Flight Evaluation of Flight-Path Control for the STOL Approach and Landing

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Flight experiments have been conducted to assess requirements for flight-path control for glide-slope tracking and for control of the flare and landing, particularly as applied to powered-lift STOL aircraft. In some instances, these results are also pertinent to other types of STOL aircraft. The NASA Ames Research Center's Augmentor Wing Research Aircraft was used to perform landing approaches on a 7.5-deg glide slope to landings on a 30×518 m (100×1700 ft) STOL runway. The aircraft's research flight-control system provided the capability for evaluating a wide range of flight-path control characteristics. The flight results identified flight-path overshoot, flight-path/airspeed coupling, and vertical velocity damping to be the dominant aircraft response characteristics that affect glide-slope tracking. The one prominent contribution to control of flare using pitch attitude was the short-term path response. A range of these characteristics covering satisfactory through unacceptable flying qualities was evaluated in the program. Specific design considerations for the effective thrust turning of the high-lift system, thrust response lags of the engines, and the aircraft loading and operating conditions are discussed.

Nomenclature

C_{L_α} = lift curve slope
C_μ = thrust coefficient
D_α = drag derivative due to angle of attack
$\dfrac{d\gamma}{du}$ = change of flight-path angle with airspeed for constant thrust
g = acceleration due to gravity
IFR = instrument flight rules
S = wing area
T_{θ_2} = time constant of the highest frequency real root of the attitude stabilized flight-path mode
$t_{0.5\Delta\gamma_{\max}}$ = time to 50% of the peak flight-path response to a step change in thrust
$t_{0.1\Delta\gamma_{\max}}$ = decay time for flight-path response to a step change in pitch attitude
V_A = approach airspeed
VFR = visual flight rules
W = gross weight
$X_{\Delta T}$ = longitudinal acceleration derivative due to thrust
Z_w = vertical velocity damping
$Z_{\Delta T}$ = vertical acceleration derivative due to thrust
Z_{δ_T} = throttle sensitivity
$\dfrac{\Delta u_{ss}}{\Delta\gamma_{ss}}$ = ratio of change of steady-state airspeed to flight path due to a change in thrust (constant pitch attitude)
$\dfrac{\Delta u_{ss}}{\Delta\theta_{ss}}$ = ratio of change of steady-state airspeed to pitch attitude for constant thrust
$\dfrac{\Delta\gamma_{\max}}{\Delta T}$ = peak change in flight-path angle in response to a step change in thrust
$\dfrac{\Delta\gamma_{\max}}{\Delta\gamma_{ss}}$ = ratio of peak to steady-state change of flight path due to a change in thrust (constant pitch attitude)
$\dfrac{\Delta\gamma_{\max}}{\Delta\theta_{ss}}$ = peak change in flight path in response to a step change in pitch attitude
$\zeta_\theta, \omega_\theta$ = damping ratio and natural frequency of the complex roots of the attitude stabilized flight-path mode
$\dot\theta$ = pitch rate
θ_T = effective thrust inclination angle
τ_E = time constant for thrust response to throttle
τ_γ = time constant for initial flight-path response to throttle
ρ = air density

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Introduction

THE flight experiments reported herein were part of a research program conducted to determine requirements for flight-path control during the approach and landing for STOL aircraft. Existing military flying qualities specifications,[1,2] civil airworthiness regulations,[3,4] and other design criteria for this category of aircraft[5,6] offer little information on the subject for aircraft that are operated well on the backside of the drag curve at approach lift coefficients in excess of 2 and that require modulation of a vertical force generator (aerodynamic device or direct thrust component) for longitudinal path control. The current literature contains direct or indirect suggestions for desirable levels of such things as vertical velocity damping for conventional aircraft and regulations for speed margins from stall, suggestions which tend to insure adequate flare control for conventional aircraft. However, these requirements do not consider closed-loop glide-slope tracking or flare capability for the STOL landing. Consequently, a program was initiated at NASA Ames Research Center to identify the pertinent flight-path response characteristics that affect glide-slope control and flare capability and to determine the range of characteristics that encompass satisfactory through unacceptable flying qualities.

An analytical and ground-based simulation study of flight-path control for the landing approach has been carried out and reported.[7] The flight research program reported herein was undertaken to further evaluate glide-slope tracking characteristics and to study the control of the flare and landing. This paper presents the flight-path control requirements that have been identified in the flight experiment along with the associated contributions of the aircraft's configuration and the approach flight condition influencing the dominant control characteristics for the respective segments of the approach and landing. The results are applicable for glide-slope control for powered-lift aircraft and for low wing-loading aircraft which employ direct-lift control devices. They also apply to the flare and landing of any type of STOL aircraft.

Characteristics of Flight-Path Control

The discussion of flight-path control characteristics which follows deals separately with control requirements for glide-slope tracking and for performing the landing flare. It is pertinent to make this separation since the pilot's task, the control technique, and controls utilized to accomplish each task may be substantially different.

Glide-Slope Control

Reference 7 reported the results of an analytical study and flight simulation experiment conducted to determine the dominant characteristics that influence glide-slope tracking. The investigation focused on flight-path control with thrust that was observed to be appropriate for a powered-lift aircraft operating on the backside of the drag curve. Figure 1 indicates the flight-path and airspeed response characteristics to thrust control that were evaluated in the experimental program. These characteristics are: 1) time constant τ_γ, which defines initial path response to a step change in thrust; 2) flight-path overshoot, $\Delta\gamma_{\max}/\Delta\gamma_{ss}$; and 3) flight-path airspeed coupling, $\Delta u_{ss}/\Delta\gamma_{ss}$.

Throttle sensitivity of 0.032 g/cm (0.08 g/in.) was determined to be most desirable and was used throughout the substantial part of the program. Significant flight-path overshoot was determined to have the most deleterious influence on precise path control, with the attendant path/speed coupling (the dominant source of the path overshoot tendencies for operation on the backside of the drag curve) contributing to the pilot's difficulty in maintaining the desired precision of speed control.

