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Flight-Test Evaluation of STOL Control and Flight Director Concepts in a Powered-Lift Aircraft Flying Curved Decelerating Approaches

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NOMENCLATURE

C_1 normalized speed-control gain to pitch director

C_2 normalized path-control gain to pitch director

C_3 normalized speed-control gain to throttle director

C_4 normalized path-control gain to throttle director

DME distance measuring equipment

d vertical position error relative to glide slope, m

dlc direct lift control

EADI electronic attitude director indicator

F_s pilot's pitch control force, N

g acceleration due to gravity, m/sec^2

HSI horizontal situation indicator

h vertical position error relative to desired path

ICAO International Civil Aviation Organization

ILS instrument landing system

MFD multifunction display

MLS microwave landing system

MODILS modular instrument landing system

N_H engine rpm, %

R slant range to touchdown, m

R-NAV area navigation

RTOL reduced takeoff and landing

r turn radius, m

SAS stability augmentation system

s Laplace operator, sec^{-1}

TACAN tactical air navigation system, providing bearing and distance information

V, V_A calibrated airspeed, knots

V_G, V_g measured groundspeed, knots

VOR very high-frequency omnirange, ground navigation facility providing bearing information

VORTAC co-located VOR and TACAN ground stations

V_{REF} reference airspeed, knots

X,Y,Z Cartesian coordinates of aircraft in runway axes

X_{δ_T} longitudinal acceleration stability derivative due to throttle deflection, m/sec^2/deg

Z_w vertical acceleration stability derivative due to vertical velocity, sec^{-1}

Z_{δ_T} vertical acceleration stability derivative due to throttle deflection, m/sec^2/deg

α angle of attack, deg

γ inertial flightpath angle, deg

γ_A aerodynamic flightpath angle, deg

γ_o reference flightpath angle, deg

γ_{GPIP} flightpath angle to electronic glide-slope intercept point, deg

δ_T throttle deflection, deg, or equivalent engine rpm

δ_{TFD} throttle flight director deflection, relative to pitch attitude scale on EADI display face, deg

δ_{ν} nozzle angle relative to aircraft datum, deg

θ pitch attitude, deg

ϕ roll angle, deg

ψ heading angle, deg

FLIGHT-TEST EVALUATION OF STOL CONTROL AND FLIGHT DIRECTOR CONCEPTS IN A POWERED-LIFT AIRCRAFT FLYING CURVED DECELERATING APPROACHES

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A flight test program was carried out to assess the feasibility of piloted instrument approaches along predefined, steep, curved, and decelerating approach profiles in powered-lift STOL aircraft. To reduce the pilot workload associated with the basic control requirements of a powered-lift aircraft equipped with redundant longitudinal controls and operating on the backside of the drag curve, separate stability augmentation systems for attitude and speed were provided, as well as a supporting flight director and special electronic cockpit displays. Several STOL control concepts representative of a variety of aircraft were evaluated. The tests were carried out in an environment that employed conventional ground-based navigation facilities and included the development of cockpit and operational procedures considered appropriate to powered-lift aircraft.

The design of the various system elements is provided, and flight-test data are presented describing the performance that was achieved while flying 180° turning, steep descending approach profiles. Measures of control utilization from the aircraft design and pilot workload points of view are presented. Pilot comments regarding the many issues involved in this moderately complex terminal area approach task are included.

The results suggest that curved decelerating instrument approach profiles having moderately low rollout altitudes to the final straight approach segment may indeed be feasible from a pilot acceptance point of view, given an adequate navigation environment. Systems similar to those employed here together provide the potential of carrying out manual flying operations to weather minima corresponding to present day CTOL Category II criteria, while also providing a means of realizing more efficient approaches during visual flight conditions.

Although a few STOL transportation systems have emerged in recent years in response to particular circumstances of economics or geography, widespread development of STOL systems to complement existing transportation networks in medium- and high-density areas has not occurred. The reasons for this are varied and complex. In general, however, it is recognized that a highly integrated infrastructure must exist before STOL systems will be able to achieve economic justification. This condition suggests that the required developments are perhaps more in the area of effective systems integration than in bridging technological gaps. The potential development and application of powered-lift STOL aircraft in particular are especially sensitive to economic and environmental efficiencies, thus placing additional emphasis on this need for an effective, integrated systems approach to developing STOL transportation networks.

In consequence, the work reported here addressed the integration of the navigation, guidance, and manual control constituents of the terminal-area approach and landing tasks, with the objective of better assessing the potential for optimizing this aspect of the STOL transportation problem.

In addition to fuel conservation considerations, which are bound to affect all terminal-area operations in the coming years, the requirement for specialized STOL arrival procedures arises in either the downtown-to-downtown STOLport operation, or the spoke-to-hub operation, where desirable arrival routes almost certainly will be constrained by obstruction clearance requirements, authorized environmental corridors, or traffic integration problems with CTOL aircraft. In the latter case, the capability of STOL systems to provide additional transportation capacity, competitive in block travel times and without an attendant increase in congestion, may rest upon having direct and specialized

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access to designated STOL runways at the major hub airport or to a downtown STOLport, which may be located in potentially conflicting proximity to CTOL arrival routes to other outlying airports. Moreover, these operations, especially at hub airports where the major function may be in connecting to main-line CTOL carriers, must be carried out with the same degree of reliability in respect to weather conditions as that achieved by CTOL aircraft. These requirements for improved operational efficiency arise at a time when deployment of the forthcoming ICAO microwave landing system (MLS) and advances in in-flight computing capability and cockpit display hardware present the distinct possibility of realizing an acceptable system at acceptable cost.

To develop a body of data that can be used to define criteria for this aspect of STOL operations, Ames Research Center has been conducting a number of STOL operating systems investigations involving both simulation and flight studies. Some of these investigations have been directed toward relatively conventional low-wing-loading STOL aircraft, using a DeHavilland DHC-6 Twin Otter aircraft on loan from the Canadian Government as the test aircraft. The powered-lift investigations have employed the Augmentor Wing Jet STOL Research Aircraft (AWJSRA) equipped with an easily programmable advanced digital avionics system as the test vehicle. The Augmentor Wing research program is also a cooperative venture with the Canadian Government. A research-pilot-engineer from the National Aeronautical Establishment, a division of the National Research Council of Canada, was assigned to these programs in 1976 with the responsibility for implementing and carrying out, to meet mutual objectives, the work reported here.

This work considers the manual control aspects of flying constrained terminal-area flightpaths in a powered-lift STOL aircraft, with the aid of a flight director, to weather limits corresponding to CTOL Category II operations (nominally 30.5-m (100-ft) decision height, and 366-m (1200-ft) runway visual range). This class of aircraft is characterized by a thrust vector orientation in the approach configuration that is nearly orthogonal to the flightpath. The details associated with managing the relative proportions of what can be considered for simplicity the more conventionally wing-generated aerodynamic lift, and the powered lift provided by the propulsion system, result in added complexity to the usual pilot's control tasks of controlling glidepath and preserving safety margins. This investigation considered these control-related issues, which had not previously been addressed in flight and in the context of a demanding instrument approach task. Moreover, the investigation was conducted in a navigation environment that employed conventional ground-based facilities, and evaluated a more constrained approach path than previously had been considered for either automatic or manual flight. Consequently, this work extends considerably the flight tests reported in reference 1, in which a constant-speed approach was flown in a more conventional low-wing-loading STOL aircraft along curved profiles, but in a simulated navigation environment with near perfect and continuous navigation data.

The peculiarities associated with flight control of powered-lift aircraft have prompted a considerable research effort into the problems of operating this class of aircraft. References 2 and 3 consider in detail the longitudinal flight dynamics of powered-lift aircraft and their effect on handling qualities. Reference 4 describes some of the fundamental features of powered-lift aircraft and proposes civil certification criteria possibly appropriate to their general design features and operational characteristics. References 5 and 6 address automatic flight control considerations for powered-lift aircraft, specifically the automatic configuration management aspects. This report provides data on the operation of these aircraft in the context of a moderately complex piloted instrument approach task.

To better relate the results of this investigation to the variety of powered-lift STOL aircraft (refs. 7-10) that have resulted from recent aerodynamic studies, three representative STOL control concepts and their associated flight directors were evaluated. This was made possible by the high degree of flexibility in the variable stability flight-control system of the research aircraft used in these tests.

The report first discusses some of the important operational factors associated with the steep and turning STOL approaches that originate from the peculiarities of powered-lift STOL aircraft and from the nature of the approach task. Many of these considerations are also pertinent to V/STOL aircraft and, to a lesser extent, low-wing-loading STOL and RTOL aircraft. Subsequent sections provide a comprehensive description of the systems employed in the flight experiment, and furnish flight-test data that range from net outer-loop performance measures, which are applicable to defining authorized flightways, to control utilization data, that are applicable to aircraft design criteria. The data presentation concludes with a discussion of pilot acceptance factors pertinent to this kind of STOL operation.

I. SYSTEM DESIGN CONSIDERATIONS

Many factors require special consideration in the design of a system to meet the objectives of this investigation. Some are kinematic factors that relate to the low approach airspeeds that will be flown, and the effect of relatively larger atmospheric wind and turbulence fields. There are special factors that relate to the control of a powered-lift aircraft through nearly its entire unaccelerated flight envelope from conventional cruise to STOL landing configurations. And special consideration must be given to the realities of the navigation environment in which the approach is conducted. This section first describes the general approach profile that was chosen as the basis for this investigation, and subsequently discusses in a general way the associated system design requirements.

Approach Task Definition

To ensure that attention would be given to a variety of potential problem areas, the approach profiles chosen as the basis for this flight study had the general features shown in figure 1. The 180° descending turn ensured that methods would be developed to deal with (1) the discontinuity in the terminal-area navigation environment at the transition from lower accuracy en route navaids (VOR/DME or TACAN) to precision approach navaids (MLS), and (2) the effects on lateral and longitudinal control requirements of changes in the relative direction of significant winds. The scenario involves entering the approach profile (implemented by area navigation (R-NAV) techniques) in the conventional flight configuration at a representative terminal-area maneuvering speed – 140 knots in the test aircraft. It is desired to maintain this entry airspeed for as long as feasible, within the constraints of reasonable pilot workload, prior to transitioning to the much less

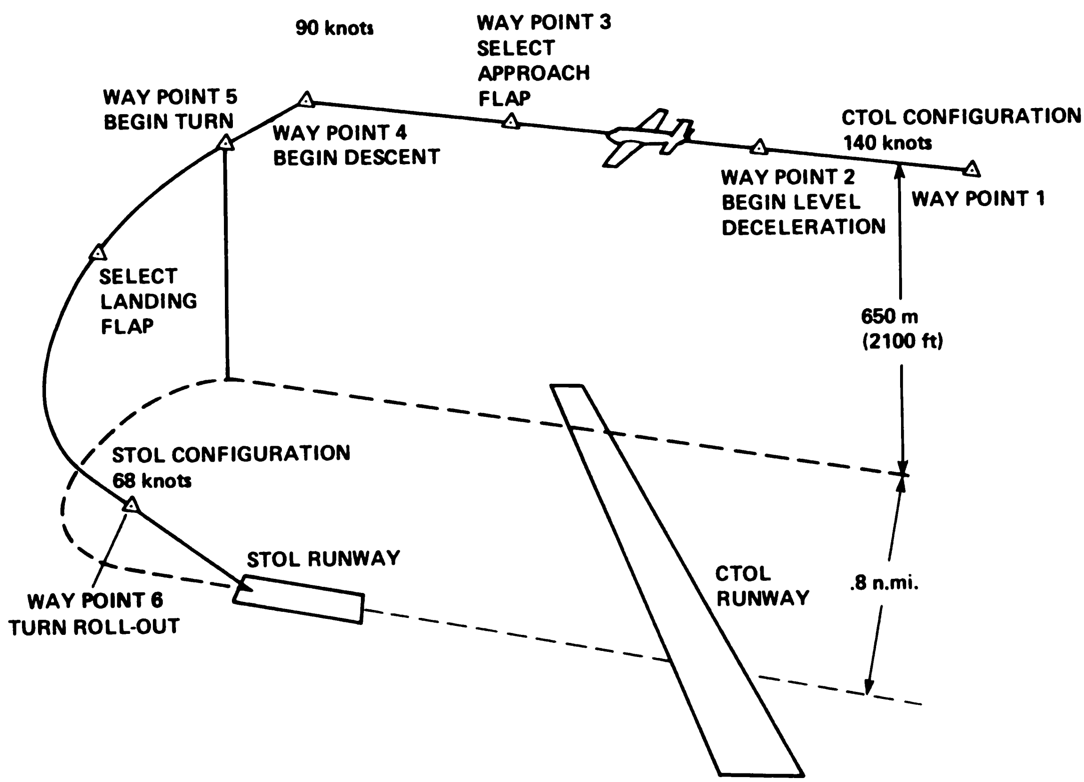


Figure 1.– STOL approach profile.

economical STOL approach and landing configuration where airspeeds might be as low as 65 knots. Since this type of approach profile could not be flown realistically without the aid of a flight director, the final straight segment prior to breakout also provided the opportunity to evaluate the potential applicability to powered-lift STOL operations of various existing criteria for comparable CTOL Category II operations. Landing transitions to a STOL runway were carried out from a simulated decision height of 30.5 m (100 ft) as a final measure of the system performance.

