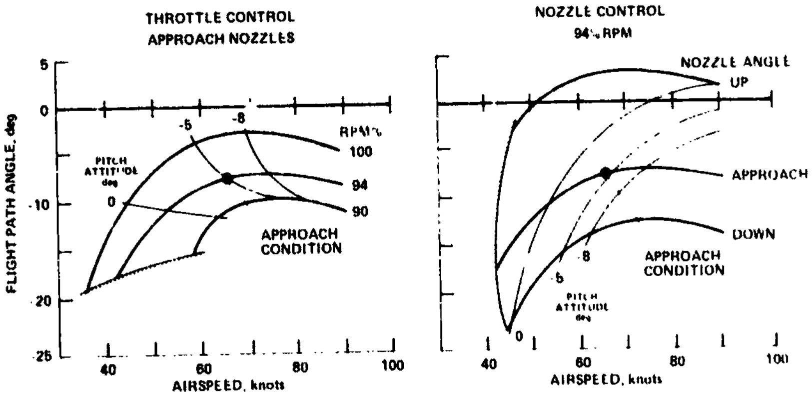


Figure 2.- Performance characteristics: approach configuration.

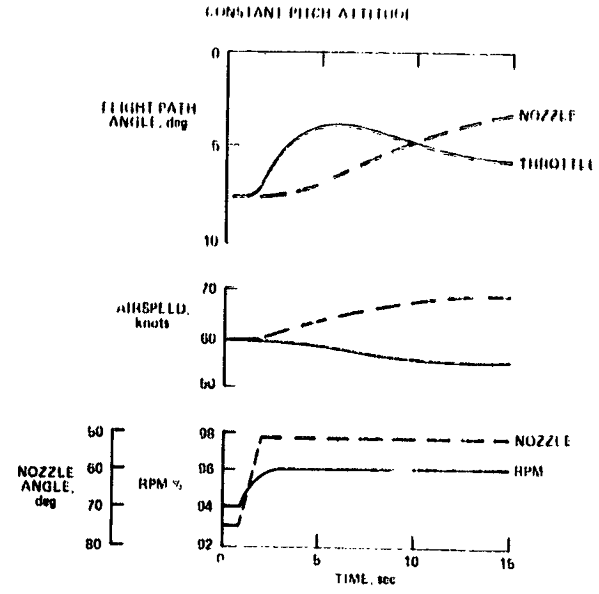


Figure 3.- Dynamic response characteristics: approach configuration.

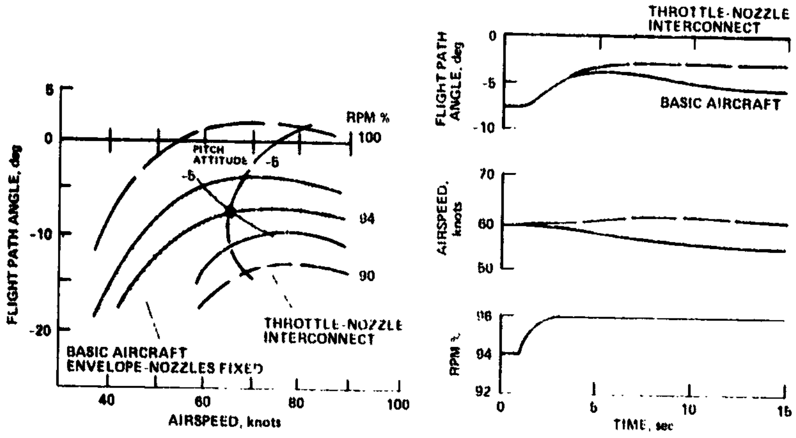


Figure 4.- Throttle-nozzle interconnect.

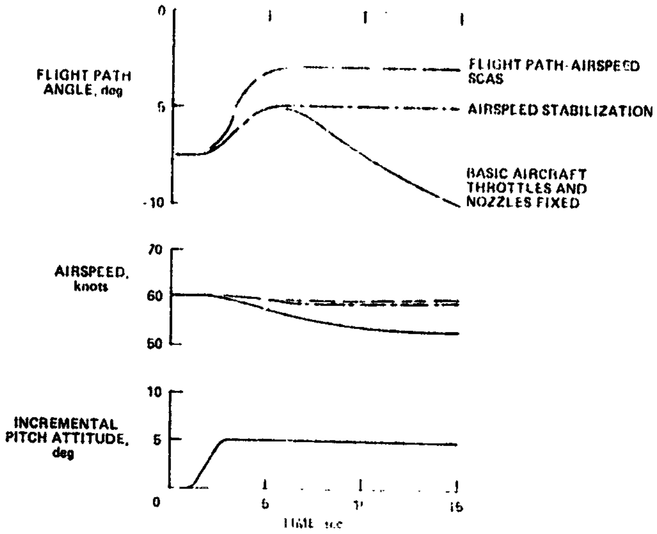


Figure 5.- Speed stabilization and flight path-airspeed SCAS: glide-slope tracking.

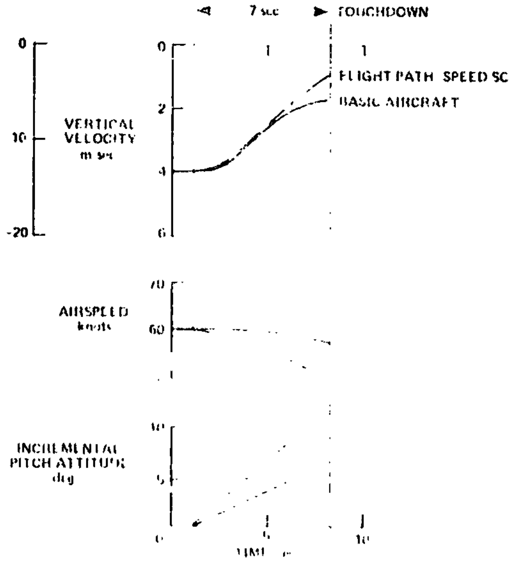


Figure 6.- Flight path-airspeed SCAS: flare control.

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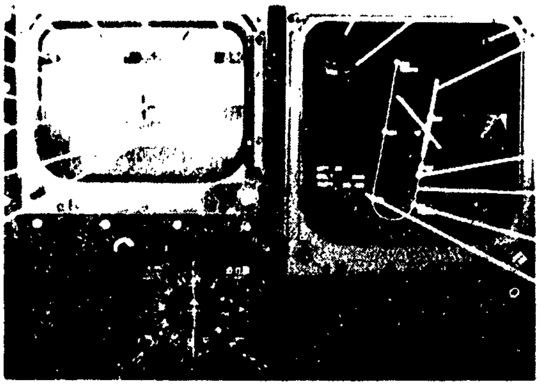

Figure 7.- Avionics system displays.

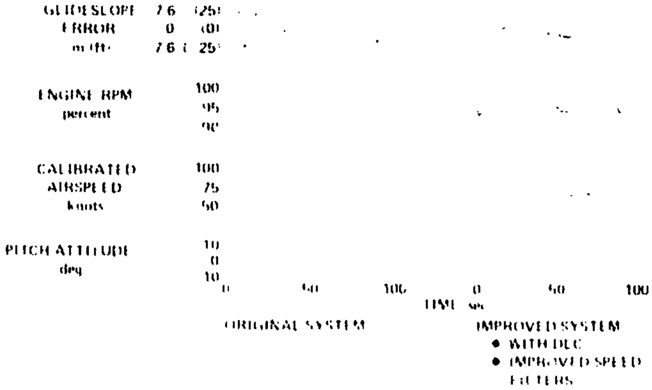

Figure 8.- Automatic glide-slope tracking.