It was also observed in the analytical study of Ref. 7 that the ability to maintain acceptable closed-loop flight-path control would be related to how tightly the pilot could control flight-path with thrust, but without inducing oscillatory glide-path tracking tendencies. This ability was related analytically to the thrust/flight-path transfer function bandwidth that could be achieved with an acceptable phase margin. The bandwidth associated with path control and the corresponding phase margin are dominantly influenced by the frequency and damping (ω_θ and ζ_θ) of the characteristic mode if it is oscillatory, or the time constant of the higher frequency of two real roots (T_{θ_2}) if the characteristic modes are nonoscillatory. While these characteristics were not varied substantially in the simulation study of Ref. 7, they were subsequently shown (in the simulation experiments described in Refs. 8 and 9) to have a significant influence on the pilots' evaluation of glide-slope control in turbulence.

Flight-path response characteristics related to thrust-control that were selected for evaluation in the flight research program were flight-path overshoot, flight-path/airspeed coupling, and the response time of the initial path response. As noted in Ref. 7, flight-path overshoot and flight-path/airspeed coupling are strongly influenced by thrust turning angle, $\theta_T = \tan^{-1}(-Z_{\Delta T}/X_{\Delta T})$, while the path response time can be affected by the amount of thrust turning, the vertical velocity damping, or by the engines' thrust time response. Variations in these characteristics were made by altering the thrust turning angle.

Closed-loop path bandwidth and damping were also evaluated. The vertical velocity (heave) damping Z_w and the thrust time response both exert powerful influences on these closed-loop control characteristics. Variations were obtained during the flight program by changing heave damping, since the basic engine response could not be readily altered ($\tau_E \doteq 0.75$ s). No variations were made in the throttle control sensitivity ($Z_{\delta_T} = -0.04$ g/cm or -0.1 g/in.).

Pitch attitude was assumed to be the primary control for maintaining the approach flight reference. Reference 7 indicated that approach flying qualities were not significantly affected by variations in airspeed-attitude sensitivity ($\Delta u_{ss}/\Delta\theta_{ss}$), hence this characteristic was not independently investigated in the flight program.

Flare Control

The landing flare maneuver for STOL aircraft may demand little of the pilot for its execution, or may require a coordinated application of the available controls for orienting the aircraft for touchdown and arresting its sink rate. It is possible that no flare action would be required of the pilot if the aircraft were designed to absorb high sink rates and the ground effects were favorable for cushioning the landing without inducing floating tendencies. When some pilot action is required to accomplish the landing, it can range in complexity from an open-loop control of pitch attitude or thrust to partially arrest the rate of sink, to continuous, closed-loop modulation of the pitch and thrust controls and even an auxiliary lift control device (such as an independent direct lift control). It should be clear that the no-flare or the open-loop flare requires little design consideration for control by the pilot (which, at the same time, indicates the skill or good fortune of the aerodynamicists and the structures and landing gear systems designers). The purpose of this investigation was to consider the requirements for performing a flare to a reasonably low sink rate while utilizing either the pitch or thrust controls. This maneuver could conceivably require closed-loop control of the aircraft through the flare to make adjustments for achieving a reasonable and repeatable touchdown point and sink rate. Hence, the dynamic response of the aircraft to either pitch or thrust controls should be considered in defining the aircraft's flare characteristics.

Response of the aircraft to a step change in pitch attitude is illustrated at the top of Fig. 2. Thrust is held constant during the maneuver. Two characteristics of flight-path response to pitch attitude stand out in these time histories: 1) the short-term change in flight path in relation to the step change in pitch attitude, $\Delta\gamma_{\max}/\Delta\theta_{ss}$; and 2) the time interval for which the flight-path correction can be sustained, such as the time for the flight-path transient to wash out to an arbitrary fraction of the initial correction, $t_{0.1\Delta\gamma_{\max}}$.

The initial flight-path response to pitch determines the ability to substantially reduce the rate of descent without an excessive requirement for pitch rotation. For aircraft which are operated near or on the backside of the drag curve, the

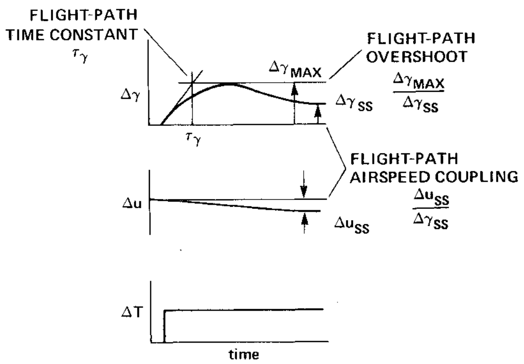

Fig. 1 Characteristics of flight-path and airspeed response to thrust.

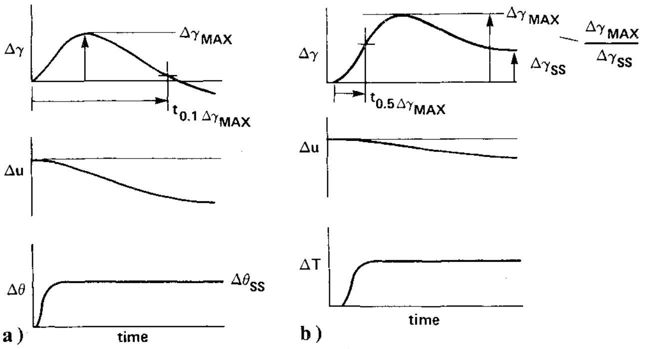

Fig. 2 Characteristics of flight-path and airspeed response to a) attitude change at constant thrust and b) thrust change at constant attitude.

initial change in flight path following a step change in pitch attitude cannot be sustained and will subsequently decay to some lesser value (for operation on the backside of the drag curve, the path correction will eventually reverse in sign and the steady flight path will be steeper than the initial path). The ability to sustain the flight-path correction for a duration required to complete the flare was considered to be a factor of possible significance to the pilot for landing precision. Too rapid a washout of the path correction could possibly lead to hard landings, while too little a washout could conceivably induce floating and lead to excessive landing distances.