Navigation Environment

A unique feature of the approach task relative to a conventional ILS task, for example, is not just the curvilinear nature of the task but also the relatively late transition into coverage of the precision landing guidance system. This will generally cause a maneuver transient that arises from lateral and vertical differences in the position measurements from the navaids and altitude sensors that are used before and after entering the zone of precision coverage. The ability of the system to first minimize and then satisfactorily correct these delivery errors will strongly influence the range of potentially acceptable approach profiles. Important factors in this regard are (1) the design of the navigation filters that typically complement the raw ground-based navigation signals with on-board data from barometric and strapped-down inertial sensors, hence providing wideband three-dimensional estimates of aircraft position; (2) the location relative to the STOLport, and the signal transmission and reception characteristics of the VOR or TACAN facility used for terminal-area navigation, and (3) perhaps the most important factor is the available coverage volume of the precision landing guidance system located at the STOLport. This report does not address the various regulatory considerations that would be involved in authorizing instrument approach profiles in a discontinuous navigation environment.

An interim microwave landing system, MODILS, was used for these tests. The facility provided a lateral coverage of only ±20°, about half that proposed for the ICAO standard MLS. Relative characteristics of these two systems are summarized in table 1. Details of the on-board navigation system used are provided in a subsequent section.

TABLE 1.– MICROWAVE LANDING SYSTEM CHARACTERISTICS

Coordinate			MODILS[a]	MLS[b]
AZIMUTH	Coverage:	Azim	±20°	±40°
		Elev	0 to 15°	-1 to 15°
		Range	40 nm	20 nm
	Resolution		0.1°	0.01°
ELEVATION	Coverage:	Azim	±25°	±40°
		Elev	2 to 16°	1.9 to 10.7°
		Range	40 nm	20 nm
	Resolution		0.01°	0.01°
RANGE	Coverage:	Azim	±60°	±70°
		Elev	0 to 15°	-1 to 15°
		Range	20 nm	20 nm
	Resolution		18.3 m	1.83 m

[a]Interim design system used for these tests.
[b]Basic narrow aperture MLS proposed for ICAO use.

Wind Effects

Winds, which may be a significant percentage of approach airspeeds, can have a profound effect on STOL operations, particularly during descending turns. Some of the factors requiring consideration when following inertially referenced approach profiles in moderate or severe winds are (1) the changing bank angle requirements during sustained turns, (2) the ability to maintain satisfactory trim descent conditions over a much wider range of aerodynamic flightpath angles than is normally the case for CTOL aircraft, and (3) the choice of an approach configuration and airspeed appropriate to the headwind conditions at touchdown.

Sustained turn considerations– To help keep the nominal roll angle within assumed limits of pilot and passenger comfort (±25°) over the range of airspeeds and groundspeeds expected, it was decided to provide the pilot with a choice of turn radius for the approach. A turn radius of 760 m (2500 ft) was typically used in light winds; a radius of 914 m (3000 ft) could be used for approaches in stronger winds or at higher airspeeds. Data are presented in a subsequent section describing actual bank angle utilization during the descending turn.

Descent trim considerations– The aerodynamic characteristics of powered-lift aircraft typically require the use of an auxiliary longitudinal control to adjust trim configuration drag during steep approaches in varying wind conditions. Excessive trim drag for the trim aerodynamic descent angle will result in too high a power setting to follow the inertial glidepath, and vice versa. These effects, although generally true, are of significantly greater consequence for low-speed aircraft operating in stronger winds on a fixed inertially referenced glide-slope angle because of the relatively large variations in approach groundspeed and hence aerodynamic flightpath angle that can occur for any fixed approach airspeed. For powered-lift STOL aircraft that are designed to use relatively high approach power settings, excess trim drag can result in uneconomically higher-than-nominal approach power settings. In addition, there may be insufficient reserve thrust, particularly following an engine failure, to accomplish satisfactory glidepath corrections from below. The situation of insufficient trim configuration drag, as might be encountered during an approach in unexpectedly calm or tailwind conditions, for example, is also to be avoided in powered-lift aircraft because the associated low power setting will result in a higher than desired angle of attack, unless speed is also increased. To deal with this problem in powered-lift aircraft, the pilot is generally required to make an advance evaluation of the expected wind conditions during the approach, then set an auxiliary control accordingly, perhaps making one or two subsequent iterative adjustments during the course of the approach. Ideally, the auxiliary control will affect only drag and have an insignificant effect on lift; the control could be, for example, final flap angle, drag brake setting, or vectored thrust nozzle angle, depending on the specific design.

The additional control management task imposed on the pilot, in the absence of sophisticated stability- and control-augmentation systems, may be a source of significant additional workload, in terms of planning and manipulation, even for straight-in approaches. The potential for difficulty is apparent during steep turning approaches in strong winds, where the aircraft is effectively subjected to large wind shear forces. This problem received considerable attention in the design of the approach flight director concept used in this work; a means of resolving the problem is described in a subsequent section. Implementation of this trim management system, which directed the pilot with the required position of the control used for trim, based on a system estimate of current along-track wind, was instrumental in obtaining favorable pilot acceptance of the curved, decelerating steep approach.

Landing configuration options– The requirement for STOL in general is ultimately governed by the shortest runway lengths from which operations at a given load are required. The requirement for powered-lift STOL results from a desire to also achieve economical high-speed cruise performance. Although the design costs associated with achieving the short-field capability are fixed for any specific STOL aircraft, the operational costs need not always be incurred for circumstances in which the maximum STOL capability is not required. Where longer runway lengths are available, or where significant headwinds could reasonably be "guaranteed" to prevail at landing, a higher approach airspeed and correspondingly less powered lift would be more efficient. Under those circumstances, a steep approach angle could still be flown, provided that aircraft characteristics permitted and that associated sink rates were not excessive. When time is also taken into account, this procedure would also reduce airspace utilization during approach. It is probable that powered-lift operations would require the pilot to take these factors into account and to determine an approach airspeed that would not only be appropriate to current aircraft weight, but one that would be primarily governed by the chosen approach and landing configurations. The landing configuration would be determined by the runway and wind conditions. The cockpit procedure and the approach flight director system that were developed for this investigation provided flexibility in choice of separate approach and landing configurations, and of their associated reference airspeeds. A modest deceleration capability while on descent was also incorporated between the initial approach and final landing configurations, as described in a later section.

Aircraft Operating Characteristics and Stability Augmentation Systems

Powered-lift STOL aircraft in the approach configuration generally operate at high levels of induced drag and on the backside of the drag curve. Backside operation is characterized by a steepening of the descent angle with any sustained reduction in airspeed, unless power is increased. This longer term effect is inconsistent with the pilot's more conventional and perhaps instinctive use of pitch attitude to bring about shorter term corrective changes in flightpath angle, since the long-term response ultimately will stabilize in a direction opposite to that of the initial response. Details associated with these characteristics, and their effect on pilot control technique, are discussed in reference 2. Three different control techniques or systems for dealing with these characteristics will be introduced in this section.

In general, these features require the pilot to employ a "backside" control technique in the landing configuration. The technique involves the use of power for glidepath control and pitch attitude for airspeed control, just the opposite of the "frontside" technique used in almost all circumstances for CTOL transport aircraft. The degree of backsidedness exhibited by a particular aircraft may be such as to require tight speed regulation in order to preclude unwanted changes in flightpath angle. Contributing to potential difficulties in the speed regulation task are atmospheric disturbances, including shears, and perhaps pilot control difficulties in pitch, as may arise from control cross-couplings. These cross-couplings may be manifested by either unwanted pitching moment changes, effectively resulting from modulation of a thrust vector which is offset from the center of gravity (a relatively common problem), or by flightpath-airspeed coupling. As an example of the latter type of cross-coupling, a thrust vector inclination angle that is substantially forward of the normal axis of the aircraft will result in both speed and flightpath angle responses whenever thrust is changed; this will usually require a subsequent change in pitch to prevent undesired excursions. This situation will generally exist during the conversion to powered-lift, where progressive changes in configuration, usually increasing flap angle, have the effect of deflecting the thrust and correspondingly rotating the thrust vector from the longitudinal axis (approximately) toward the normal axis. Although the effects of these intermediate inclination angles can be tolerated for the relatively short period of time required to make the conversion, sustained operation in these configurations is undesirable. A thrust vector inclination than is aft of the normal axis, caused by a very efficient and perhaps excessive thrust-deflection mechanism, could have even more profound implications, evoking the distinctly unconventional response of slowing down, unless the pilot also pitches down, when power is added.

The use of a flight director that incorporates control position direction for throttle and pitch attitude, in order to help maintain specified glidepath and speed references, simplifies this aspect of the control task. The reduced workload resulting from more closely controlled aircraft responses to any existing cross-couplings or any other disturbances enables complex terminal-area approach tasks to be realistically considered. This case of dealing with these thrust-vector-related cross-couplings – as they may exist for any particular aircraft, without the aid of any associated stability augmentation system – will be referred to throughout this report as the "basic" control configuration.

The degree of backsidedness may be severe enough to require the use of an automatic speed-control and stability augmentation system (SAS) to accomplish the very tight speed control required, and hence reduce pilot workload to acceptable levels. A desirable design would incorporate a device that could modulate longitudinal thrust-drag forces over a moderate range with rapid response characteristics and without affecting lift. This SAS would be described as a "backside speed control SAS" since it is associated with correcting the relatively small but consequential speed errors arising from maneuvering and any inherent cross-coupling arising from use of the backside control technique. Perhaps equally important, it would also assist in offsetting undesirable effects due to low-frequency atmospheric disturbances such as wind shears. For this variation in backside control technique, the primary control task of glidepath tracking is still achieved through power modulation. Because the speed-control device carries out the secondary control task of maintaining adequate safety margin, pitch attitude assumes a tertiary role of governing the descent trim condition, allowing the approach to be flown with an essentially fixed pitch attitude. This definition of control functions, together with the assignments pertinent to this particular control concept, is one that will be referred to throughout this report.

Alternatively, a means of producing greater longitudinal control authority might provide enough thrust-drag force modulation to allow the aircraft to be flown using the frontside control technique despite the fact that it may be operating on the backside of the drag curve. Under these circumstances, large changes in induced drag caused by pitching and changes in the component of gravity along the flightpath can be adequately offset, hence allowing use of a single pilot control technique throughout the entire flight envelope. Use of an automatic speed-control system to modulate the longitudinal-force device ensures the very close speed regulation required at these backside operating points, despite the otherwise upsetting use of pitch attitude for glidepath control. In the approach configuration, the pitch attitude, the longitudinal force device, and the power setting are assigned to the primary, secondary, and trim control functions, respectively. Two important additional considerations that arise with use of this "frontside speed control SAS" are (1) the adequacy of initial heave response that can be obtained through pitching and (2) the effect that large changes in the longitudinal force control may have on lift. These factors will be the subject of later discussion.