While the rate at which the initial path correction can be developed might be considered to be important, it can be shown that this characteristic is dominated by the rate of the pitch maneuver. Hence, this factor is more associated with pitch response and was not considered for this investigation of flight-path control.

Response of the aircraft to a step application of thrust was previously illustrated in Fig. 1 and is repeated at the bottom of Fig. 2. Concerns for flare control that can be identified therein are: 1) how quickly the initial flight-path correction can be accomplished, as indicated by $t_{0.5\Delta\gamma_{max}}$; 2) the short-term flight-path increment related to the increment in thrust, $\Delta\gamma_{max}/\Delta T$; and 3) the degree to which the initial path correction washes out, $\Delta\gamma_{max}/\Delta\gamma_{ss}$. Concerns similar to those expressed for flare response to pitch may be associated with these characteristics; namely, "Can the sink rate be substantially reduced within a short time and can this reduction be sustained for a sufficient duration to accomplish the flare?" The requirement for being able to achieve a sufficient reduction in sink rate within operational thrust limits is, of course, analogous to the requirement for checking the sink rate within acceptable attitude limits.

Additional considerations for closed-loop control during the flare similar to those identified for glide-slope tracking are found in Refs. 9 and 10. Among these are the ability to control the flare precisely without inducing oscillations in the trajectory. The significant parameters are closed-loop bandwidth and damping that relate to the control being used to perform the flare.

Flare-control characteristics related to pitch-attitude that were investigated in these flight experiments were the initial path response, $\Delta\gamma_{max}/\Delta\theta_{ss}$, and the washout time interval, $t_{0.1\Delta\gamma_{max}}$. The initial response is predominantly determined by heave damping and is only secondarily influenced by characteristics related to speed variation during the flare. Alterations in this characteristic were thus made by changing Z_w. The long-term path washout time is strongly influenced by the steady-state flight-path/airspeed gradient, $d\gamma/du$, associated with backside operation. Variations in this path-speed gradient were achieved through variations in the induced drag derivative D_α.

Although contributions of ground-effect on lift and drag have potential for altering the characteristics of the flare, they were not varied during these experiments. As described in Ref. 11, these ground effects are comprised of a slightly positive lift increment and large drag decrement at landing gear contact height.

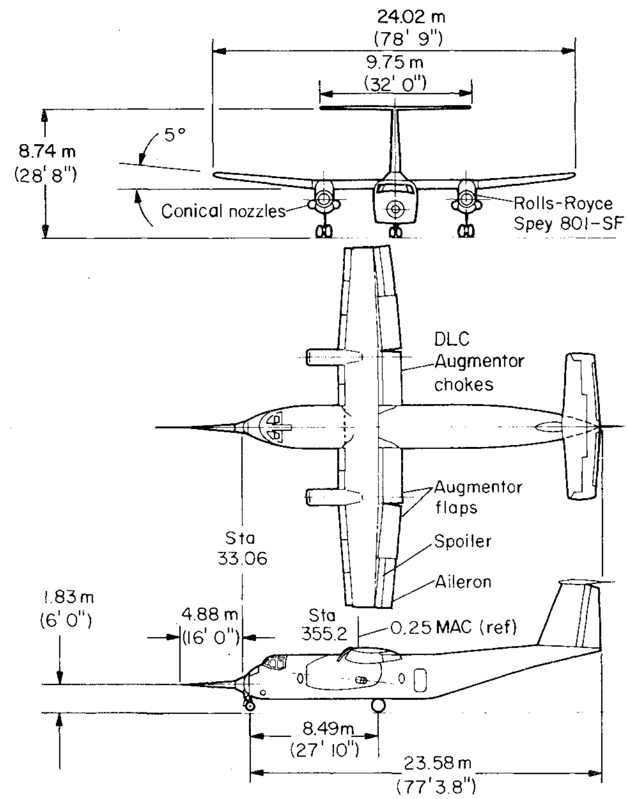

Fig. 3 Augmentor wing research aircraft.

Description of the Flight Experiments

Research Aircraft

The flight research program was conducted in the NASA Ames Research Center Augmentor Wing Research Aircraft. This aircraft, as shown in Fig. 3, is a de Havilland C-8A Buffalo, modified to incorporate a propulsive-lift system by The Boeing Company, de Havilland of Canada, and Rolls Royce of Canada. The propulsive lift system incorporates an augmentor jet flap designed for deflections of up to 75 deg. Rolls Royce Spey 801-SF engines provide fan air, which is used to blow the augmentor flap and direct hot thrust that can be vectored over a range of 98 deg through two conical nozzles on each engine. Air flow through the augmentor flap can be varied by choke controls to change local spanwise lift. Primary flight controls consist of: a single segment elevator for pitch maneuvering and trim; ailerons, spoilers, and outboard augmentor flap chokes scheduled for roll control; a two-segment rudder for yaw control; vectored hot thrust for longitudinal force control in the approach configuration; and inboard augmentor flap chokes for lift control. A more detailed physical description of the aircraft and its characteristics is given in Ref. 12.

The primary flight controls can be driven through servos commanded by a versatile digital flight control system (STOLAND). This system was developed by Sperry Rand's Flight Systems Division for use in flight controls, display, guidance, and navigation research, as well as for the flying qualities investigations reported herein. That portion of the system utilized in this program is illustrated in Fig. 4. It provides a rate command/attitude-hold stabilization and command augmentation (SCAS) capability for pitch attitude control, as well as commands to the nozzles and inboard augmentor chokes in proportion to engine rpm, pitch attitude,