This discussion also explains the frequently encountered terminology that describes the trim or auxiliary longitudinal control as a redundant control. Any two longitudinal controls, each having sufficient authority, can be used to control the two linear degrees of freedom (velocities) in the aircraft plane of symmetry, leaving the third control redundant. This terminology is only relevant when the third control also has sufficient authority, and speed of response, to be considered an alternative for providing control, thus making a variety of control concepts possible.

The three STOL control concepts considered above (basic aircraft, backside SAS, and frontside SAS) are representative of the wide spectrum of possibilities for this class of aircraft. Although they have been the subject of earlier research (ref. 11), they have not previously been evaluated within the context of a complex operational approach task nor in an environment requiring attention to trim management. Details of their implementation for this flight investigation are presented in the following section.

II. TEST AIRCRAFT AND CONTROL SYSTEM IMPLEMENTATION

General

The Augmentor Wing Jet STOL Research Aircraft (AWJSRA) is a de Havilland of Canada DHC-5/C-8A Buffalo airframe modified with an augmentor flap system (figs. 2 and 3). The integrated propulsive-lift system incorporates two Rolls Royce Spey 801 split-flow turbofan engines providing cold fan thrust to internally blow the augmentor flap for powered lift. The residual hot thrust (approximately 60%) can be independently vectored over a range of 98° by means of two conical nozzles, thereby providing generous (and immediate) steep descent or go-around capability over a range of about 12° of flightpath angle. The cold thrust is cross-ducted in appropriate amounts so that minimum asymmetric lift results in the event of engine failure.

Pitch, yaw, and roll controls are hydraulically powered. A single-segment elevator is used for pitch maneuvering and trim, and a two-segment rudder is used for yaw control. Roll control is provided by blown ailerons, outboard upper-surface spoilers, and augmentor chokes that are scheduled with wheel angle and flap angle in order to maintain constant roll-control sensitivity as speed is reduced. The augmentor chokes consist of surfaces located within the augmentor flap segments. For roll control they function by differentially restricting the augmented airflow through the outboard segmented flap section, thereby asymmetrically altering the spanwise lift distribution.

In the approach configuration, engine power controls the magnitude of the flap-deflected cold thrust and nozzle-vectored hot thrust. The direction of the latter can be independently vectored between 6° and 104° relative to aircraft datum. Typically, the nozzles are deployed to a setting near 75° to 80° for steep descent in order to provide both additional drag and powered lift in the approach configuration. Modulation of nozzle angle in the region between about 45° and 104° provides independent longitudinal force control while also contributing an approximately constant amount of powered lift separate from that furnished by the augmentor flap. Provision exists for a modest amount of direct-lift-control (dlc) through symmetric actuation of electrohydraulic choking surfaces designed as part of the inboard augmentor flap segments; however, the pilot has no direct control over this function. Figure 4 illustrates the overhead cockpit control layout used for propulsion system management. The physical characteristics of the aircraft are discussed in greater detail in references 12 and 13.

Basic Angular Stability Augmentation

Limited authority electrohydraulic actuators are incorporated in series with the pilot's pitch, roll, and yaw controls; they are driven by the attitude SAS to provide rate command, attitude-hold characteristics in pitch and roll, and rate-damping and turn-coordination characteristics in yaw. This SAS mode is

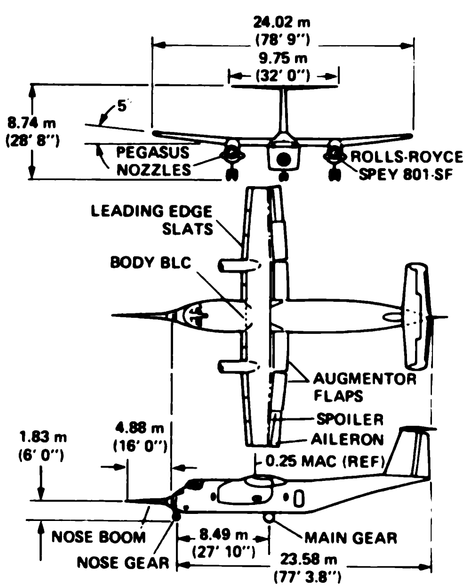


Figure 2. – Augmentor Wing Jet STOL Research Aircraft.

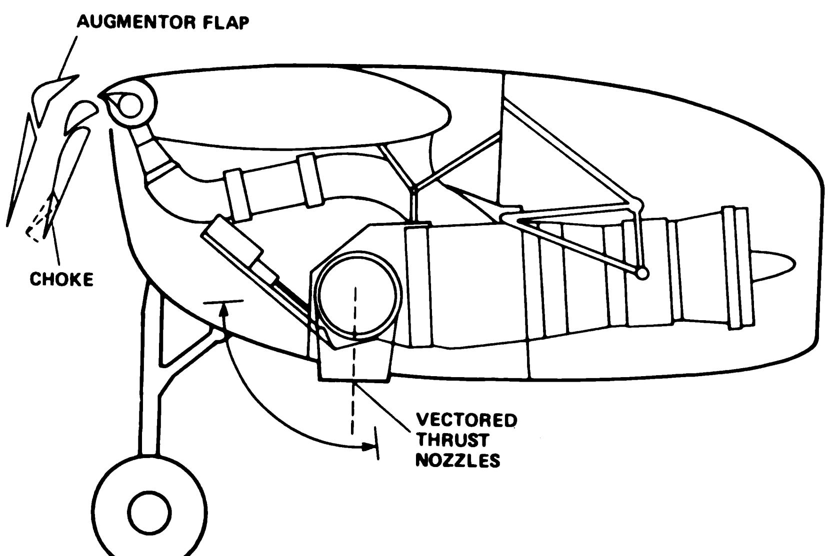


Figure 3.– Augmentor wing propulsive lift system.

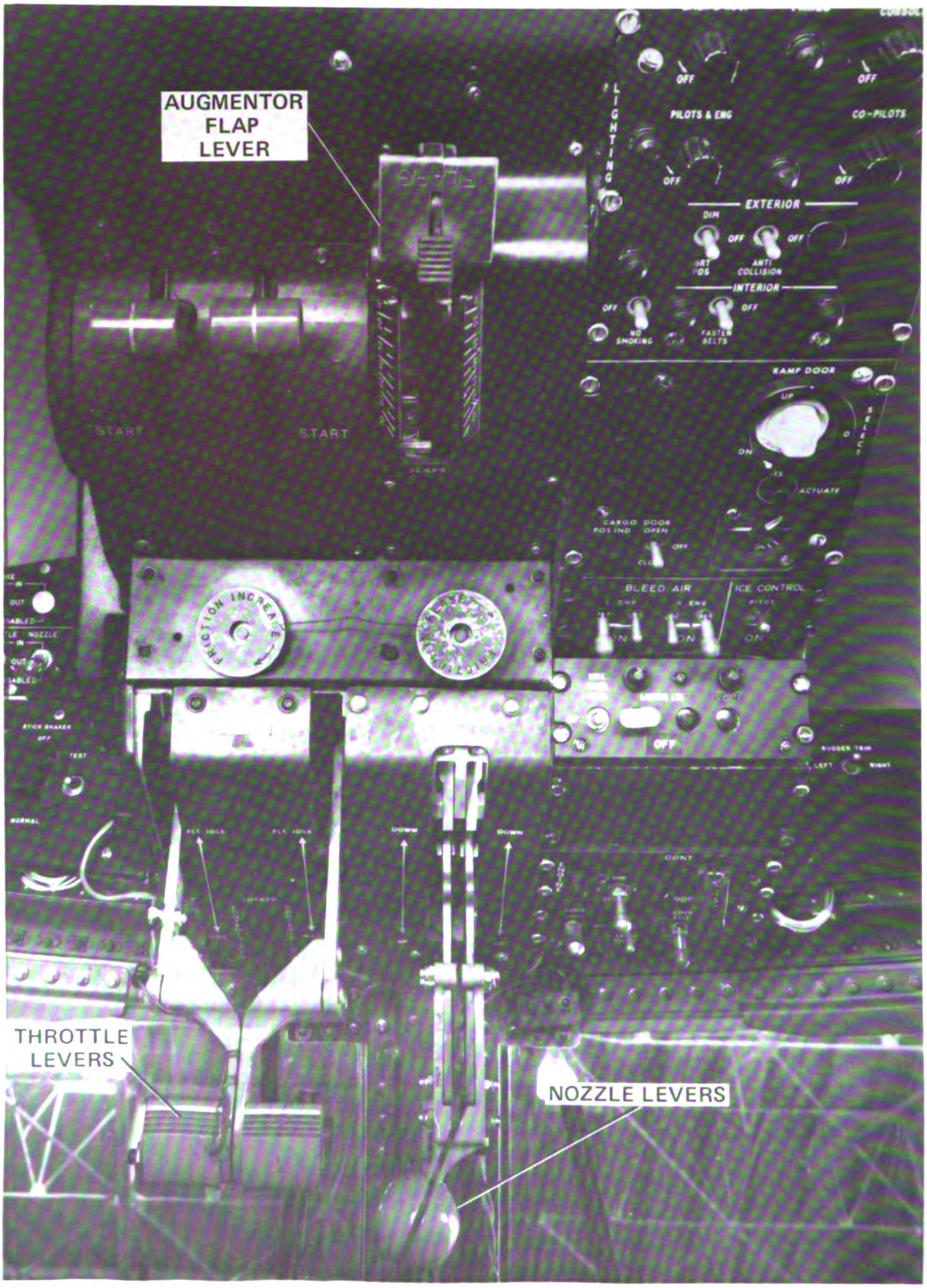


Figure 4.– Overhead propulsion system controls.

available for use at speeds below 140 knots, although the requirement for its use is only significant in the approach configuration at speeds below 90 knots. A trim follow-up circuit in pitch slowly repositions the pilot's control to restore the full authority of the series pitch actuator.

The pitch-attitude SAS in particular is a useful workload-reducing feature which is gaining wide acceptance for this class of aircraft. Often the need for such a system derives not only from the low stability inherent in low-speed flight, but also from significant variations in the aerodynamic center of pressure, or from induced-flow effects at the tailplane which may occur either during transition to powered lift or while modulating the propulsive-lift controls used for longitudinal path control in the approach configuration. These difficulties are minimal in the AWJSRA, however, because of the T-tail arrangement and the high degree of center-of-pressure stabilization effected by the internally blown augmentor flap. In addition, the thrust lines of the vectorable hot-thrust nozzles are located close to the aircraft center of gravity range; thus, they minimize pitching-moment changes arising from their sometimes aggressive and rapid use. The practical results of these design features, beyond obvious implications for tailplane design, are (1) trim follow-up at the pilot's control is barely perceptible, and (2) maximum SAS authority for maneuvering and for pitch stabilization in gusts is retained. Although the SAS actuator has only 40% authority over the elevator (unmodified from the original Buffalo dimensions), it has good margin from saturation, even during such demanding maneuvers as go-around. The rate-command attitude-hold pitch SAS was employed for all evaluations reported here. Details of the rate-command attitude-hold SAS are given in reference 11.

Performance Envelope: Descent Configuration

Data describing the trim control positions for this aircraft in the descent configuration without any form of speed-control augmentation are shown in figures 5 and 6 for the cases of (1) fixed nozzle and (2) fixed throttle. In each case a substantial amount of flightpath authority is available over the useful range of operation of the variable propulsion system control, either throttle or nozzle. It was explained in a previous section that this authority can be significantly eroded unless proper attention is given to the setting chosen for the fixed control, which is used for trim. The basis for determining these settings is described in a subsequent section that details the trim management portion of flight director design.

In the first case, in which the aircraft is flown with a backside control technique using throttle for glidepath control, adverse coupling between the responses in glidepath and in speed to power changes is evidenced by the slope of the constant attitude contours shown in figure 5. This requires the pilot to unconventionally coordinate pitch attitude and power, pitching down in order to maintain speed, for example, whenever power is added to effect an upward correction. The degree of this effect is strongly influenced by the trim nozzle angle that is employed. It becomes more severe for steep descents in tailwinds, where large trim nozzle deflection angles are required in order to preclude unacceptably low power settings that would result in undesirably high angles of attack.

This coupling characteristic of the basic aircraft configuration can be removed by incorporating the backside speed-control SAS mentioned in the previous section. The responses can be effectively decoupled by a speed-hold SAS which conceptually rotates the constant attitude contours until they are vertical. This is accomplished through small changes in nozzle angle that offset the longitudinal thrust or drag changes associated with power adjustments. Maintaining the particular pitch attitude appropriate to the desired operating point ensures that the mean nozzle angle about which speed control occurs, and the average power setting needed to track the required glidepath, will be correct for the wind conditions of the day.

Analysis of figure 6 indicates the mechanism of the frontside speed-control SAS which was implemented for the aircraft. The nearly vertical orientation of the constant angle-of-attack contours represents the nearly ideal function of the nozzles as a longitudinal thrust-drag control, at least in the region of 80° ± 25°. Automation of this function enables pitch attitude to be used aggressively for glidepath control, since the nozzles have enough authority to offset the corresponding changes in the longitudinal component of gravity, as well as the large but temporary changes in induced drag that result from the associated angle-of-attack transients. These dynamics require that the nozzle follow the pitch changes almost immediately to prevent speed changes; this is unlike the case for conventional aircraft in which the requirement for thrust changes presents a substantially lower frequency control task

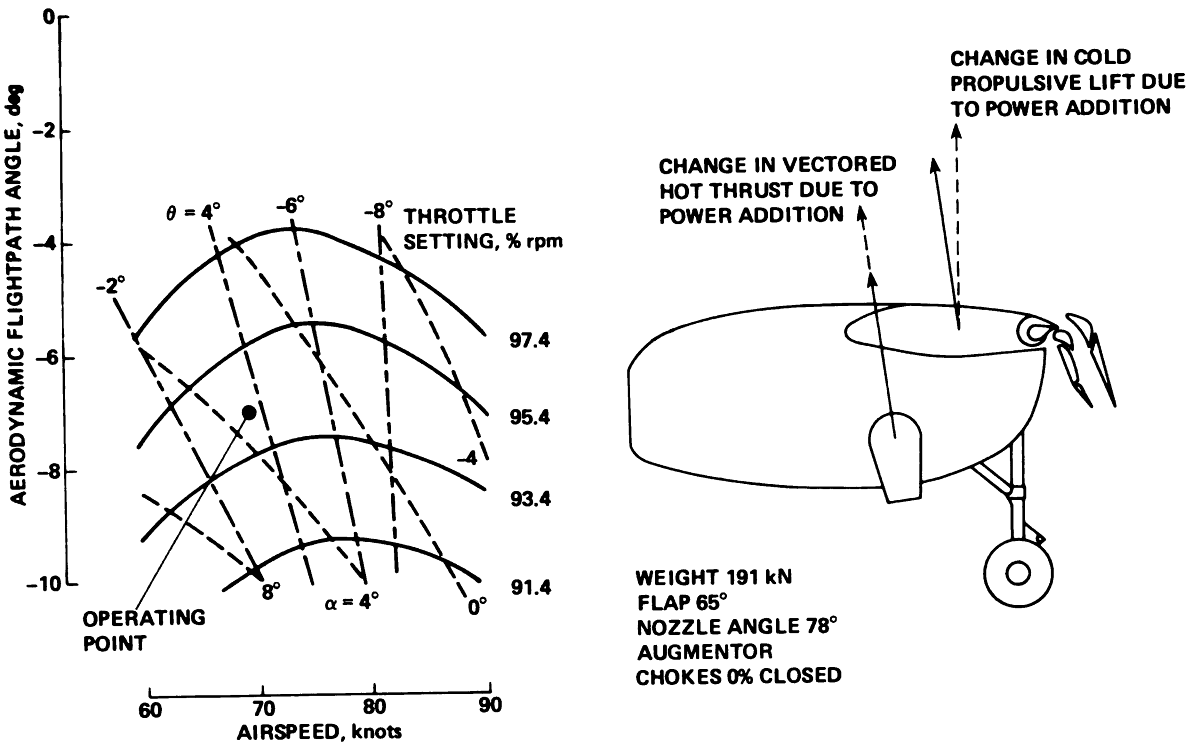


Figure 5.– Descent trim conditions, nozzles fixed.

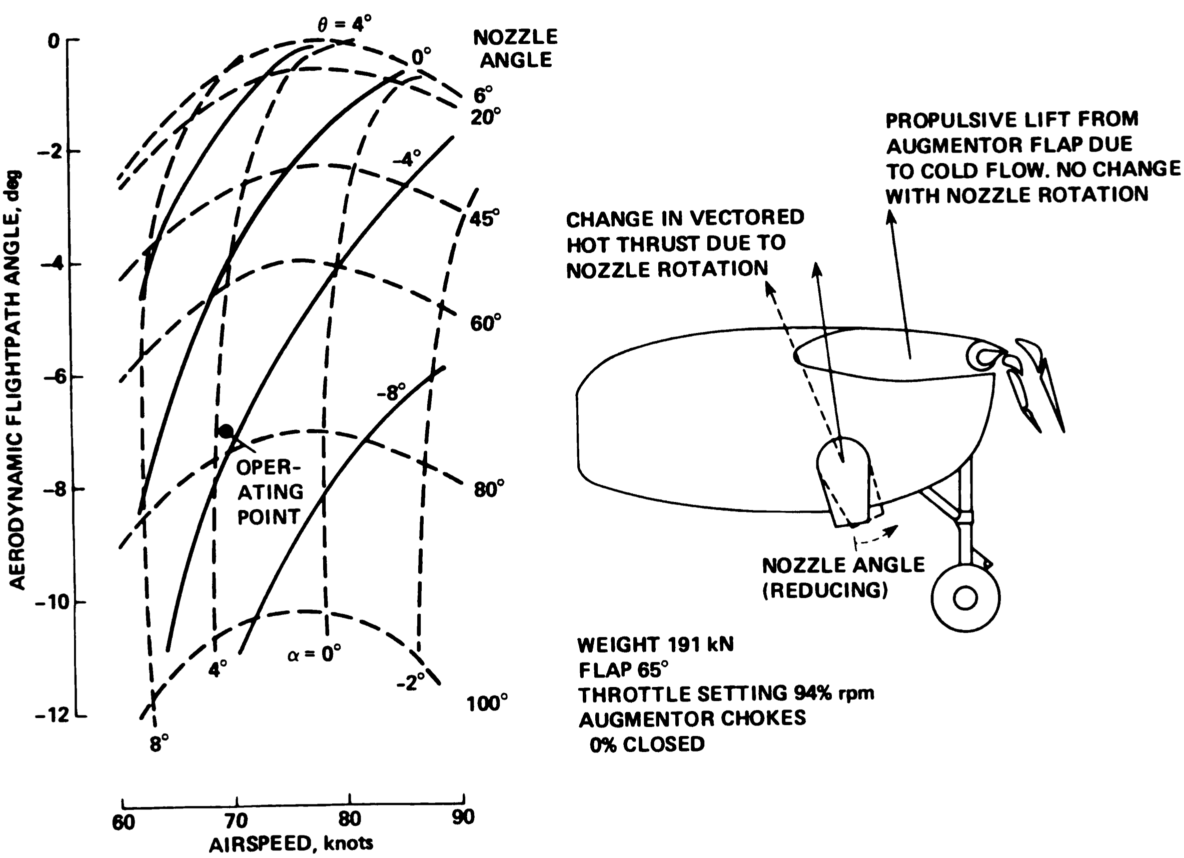


Figure 6.– Descent trim conditions, throttle fixed.

relative to the more active pitch control inputs. The rounding of the angle-of-attack contours in the upper portion of the envelope is caused primarily by the loss in the hot-thrust component of lift as the nozzles are retracted to their up position, for example, during the course of a large upward correction. In the speed-hold system that was implemented, this lift loss was experienced as a reduction in the steady-state flight-path angle response to pitch attitude control, since with constant speed this lift could only be furnished through an increment in the angle of attack. In fact, the inboard augmentor chokes were used to reduce this undesirable effect, as described later. Similar to the other control modes, proper choice of the power setting used for trim ensures that the mean pitch attitude and nozzle angle used in the course of tracking the glidepath result in the preservation of adequate control authorities and safety margins.

Table 2 summarizes the control assignments for the three control concepts just discussed. It should be pointed out that the earlier research of reference 11 had already identified the fundamental handling quality issues associated with these STOL control concepts. This enabled a design to be readily developed, particularly for the frontside speed control SAS, which incorporated desirable features into a more operationally usable system as was needed for this flight investigation, and which also more closely approached an operational design for an aircraft such as this. The design details will now be discussed.

Speed Control SAS Systems and Response Characteristics

Both versions of the speed-control SAS can be obtained from essentially the same mechanization, since the system will act to maintain speed at the reference value regardless of which control (or outside disturbance) may be the cause of an error. The system, which is shown conceptually in figure 7 and in detail in figure 8, was implemented using the research avionics system described in a following section. The system relies on nozzle vectoring in the range of 45° to 105° for the necessary longitudinal force modulation. Consequently, speed control by this means is only effective during steep descent, that is, when the nozzles are typically deployed to this range in order to help furnish the large amount of net drag that is in any event required. After the nozzles are deployed to initiate the descent, the speed-control SAS becomes active, if selected. From the figures, it is noted that the fundamental outer velocity loop has its reference value controlled indirectly by the pilot through his selection of flap angle, obviating the need for any additional action to manage the speed SAS, once selected. The scheduling of this speed reference to flap angle is discussed in more detail in a later section that describes the design of the flight director.

The loop structure used in the design of the speed-control SAS includes a direct feed-forward from pitch attitude to nozzle angle in order to immediately compensate for changes in the component of gravity along the flightpath. This structure assists with the higher-frequency loop performance resulting from occasionally aggressive pitch-attitude maneuvering and reduces substantially the gain which would otherwise be required in the velocity feedback loop. The velocity feedback loop provides gust and shear protection, ensures following of the slewing reference when flap settings are changed, and compensates for minor inadequacies associated with the pitch maneuvering term. The use of a second-order, 0.25-rad/sec complementary filter on the airspeed feedback quantity, rejecting turbulence but retaining the higher-frequency inertial response, further leads to good bandwidth in response to maneuver-generated inputs without excessive or objectionable nozzle activity arising from atmospheric disturbances. An integrator, included to prevent velocity standoff errors, also provides a means for trim positioning of the nozzles (a feature discussed in more detail in conjunction with the flight director design).