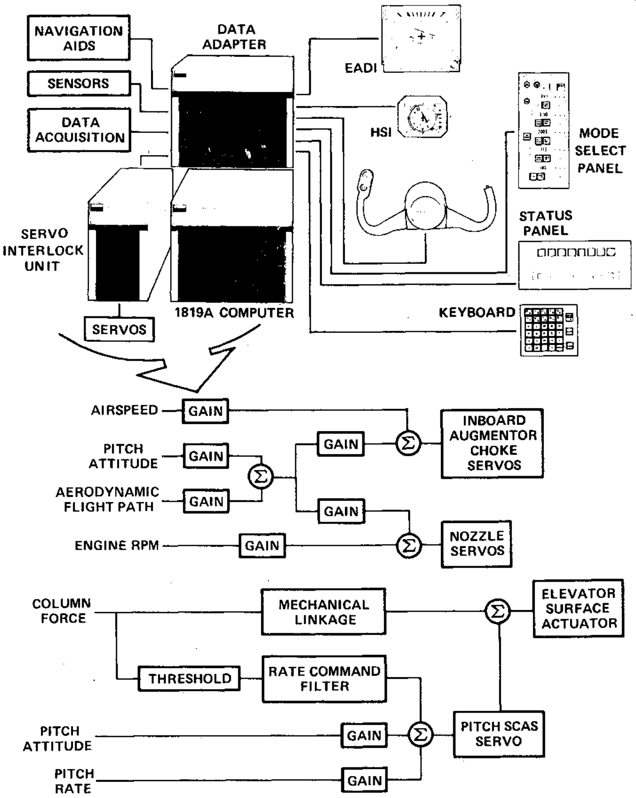

Fig. 4 STOLAND control system schematic and control logic.

airspeed, and aerodynamic flight-path inputs. These commands are conditioned, where appropriate, by complementary filters to remove high-frequency gust disturbances. Details concerning the STOLAND system's computational capability, sensors, and filtering are included in Ref. 13.

A view of the cockpit interior showing the pilot's instruments and arrangement of the controls is presented in Fig. 5. An electronic attitude display (EADI) provides the pilot with pitch and roll attitude, aerodynamic flight-path angle, and glide slope and localizer deviation, as well as digital readouts of calibrated airspeed, vertical velocity, and radio attitude. A three-axis STOL flight director may be selected if desired. A mechanical horizontal situation indicator (HSI) presents heading and bearing, as well as glide slope and localizer deviation.

Evaluation Task

Assessments of glide-slope tracking and flare and landing capability for the configurations described previously were obtained from landing approaches flown on a 7.5 deg glide slope at airspeeds of 65 to 70 knots to landings on a 30×518 m (100×1700 ft) STOL runway. Landing approach guidance was provided by a prototype microwave landing system (MODILS). Two Ames Research Center pilots conducted all flight evaluations in this program. Both VFR and simulated IFR approaches were flown in calm-to-light wind conditions, and additional evaluations were made under surface conditions ranging from light tailwinds to strong headwinds and light-to-moderate turbulence. Evaluations commenced following glide-slope acquisition at altitudes of approximately 460 m (1500 ft).

Pitch attitude was selected as the primary approach flight reference to maintain adequate gust and maneuver margins. Choice of pitch attitude for the flight reference also provides a potential for reducing secondary control workload since attitude is stabilized by the pitch SCAS. While it was not always required to control airspeed precisely, some attention had to be devoted to speed control to achieve acceptable landing distances, to assure adequate flare capability, and to suppress undesired flight-path coupling with airspeed.

Pilot commentary and opinion ratings based on the Cooper-Harper scale of Ref. 14 were obtained for all configurations. The pilots' assessments of the acceptability of the flare and touchdown were based on the repeatability of the touchdown point and sink rate that could be achieved. The touchdown zone painted on the runway edge provided a target landing area and the pilots generally performed complete flares to touchdown at sink rates of between 1 and 2 m/s (3 to 6 fps). However, consistency rather than ability to achieve a target point or sink rate was considered the figure of merit for the flare evaluation.

Discussion of Results

Glide-Slope Control

Results of the pilots' evaluation of glide-slope control are presented in Figs. 6 and 7 in terms of pilot ratings as a function of flight-path overshoot, flight-path/airspeed coupling, and initial flight-path response time. The pilots preferred flight-path response with little or no overshoot or coupling and levels of heave damping comparable to current generation jet transports ($Z_w = -0.8\ s^{-1}$). The plot at the top of Fig. 6 illustrates the trend of pilot rating with flight-path overshoot and flight-path/airspeed coupling for a fixed level of heave damping ($Z_w = -0.5\ s^{-1}$) and for both VFR and IFR conditions. The degration in pilot rating with increasing overshoot and coupling reflects an increase in attention the pilot must devote to flight-path control in attempting to acquire and track the glide slope. If the pilot maintained a constant pitch attitude reference, the flight path washout following a glide-slope correction made it difficult for him to anticipate the amount of control required to quickly establish the correction. Hence, he was forced to monitor flight path or rate of descent more closely while tracking the glide slope, which, for the configurations with large overshoot, produced an unacceptable workload. For these configurations, the path overshoot could be suppressed by controlling airspeed, and, in fact, it was necessary for the pilot to adopt such a technique to be able to successfully fly the approach. However, the secondary control task of speed regulation was also a major contribution to pilot workload for the most highly coupled configurations, since the pilot was forced to tightly monitor and simultaneously control both flight path and speed. In addition, the speed control technique was unnatural, in that the pilot had to lower the nose to maintain speed when attempting to reduce the rate of descent, and vice versa. Consequently, the control workload was still judged to be unacceptable for these configurations. From the results presented in Fig. 6, the limits of flight-path overshoot for acceptable pilot ratings are approximately 3.0 for VFR and 2.5 for IFR operation. The corresponding levels of path/speed coupling were -6.5 and -5.0 knots/deg, respectively.

As indicated at the bottom of Fig. 6, some degradation in pilot ratings is also associated with configurations that have initial path response $t_{0.5\Delta\gamma_{max}}$ approaching 6 s. These response characteristics begin to appear for thrust inclination angles less than approximately 45 deg and are accompanied by conventional (positive) path/speed coupling and no path overshoot. If a constant attitude reference was maintained for these configurations, the pilot objected to excessive time required for the flight path to stabilize following a correction and to the fluctuations in airspeed which compromised safety margins or landing field performance. If the pilot maintained airspeed, the initial flight-path response time was reduced; however, the secondary control task required simultaneous activity with the thrust and attitude controls and produced an objectionable level of workload.