It is desirable to increase the relatively pure longitudinal force modulation available from the vectoring nozzles by extending their operation into a range where lift coupling may become significant. The aerodynamics require that any lift loss encountered due to nozzle retraction (in the course of moving to hold speed following a sustained upward correction, for example) be compensated by a sustained increase in angle of attack, since power is assumed constant for this configuration. This results in a reduction in steady-state $\Delta\gamma/\Delta\theta$ response which is an undesirable feature that not only affects safety margins but also accentuates the amount of pitch activity needed to obtain a desired path change. To offset this effect, the frontside speed control SAS incorporated the inboard augmentor chokes in a direct-lift-control mode, opening the chokes from a midrange nominal position increasing the augmentor flap component of lift whenever the nozzles retracted reducing their vectored thrust component of lift. The concept is illustrated in figure 9. This improvement is achieved at the expense of carrying a bias in the

TABLE 2.– SPECTRUM OF STOL CONTROL CONCEPTS

Control concept	Basic aircraft	Backside SAS	Frontside SAS
Primary control (path)	Throttle	Throttle	Pitch attitude
Secondary control (speed)	Pitch attitude	Nozzle[a]	Nozzle[a]
Trim control	Nozzle	Pitch attitude	Throttle

[a]SAS managed

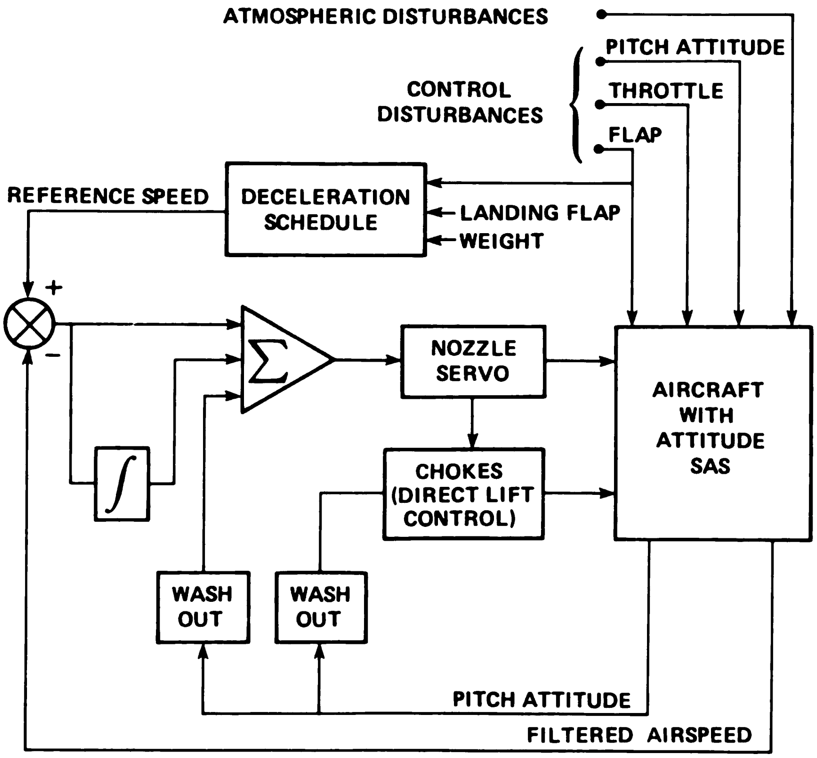
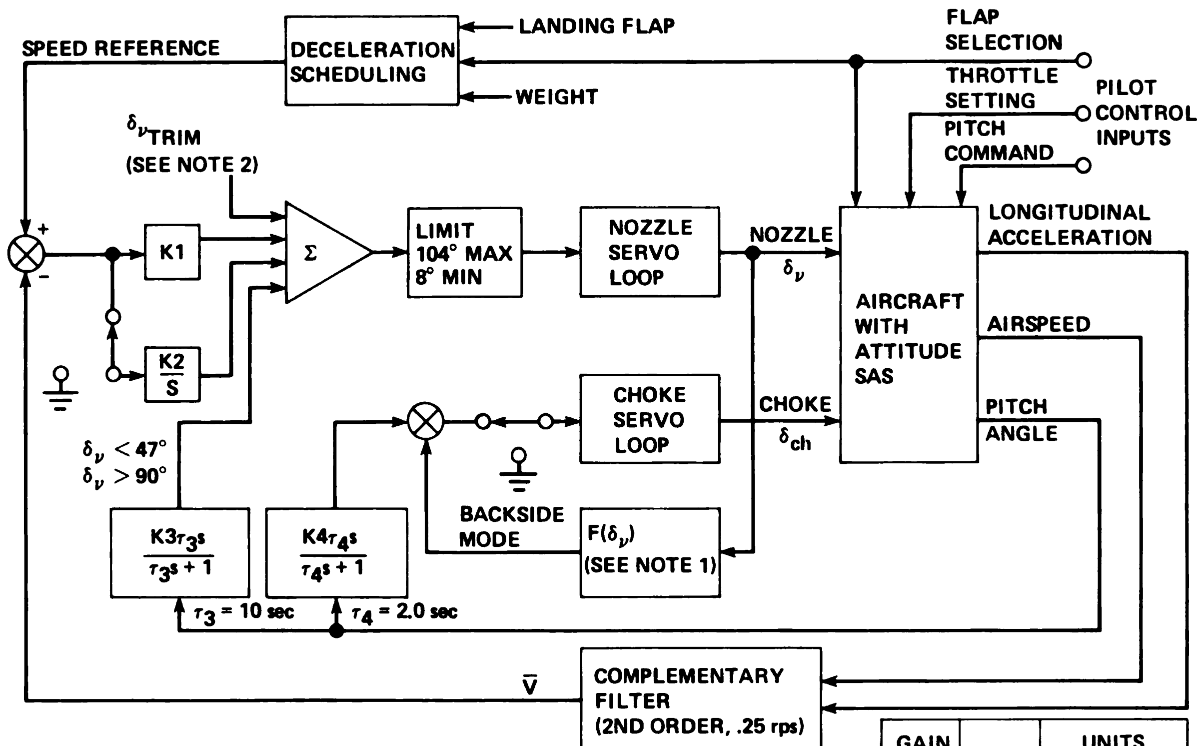


Figure 7.– Autospeed control system concept.



NOTES:

1. CHOKE SCHEDULING TO COMPENSATE NOZZLE LIFT LOSS

$$F(\delta_\nu) = \left| K5\,(\delta_\nu - \delta_{\nu TRIM}) + 25 \right| \Big|_{max = 40\%\ closure}$$

2. TRIM NOZZLE ANGLE FOR INITIAL DEPLOYMENT BEFORE SPEED, ATTITUDE LOOPS CLOSED. DEFINED IN FIGURE 24.

GAIN		UNITS
K1	-9.2	deg/knot
K2	-1.74	deg/knot-sec
K3	-5.0	deg/deg
K4	-7.5	percent/deg
K5	0.75	percent/deg

Figure 8.– Speed-control system details.

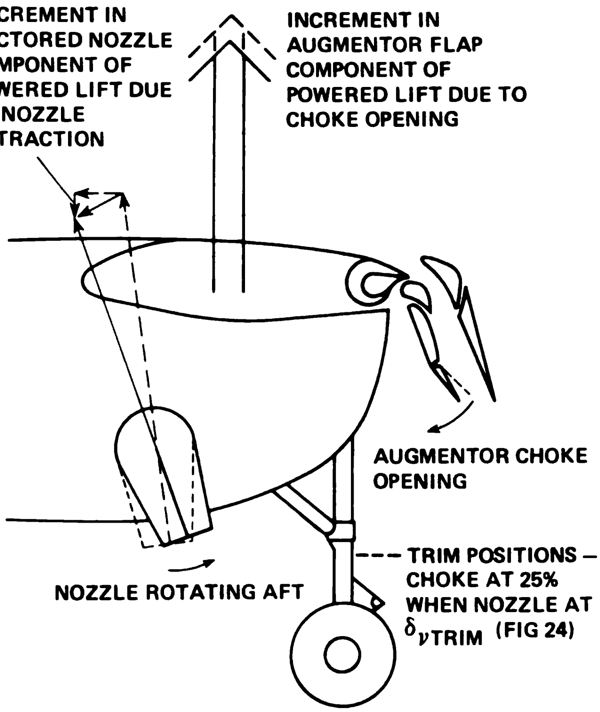
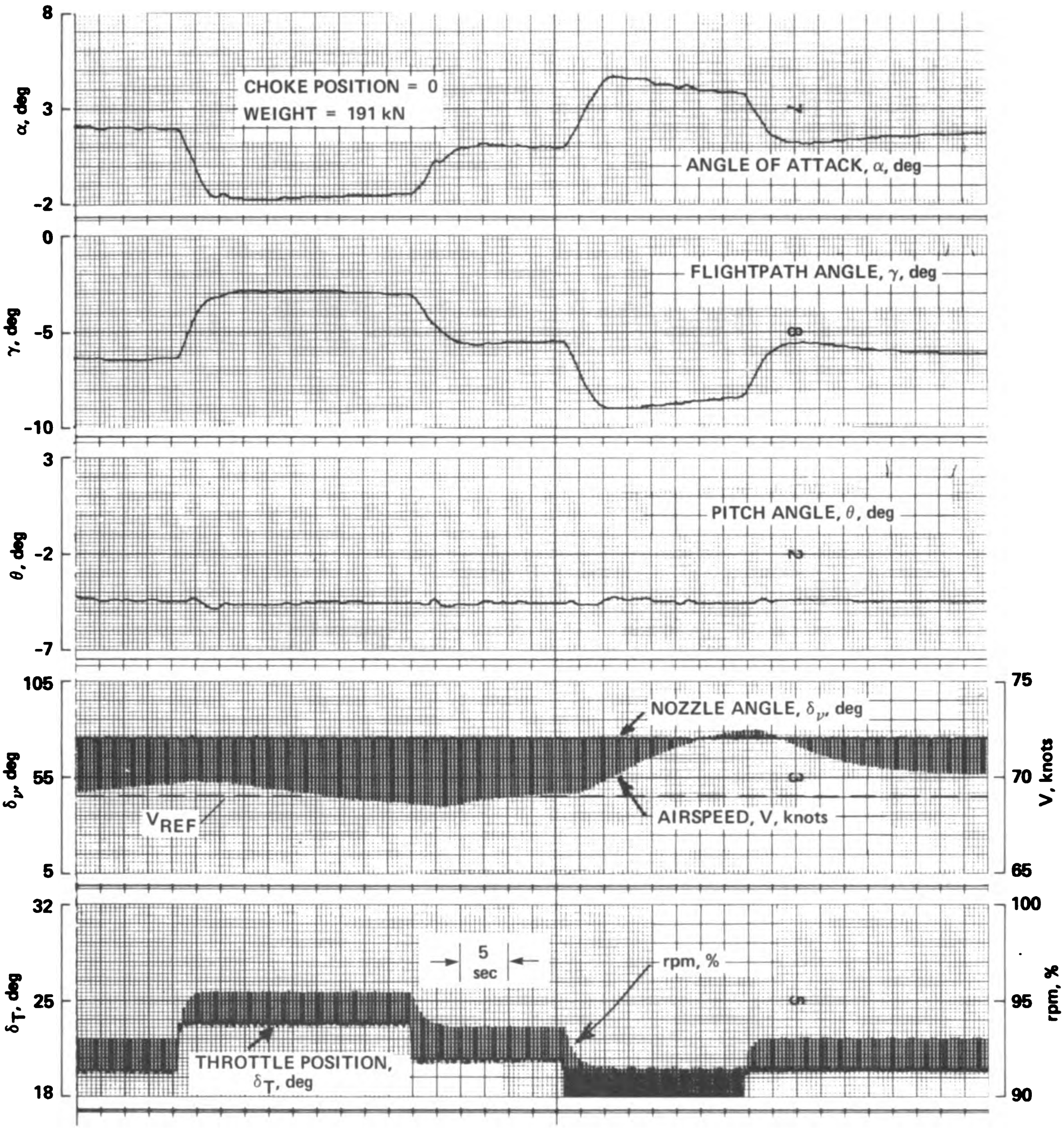


Figure 9.– Nozzle-choke gearing.

choke position at the trim-approach configuration, which reduces trim lift and results in the need for a small increase in trim approach power setting to keep angle of attack at desirable values. In the implementation used here, the lift compensation was achieved by a direct gearing from nozzle to choke, and also included trim compensation to maintain the choke bias position at 25% of fully closed as the trim nozzle angle varied in the low-frequency wind field. With this mechanization, steady-state $\Delta\gamma/\Delta\theta$ ratios of 1.0 or slightly better were achieved for excursions in flightpath angle of ±4° about the nominal operating point.

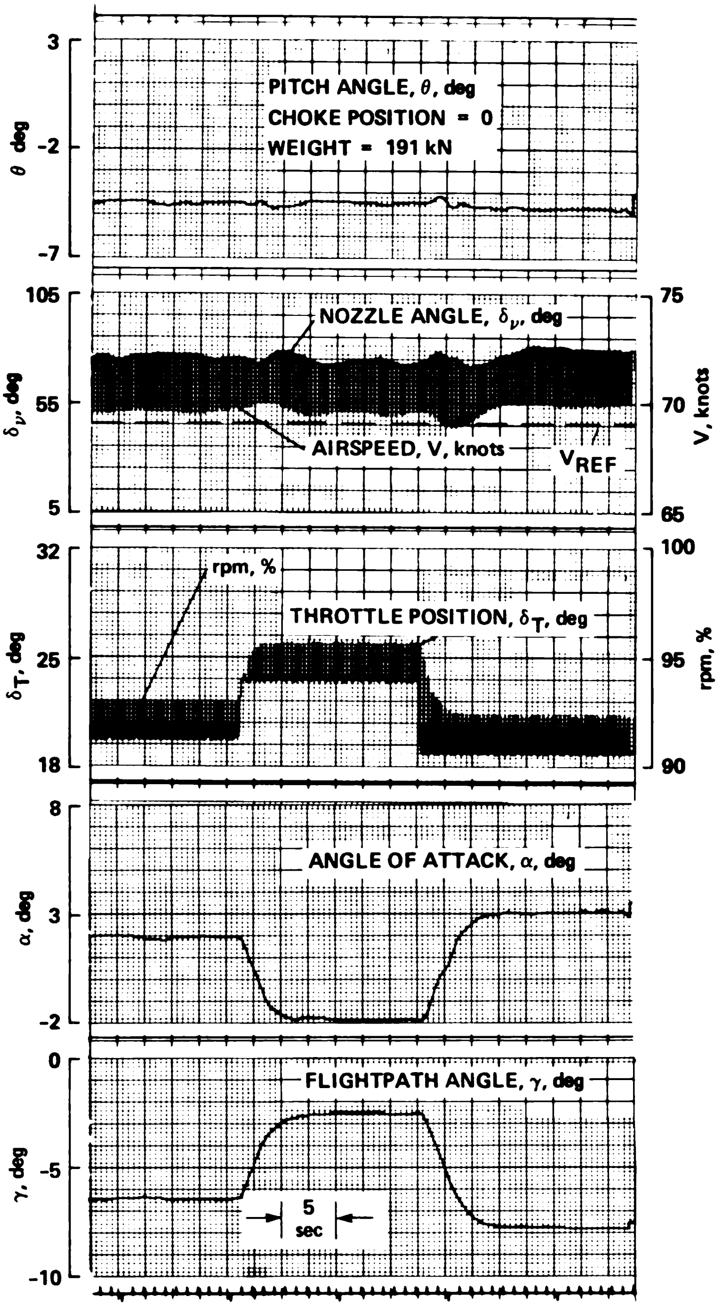
Additional high-frequency use of any residual choke authority is made, however, by incorporating a cross-fed washout from attitude, thus effectively providing heave damping augmentation. Research reported in reference 11 revealed that the acceptability of a frontside speed-control system is significantly improved if the initial heave response to pitch-attitude changes can be substantially quickened. Heave damping corresponding to $Z_w \doteq -0.9$ was available whenever the chokes were not limited by the higher-priority nozzle crossfeed term. These features are shown in figures 7 and 8. Because the nozzle excursions associated with the backside speed-control SAS are quite small (typically ±20° maximum) and because attitude remains essentially fixed in this mode, no use was made of the direct-lift choke control when the system was flown in this manner.

To summarize the characteristics of the three STOL control concepts used in this experiment, figure 10 presents the response of each to a step-like change in the primary control used for glidepath tracking. The responses, derived from a piloted simulation, illustrate the changes in the pertinent longitudinal response parameters for moderately large control inputs.



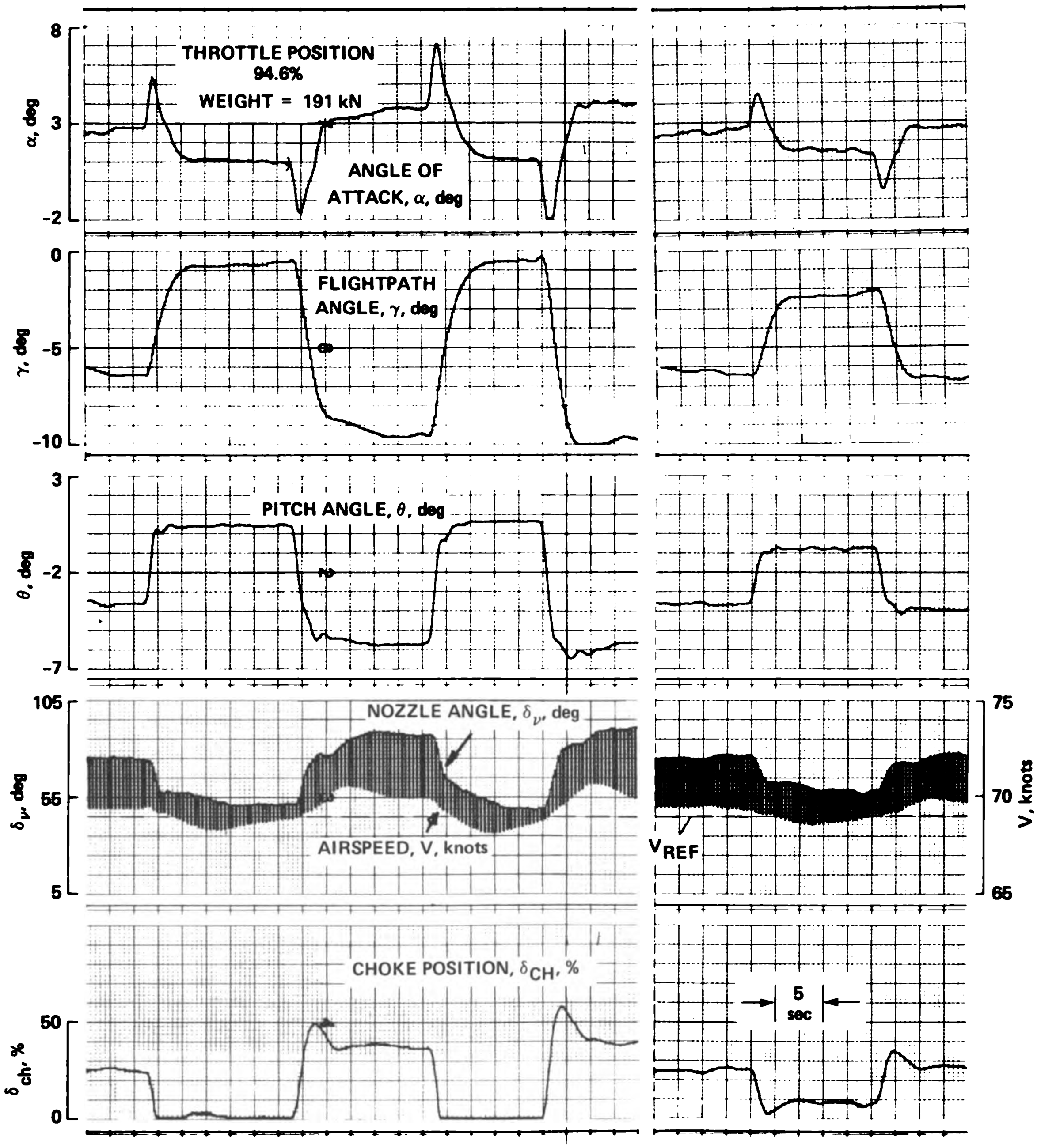
(a) Basic aircraft response to step throttle inputs.

Figure 10. – Aircraft responses to step inputs of the primary control (various configurations).



(b) Backside SAS response to step throttle inputs.

Figure 10.– Continued.



(c) Frontside SAS response to step pitch inputs.

Figure 10.– Concluded.

III. RESEARCH AVIONICS SYSTEM

General

The AWJSRA is equipped with a comprehensive and flexible digital avionics research system referred to as STOLAND. STOLAND provides the primary functions of navigation, guidance, control (via flight director or automatic servos), display generation, and system management. The system is shown schematically in figure 11; it is more extensively described in reference 14. A laboratory fixed-base simulation facility provided the means for software development and verification, and was also used for pilot familiarization and preliminary evaluation during the concept development stages of the program. Only those hardware and software details that are of principal concern to these tests will be described here. A separate section is devoted to flight director design features.

Horizontal Navigation Features

As is shown in figure 12, aircraft position estimates obtained from conventional ground-based navigation facilities are combined with data from aircraft-fixed inertial sensors by means of third-order complementary filters. The resulting smoothed position estimates (referenced to runway coordinates) are then used in the pilot's map and display system, and for calculating the guidance errors relative to the desired R-NAV flightpath. Appropriate provision is made for filter initialization; a dead-reckoning mode is included in order to maintain navigation in the presence of temporary losses of navaid signal, or whenever changes in the raw position measurements temporarily exceed prescribed tolerances. Resolution of the filtered position data is 1.22 m (4 ft) due to software scaling (in the fixed-point arithmetic computer) regardless of the navigation source that may be feeding the calculations. An estimate of ambient winds is also available as shown in the figure.

The algorithms employed are essentially those described in reference 15; however, it was found necessary to operate with higher complementary filter gains in the TACAN region, which had the effect of suppressing the integrated history of the aircraft-fixed inertial data and emphasizing instead the raw TACAN data. This was required in order to reduce errors in position estimates that would otherwise be generated by prolonged gimballing errors in the vertical gyro entering the position calculation via the axis-transformation equations, following steep climbing turns to the downwind leg. Once in the MODILS region, these moderate filter gains were initially maintained until the aircraft was within 60° of the runway heading, whereupon gains were smoothly increased further to values appropriate to the precision final straight approach segment. Differences in the raw position estimate at the instant of changeover to MODILS were accommodated by re-initializing the navigation filter position outputs to the new raw values, thereby preventing transients from propagating through the filters as erroneous velocities and upsetting the guidance laws. Discrete changes in position on the pilot's displays were prevented by applying an acceptable rate limit to the otherwise instantaneous position transient. The same protection was incorporated to allow single, or successive, smooth recoveries from the dead-reckoning mode caused by temporary loss, or tolerance exceedance, of navaid signals. This frequently occurred when passing close abeam the TACAN station on the downwind leg; however, it lasted only for short intervals and thus had no major effect on the net quality of navigation.

During the final straight localizer tracking segment following turn rollout, across-track navigation continued to be furnished by the filter shown in figure 12 with the increased gains shown, but with no increase in resolution.

Vertical Navigation Features

Vertical position and rate measurements were obtained from a second-order complementary filter which combined normal acceleration in Earth axes with either standard barometric altitude or vertical position calculated from the MODILS azimuth, elevation, and range data. No correction was incorporated to account for nonstandard atmospheric conditions, so that true inertial height estimates could not be obtained until within the MODILS zone of coverage. The difference in vertical position that typically occurred was removed over a period of 60 sec. In the case of the approach profile geometry chosen for this investigation, this transition did not occur until halfway around the final turn, where on hot days a flightpath angle which was temporarily steeper by as much as 1° could be required. However, this system deficiency did not