The influence of variations in heave damping in combination with various levels of path overshoot is presented in

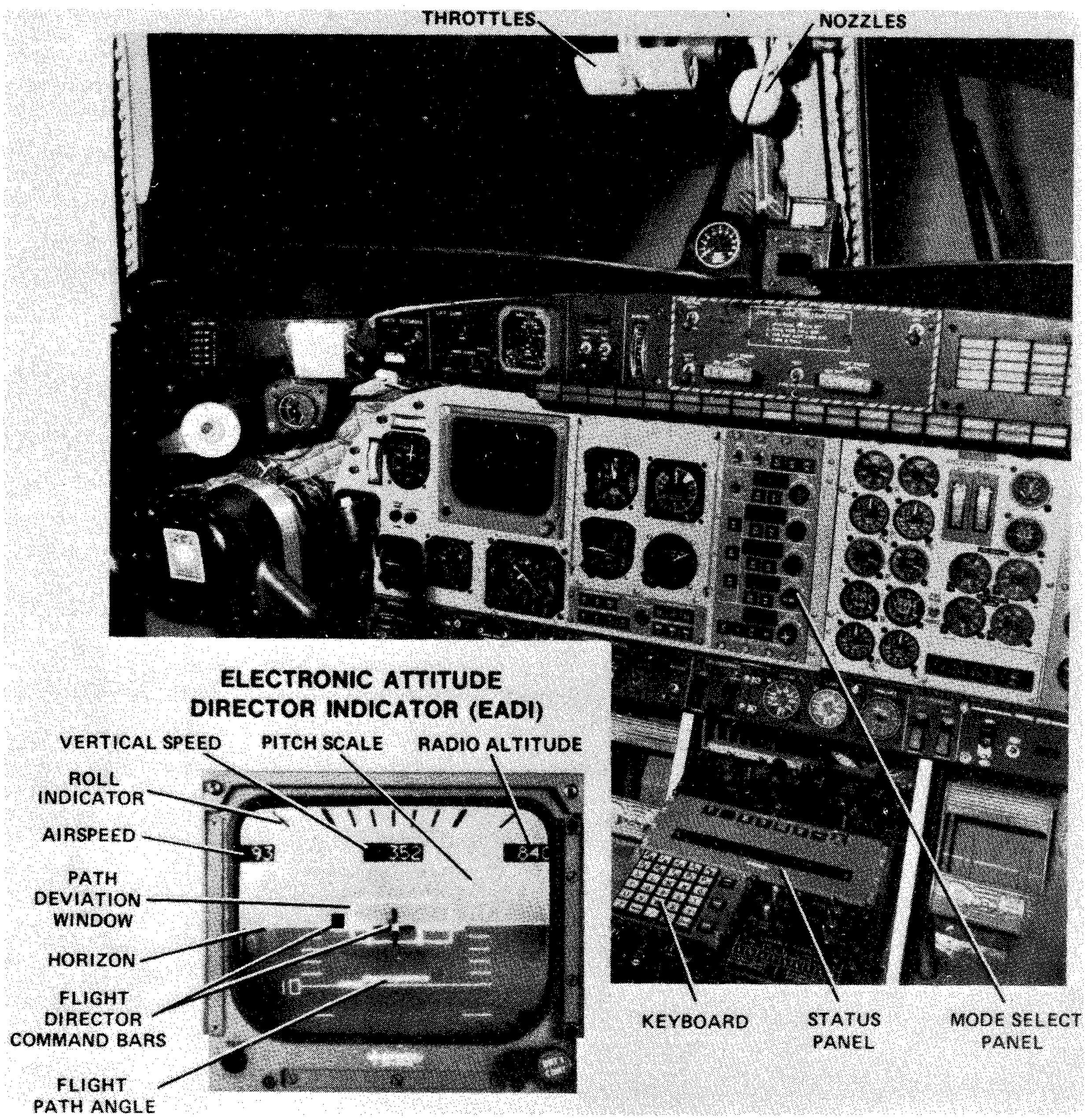

Fig. 5 Cockpit interior and control and instrument layout.

Fig. 7. The degradation in the pilot's ability to control the aircraft on the glide slope when heave damping is reduced is apparent in the pilot rating trends. With otherwise good path response characteristics ($\Delta\gamma_{max}/\Delta\gamma_{ss}=1.0$), the path control capability is rated unacceptable for $Z_w=-0.3$ s^{-1}. With increasing overshoot, reductions in heave damping are even less tolerable. For the configurations with the poorest damping, oscillatory path tracking was clearly evident, and the pilots complained of being unable to stabilize the aircraft on the glide slope. Under IFR conditions, pilot ratings are further degraded by about one unit over the range of configurations which were evaluated, and the lowest tolerable value of heave damping for configurations with no overshoot is on the order of -0.4 s^{-1}.

The results presented in the foregoing discussion were obtained for either calm wind conditions or no worse than light turbulence. Some of the configurations were evaluated under conditions assessed as light-to-moderate turbulence, with measured steady winds of 35 knots and peak horizontal gusts up to 4.6 m/s (15 fps) during the last 150 m (500 ft) of the approach. For the worst conditions encountered, the degradation in pilot rating was one-half to one unit for the baseline configuration ($\Delta\gamma_{max}/\Delta\gamma_{ss}=1.0$, $Z_w=-0.5$ s^{-1}), one unit for the low-heave-damping configuration ($\Delta\gamma_{max}/\Delta\gamma_{ss}=1.0$, $Z_w=-0.3$ s^{-1}, and from one to one and one-half units for the configuration with the longest response time ($t_{0.5\Delta\gamma_{max}}=6.5$ s, $\Delta\gamma_{max}/\Delta\gamma_{ss}=1.0$, $Z_w=-0.5$ s^{-1}).