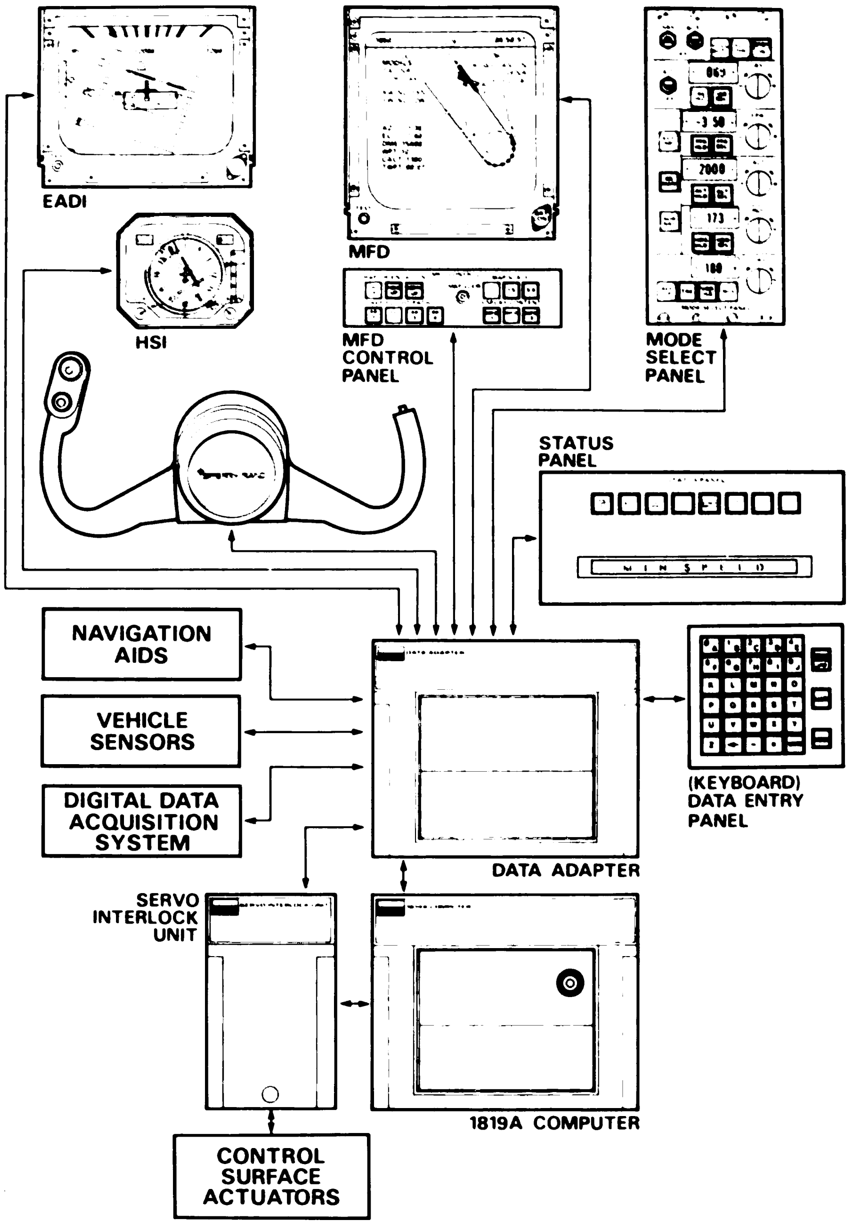


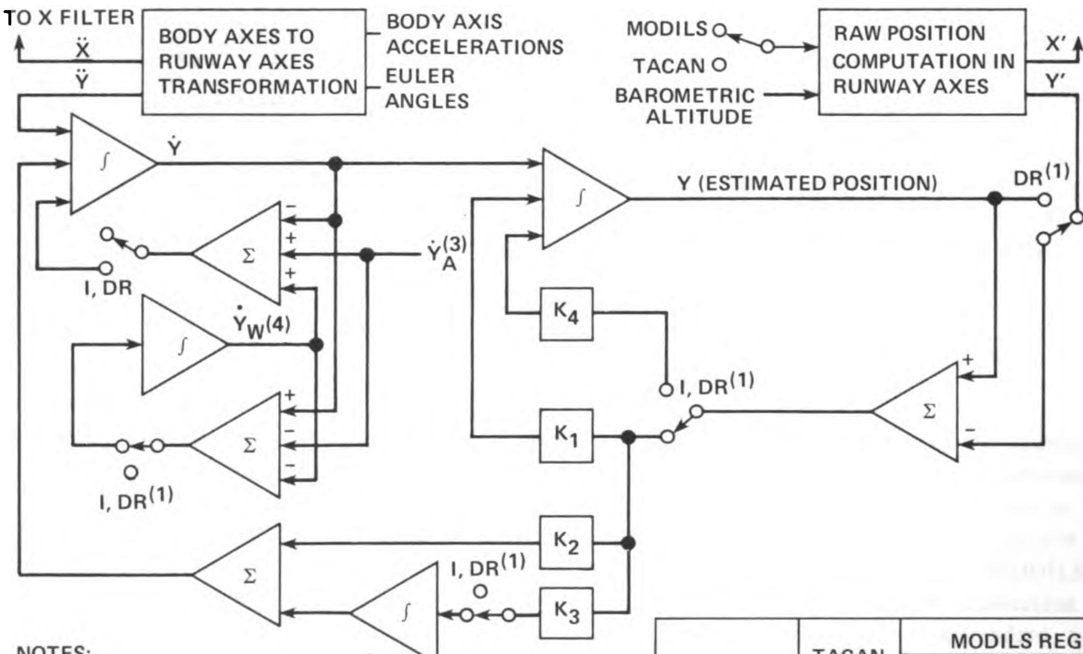
Figure 11.– STOLAND research avionics system.

make itself apparent to the pilot during the low gains operative during the more loosely tracked turn segment. This detail will not receive further comment, because it is presumed that a refined R-NAV system would have a correction feature incorporated, and that associated altitude measurement transitions would not in that case be limiting. Alternatively, the wider azimuth coverage (±40°) available from an ICAO type MLS installation combined with different approach profile geometry could provide the required inertial height estimate prior to commencing descent.

During the final straight approach segment, a separate third-order complementary filter operating with an order-of-magnitude improved resolution provided the quality of glidepath error and rate data considered necessary for precision tracking; it also avoided any offsets that might arise from installation or calibration biases in the normal accelerometer.

Some of the horizontal and vertical navigation discontinuities just discussed are illustrated in figure 13. Errors in XY position in the TACAN zone are assumed for the figure to be exclusively a result of a constant bias error in the TACAN range measurement, and the vertical position error presented arises from the influence of nonstandard hot-day conditions on true (relative to standard barometric) altitude above station. Alternative means, such as synthesis of a new path from the TACAN-to-MODILS delivery point, could be devised to deal with these difficulties. Feasible methods will be influenced by (1) the delivery volume probabilities that are associated with the en route or nonprecision terminal-area navigation facilities; (2) the performance capabilities of the aircraft; (3) the obstruction clearance or other routing tolerances allowed for a particular approach profile; (4) the computational capability of the avionics; and (5) passenger comfort and pilot acceptance factors associated with making the correction.

Admittedly, the system developments found necessary to provide the quality of area navigation needed for the curved-approach profile in this work



NOTES:

1. I = INITIALIZATION (FOR 5 sec AFTER TURN ON)
   DR = DEAD RECKONING
2. $\psi_e = \psi - \psi_{RWY}$
3. $\dot{Y}_A$ = TRUE AIRSPEED COMPONENT IN RUNWAY AXES
4. $\dot{Y}_W$ = CROSS-RUNWAY WIND ESTIMATE
5. PROTECTION LOGIC FOR EXCESSIVE NAVAID NOISE, AND NAVAID SWITCHING NOT SHOWN
6. X FILTER IMPLEMENTED IDENTICALLY

FILTER GAINS	TACAN REGION	MODILS REGION		
		$\psi_e^{(2)} > 60$	$\psi_e^{(2)} < 60$	
	X, Y	X, Y	X	Y
$K_1 = \sqrt{2K_2}$	0.14	0.14	0.258	0.577
K_2	0.01	0.01	0.033	0.166
$K_3 = K_2^{3/2}/4$	0.0003	0.0015	0.0015	0.017
K_4	0.2	0.2	0.2	0.2

Figure 12. – X and Y complementary filters.

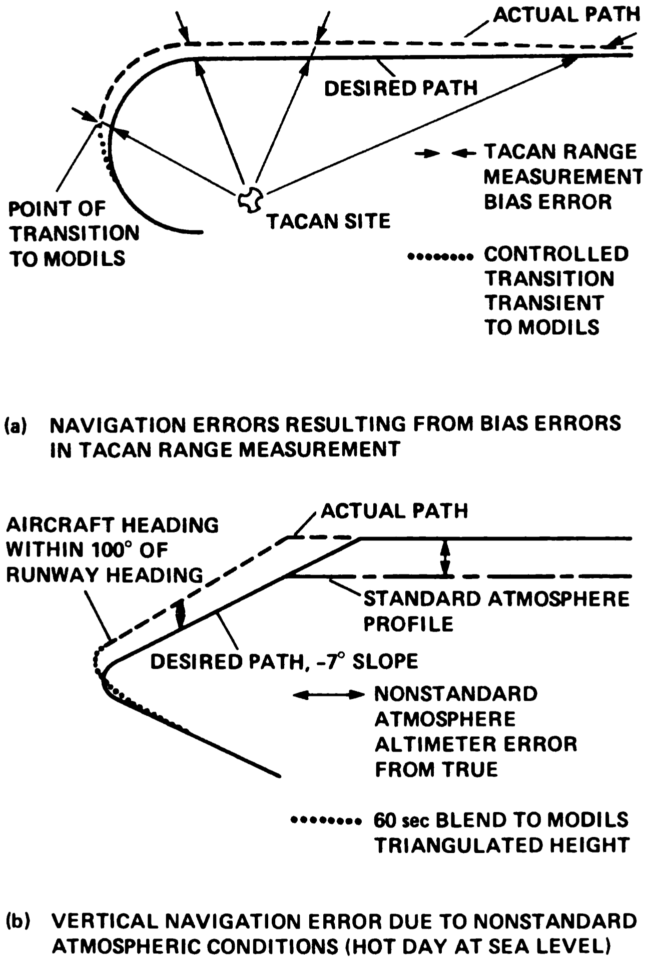


Figure 13.– TACAN to MODILS transition transients.

are largely peculiar to the aircraft, avionics, and navaid system combination of this investigation. The existence of an acceptable navigation environment was presumed in this work so that performance and handling related issues could be investigated. As a result, the consideration of a more general navigation environment when assessing the overall feasibility of these approach profiles would be an important corollary of the present study.

Cockpit Displays

An electronic attitude director indicator (EADI) and multifunction display (MFD) provide control direction and situation monitoring information to the pilot. The integrated nature of these displays contributes greatly toward the reduced workload necessary to make the curved-approach task feasible. The general cockpit display layout is shown in figure 14, and the detailed elements of the MFD and EADI are shown in figures 15 and 16.

Multifunction display– The primary utilization of the MFD map display is for approach progress monitoring (way point sequencing), for a coarse measure of tracking performance, particularly during curved segments, and for establishing initial profile capture trajectories. The map display can be used, at the pilot's discretion, in a north-up, course-up, or heading-up mode with any one of the three different display sensitivities shown in figure 15. Approach progress monitoring is of major importance to the pilot because it alerts him to impending configuration changes required as way points are approached. Other information pertinent to the approach is also presented, for example, navaid signal status and reliability. Ambient wind estimates measured by the system in runway coordinates provide assistance to the pilot in his planning of the deceleration procedure; also, they are intended to furnish some anticipation of potential shear situations if the displayed winds are substantially different from the reported surface winds at the STOLport.

Electronic Attitude Director Indicator – The EADI, the primary flight instrument, contains the elements shown in figure 16. Some constituents of this display will be discussed in detail here. The flight director symbols are discussed in a later section. It should be noted that this display, although electronic, does not differ greatly in essential features from modern electromechanical attitude director units.

Basic attitude presentation: Relative to the central fixed aircraft symbol, the inertially referenced attitude map provides basic orientation and stabilization information to the pilot. In addition to its obvious importance in a stability sense for a backside unaugmented aircraft, pitch attitude as a trim parameter also assumes a greater importance for powered-lift aircraft, primarily because of the nonunique relationship of angle of attack (and hence safety margin) to speed. Consequently, a more sensitive pitch scale is generally required to allow the pilot to observe small attitude excursions, and to set or maintain a pitch attitude often within a degree or less. The pitch scale sensitivity used here was 8°/in., more than twice that usually employed in CTOL attitude indicators. By increasing the awareness of modest intentional or inadvertent departures from the trim approach attitude, this high display sensitivity can also support the use of pitch attitude as a secondary control to regulate speed when power is