It may be seen in Figs. 6 and 7 that the pilot ratings obtained for the best configurations were only marginally satisfactory (PR = 3.5). For these configurations, the pilots' criticism was not concerned with the aircraft flight-path response characteristics but was directed at the overall raw data instrument scan workload required to achieve acceptable path tracking for the approach. The baseline configuration ($\Delta\gamma_{max}/\Delta\gamma_{ss}=1.0$, $Z_w=-0.5$ s^{-1}) was evaluated using a flight director specifically designed for powered-lift aircraft and STOL approach operations as described in Ref. 15. With the reduction in the workload afforded by the flight director, this configuration was evaluated to be fully satisfactory and was given pilot ratings ranging from 2 to 3. The same flight director also improved the rating of one of the poorly damped configurations ($\Delta\gamma_{max}/\Delta\gamma_{ss}=1.0$, $Z_w=-0.3$ s^{-1}) from 6.5 to 5 by providing adequate lead information to the pilot for glide-slope tracking. In this regard, lead information provided

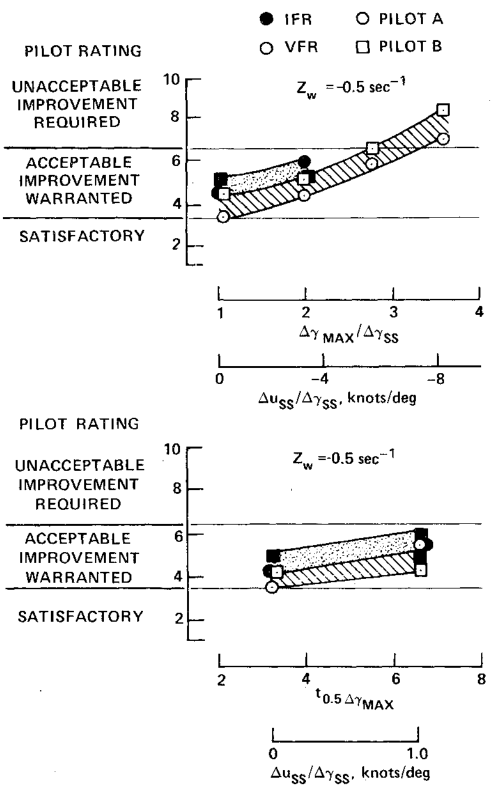

Fig. 6 Influence of flight-path overshoot and initial time response on glide-slope tracking.

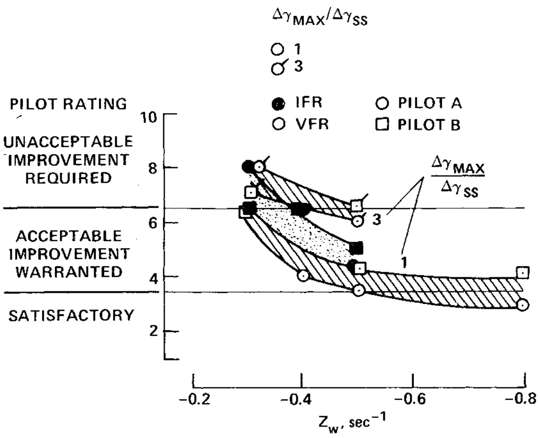

Fig. 7 Influence of heave damping and flight-path overshoot on glide-slope tracking.

by the flight-path angle bar on the EADI was considered to be useful enough to the pilots to warrant a one-half to one unit improvement in their rating over those given for the conventional instantaneous vertical speed indicator.

Flare Control

Flare evaluations were peformed by using either pitch attitude or thrust as the primary control of descent rate and touchdown position. When the flare was performed with a pitch rotation, a moderate reduction in thrust was occasionally performed to complete the landing at the desired location on the runway. When the flare was accomplished with thrust control, an open-loop pitch rotation was performed to establish the landing attitude. Under some circumstances, the flare could be successfully performed by using coordinated application of the pitch and thrust controls.

The dominant influence on the pilots' control of the flare with pitch is the ability to adequately check the sink rate prior

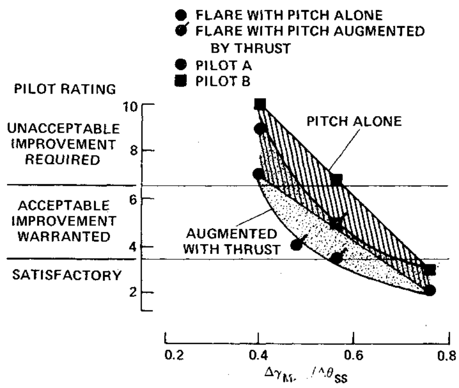

Fig. 8 Influence of flight-path response to pitch attitude on flare control.

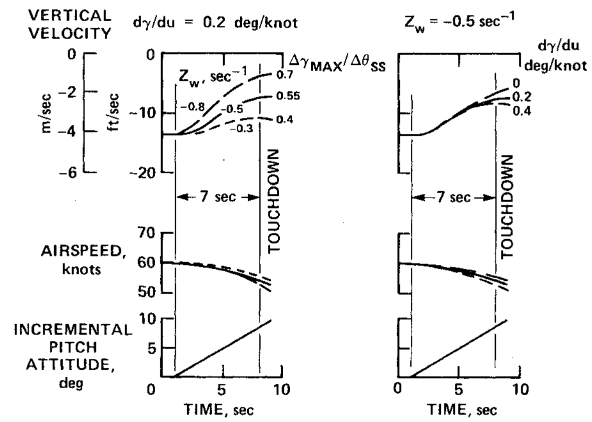

Fig. 9 Influence of heave damping and $d\gamma/du$ on flare characteristics.

to touchdown. Results of these evaluations are presented in Fig. 8, and it is apparent that the pilots prefer flight path to follow pitch attitude at a ratio approaching one-to-one in the short term. The pilots' evaluations were quite sensitive to the ability to change flight path (and sink rate) with reasonable changes in attitude (as constrained by aircraft geometry limits and comfortable rotation rates). Consequently, unacceptable ratings were obtained for the flare with pitch alone for $\Delta\gamma_{max}/\Delta\theta_{ss}$ ratios less than approximately 0.5. The pilots' impressions of flare characteristics of these configurations ranged from "gentle rotation and repeatable landing performance" ($\Delta\gamma_{max}/\Delta\theta_{ss}=0.7$) to "essentially no heave response to pitch rotation" ($\Delta\gamma_{max}/\Delta\theta_{ss}=0.4$).

As long as the pilot has adequate ability to check the sink rate with rotation, the tendency for the flight-path correction to wash out in the long term (the aircraft to "fall out" during the latter stage of the flare) does not appear to have a significant influence on flare control or landing precision. The representative flare time histories shown at the left on Fig. 9 illustrate the dominant influence on sink-rate control of the variations in short-term path responses (related in these examples to a range of Z_w) compared to the variations in operating conditions on the backside of the drag curve shown at the right of the figure. For the same flare maneuver ($\dot{\theta}=1.2$ deg/s over a 7-s duration) the reduction in touchdown sink rate varies from 1.3 to 3.2 m/s (4 to 10.5 fps) for the range of Z_w shown, compared to a variation of 1.5 to 2.3 m/s (5 to 7.5 fps) for a substantial variation in $d\gamma/du$.

Configurations that have marginal heave response to pitch alone could be successfully controlled in the flare by augmenting the heave response to pitch with application of thrust just prior to or during the flare. These thrust applications consisted of step increases to assist in reducing high rates of descent or gradual reductions to complete the landing. Pitch control was still adequate to modulate the flare. These configurations encompassed values of $\Delta\gamma_{max}/\Delta\theta_{ss}$ of 0.48 to 0.55 and were given pilot ratings of 3.5 to 5. Acceptable pilot ratings for flare control with pitch with open-loop thrust augmentation apparently can be obtained for $\Delta\gamma_{max}/\Delta\theta_{ss} > 0.45$. For the configurations that have little heave response to pitch ($\Delta\gamma_{max}/\Delta\theta_{ss} < 0.45$), successful flares were accomplished with thrust modulation. However, the combination of airframe and engine response characteristics ($Z_w = -0.3$ s^{-1}, $\Delta\gamma_{max}/\Delta\gamma_{ss} = 1.0$, $\tau_E = 0.75$ s) of this configuration produced only a marginally acceptable flare control with pilot ratings of 5 to 6. In general, the pilots had little confidence in their ability to obtain repeatable flare performance at low sink rates for this configuration.

Measurements of landing precision are shown in Fig. 10 for the configurations ranging from acceptable-to-poor heave response, and for flares performed either primarily with pitch or thrust control. In general, the touchdown dispersions are comparable for all configurations and fall within or slightly beyond the designated touchdown zone. Variations in touchdown sink rate are somewhat greater for the configurations that have poorer heave response to pitch, as well as for flares performed with thrust alone. These increased variations are reflected in the reduced confidence the pilots' expressed in obtaining precision of sink-rate control in the flare.

Design Implications of Flight-Path Control

Considering the results of these analyses and flight experiments, there are two areas where significant implications for the design of powered-lift STOL aircraft may be identified. These implications arise from the glide-slope tracking and flare control requirements, and they are associated with the effective thrust turning produced by the high-lift system and with the aircraft's heave response to its primary flight path and flare controllers.

Implications of Glide-Slope Control

One of the most significant influences on the flight-path overshoot characteristic, that so strongly affects glide-slope tracking, is the effective thrust turning of the wing-flap-

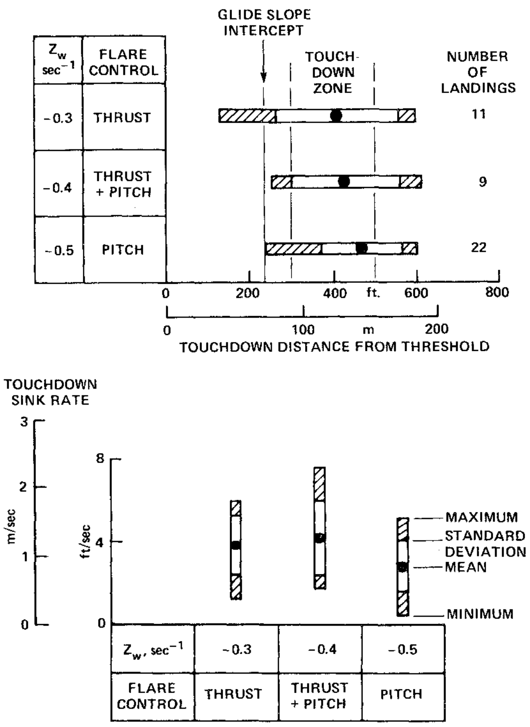

Fig. 10 Comparison of landing performance for various flight-path control characteristics.

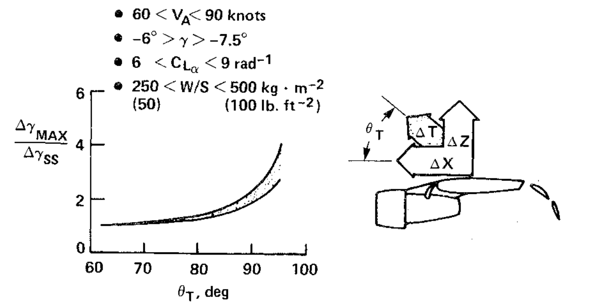

Fig. 11 Relationship of flight-path overshoot to effective thrust turning angle.

propulsion system. This relationship is illustrated in Fig. 11 for a range of other configuration variables. It can be seen in the figure that when the resultant force vector associated with changes in thrust is inclined close to or beyond 90 deg, increasingly objectionable levels of path overshoot will occur. The relationship of path overshoot to thrust turning is also influenced to some extent by other configuration characteristics such as wing loading, lift curve slope, and induced drag, as well as the approach speed and path angle. For a given amount of thrust turning, these effects produce some additional variation in the amount of flight-path overshoot as illustrated in the figure for the range of configuration characteristics indicated. These variations in overshoot attributed to effects other than thrust turning increase with increasing thrust deflection.

The information in Fig. 11 may be interpreted as restricting the amount thrust turning obtained from the high-lift system to insure adequate glide-slope control. Considering present high-lift system technology, only internally blown flap or vectored thrust concepts are likely to approach the 90 deg thrust inclination angles where degraded path control occurs. Externally blown flap designs of either the underwing or overwing variety generally turn the flow no more than approximately 75 to 80 deg, and consequently, pose no difficulty in this regard. Another means of overcoming these undesirable flight-path response characteristics for designs with high-thrust inclination angles is through suitable design of a flight-path augmentation system such as those described in Ref. 16. Appropriately integrated lift and drag control devices can readily counteract the characteristics of the basic design and produce nicely conditioned path response to the primary control, even for configurations with thrust turning in excess of 90 deg.

The dominant influences on heave response are the lags associated with the aircraft's dynamic response and the primary path controller. Results of the glide-slope tracking experiments identified the lowest tolerable value of heave damping to be $Z_w = -0.4$ s^{-1} for a thrust response time constant of 0.75 and for little or no path overshoot. This result may be generalized over a range of heave damping and thrust response as indicated in Fig. 12, based on the assumption that the same phase margin for any source or combination of lags is required for acceptable closed-loop path control. The generalized result indicates that levels of heave damping less than -0.25 s^{-1} would be expected to be unacceptable even with very rapid thrust response, and that thrust time constants in excess of 1.5 s would be unacceptable even for high heave damping. Between these two extremes, these two characteristics may be traded off to achieve combinations which fall to the right of the boundary.‡ If either

‡It should be emphasized at this point that the minimum acceptable pilot ratings that are associated with such a boundary reflect a situation where the pilot's workload to achieve adequate performance of the specified task is at the maximum tolerable level. It is unlikely that such conditions could be accepted under routine operation and design improvements should be strongly encouraged when characteristics fall on or near such boundaries.

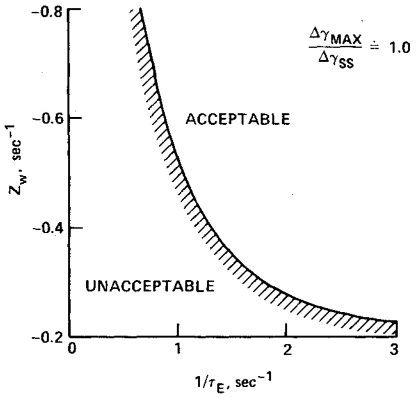

Fig. 12 Acceptable combinations of heave damping and thrust response lag for glide-slope tracking.

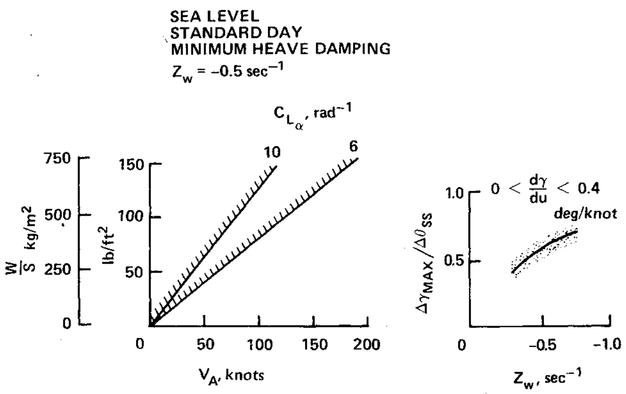

Fig. 13 Relation of wing loading and flight condition for acceptable heave damping.

heave damping or engine response are found to be deficient, lift control devices may be used to artificially augment path response characteristics in order to achieve acceptable glide-slope tracking.

Implications of Flare Control

When it is necessary to flare to sink rates substantially less than the nominal approach rate of descent and when the landing flare is performed exclusively with a pitch rotation, the results of the flight experiments indicate that the flight-path/pitch-response relationship should exceed a value of $\Delta\gamma_{max}/\Delta\theta_{ss} = 0.55$. As shown in Fig. 13, this requirement can be related to the level of heave damping, indicating a minimum level of approximately $Z_w = -0.5\ \mathrm{s}^{-1}$. With this minimum requirement and the relationship defining heave damping

$$Z_w \doteq -\left(\frac{\rho g}{2}\right)\frac{V_A}{W/S} C_{L_\alpha}(\alpha, C_\mu)$$

it is possible to determine the combinations of lift curve slope, wing loading, and approach condition which provide adequate flare capability. This relationship is indicated in Fig. 13 for a range of lift curve slopes which encompass most high-lift system designs, where acceptable configurations fall to the right of the boundary. This boundary may be relaxed somewhat if some thrust can be used to augment the flare with pitch. In this case, heave damping should exceed $-0.4\ \mathrm{s}^{-1}$.

When heave response to pitch is inadequate and the flare is performed essentially with thrust alone, the limiting design condition is the lag in thrust response. Under these circumstances, thrust response time constants less than approximately 0.8 s are required for acceptable flare control.

Conclusions

This paper has presented the results of a flight research program conducted to determine flight-path control requirements for glide-slope tracking and control of the flare and landing for STOL aircraft. These results have indicated the dominant influences on glide-slope tracking to be overshoot in flight-path response to thrust, flight-path/airspeed coupling, and vertical velocity damping. Maximum values of flight-path overshoot and path-speed coupling for acceptable approach flying qualities, in turn, define maximum allowable effective thrust turning angles for the wing-flap-propulsion system. Minimum values of vertical velocity damping define the combination of maximum wing loading and minimum approach speed for acceptable closed-loop path tracking.

The single most important influence on flare capability with pitch attitude is the short-term flight-path response to a step change in attitude. Minimum levels of path response have been established for acceptable control of the flare to low sink rates. The short-term path response can be directly related to vertical velocity damping which, in turn, defines acceptable limits on wing loading and approach speed. For flare with thrust alone, the maximum thrust response times which limit flare control have been determined.

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