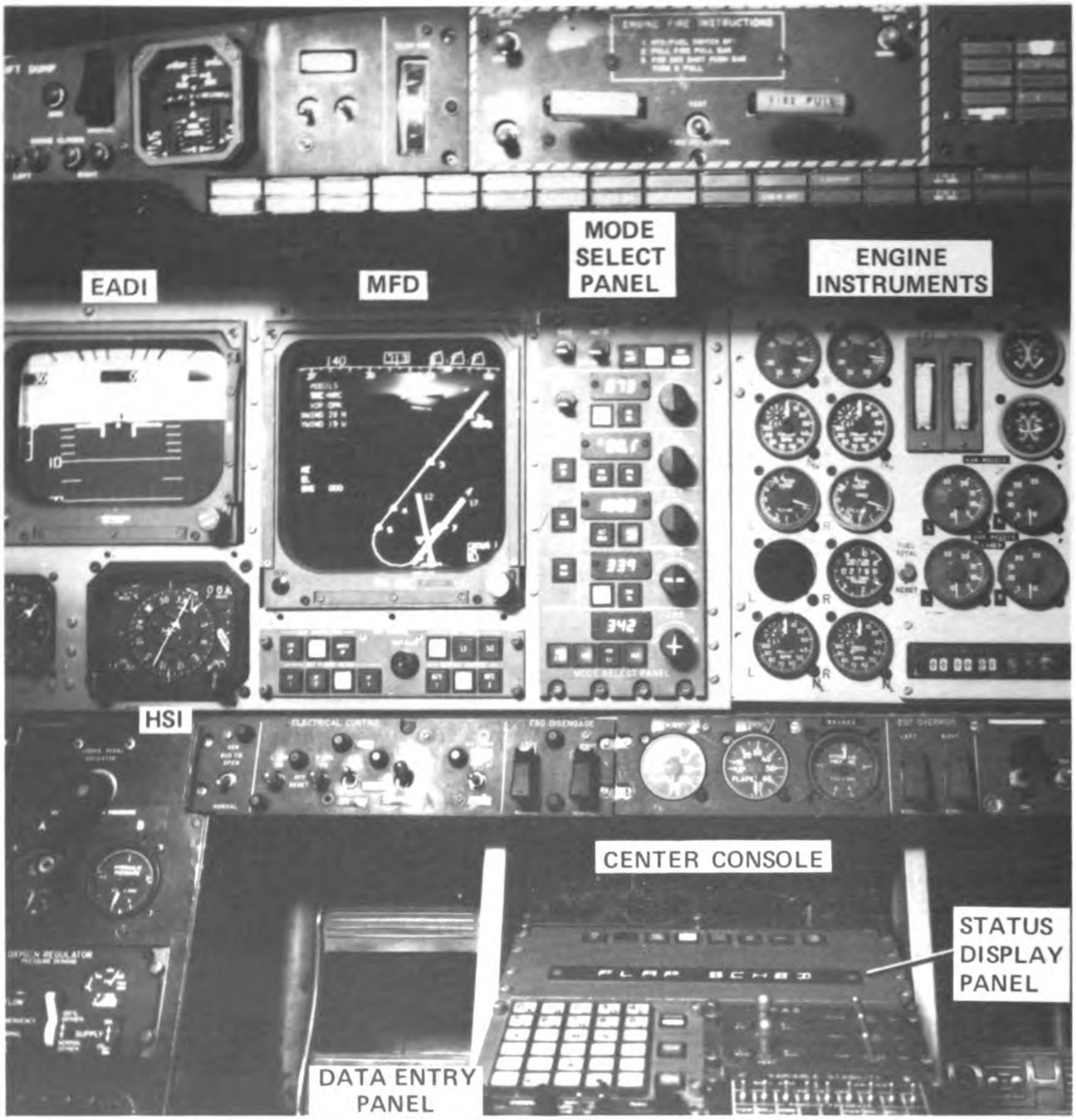


Figure 14.– Cockpit displays.

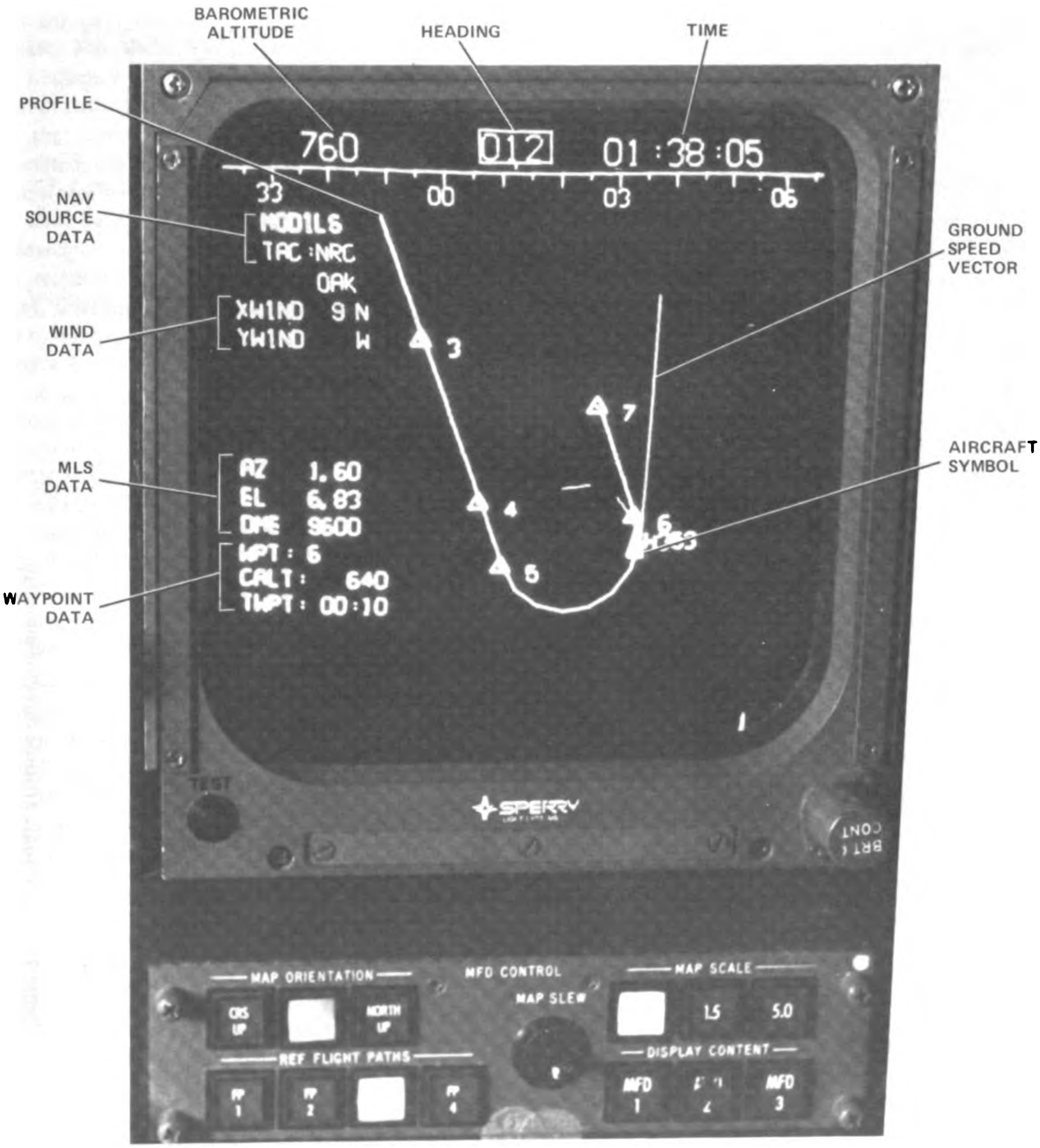


Figure 15.– Multifunction display.

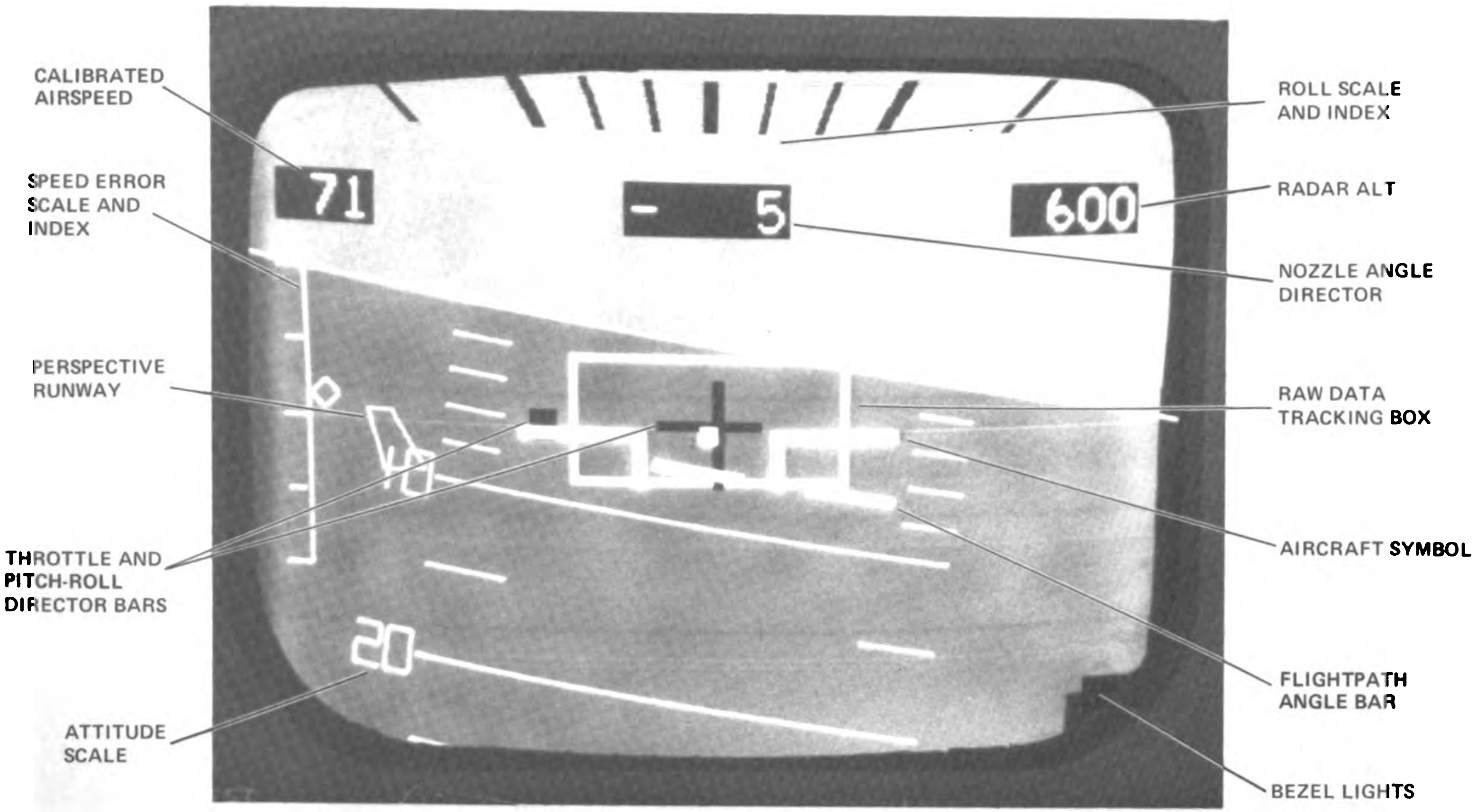


Figure 16.– Electronic attitude director indicator.

used for path control, as in the case of the basic aircraft. For these smaller, precise, predominantly low-frequency attitude changes, the following of a pitch-director bar is a relatively easy task. However, for the larger, higher-frequency pitch excursions associated with employing a frontside glidepath control technique at low speeds (where to obtain the same path correction in the same time as can be achieved by a CTOL aircraft approaching twice as fast requires twice the attitude change in the same time), this higher pitch-scale sensitivity may not be appropriate, perhaps unduly emphasizing pitch activity to the pilot. This issue is further discussed in the section describing the flight director design.

Perspective runway display: This display is calculated from position data derived from the MODILS system and provides a perspective presentation of the runway. Angular scaling is determined by the underlying attitude scale, allowing registration with the flightpath angle bar (discussed next) and providing a lateral field of view of ±20° on the 12.7-cm (5-in.) wide display face. Since the display is a head-down unit, angular correspondence with the outside world is not necessary. Indeed, viewing distances to the pilot's eye are typically 3 times the 18 cm (7.1 in.) for which precise correspondence would occur. To improve visibility and harmony of the presentation at long ranges, runway dimensions of 1220 m (4000 ft) by 122 m (400 ft) are used, with an electronic threshold coincident with the MODILS glidepath intercept point. This display feature has been found desirable in other studies, and was used for a number of the evaluation approaches reported here. Comments on its utility are presented in a later section.

Flightpath angle bar: The flightpath angle bar displays the quotient of inertial height rate and along-track groundspeed, and represents the direction of the longitudinal velocity vector above or below the horizon. It is displayed against the gyro horizon in units of degrees. The pilot generally uses this parameter, as he does rate of descent in a CTOL aircraft, to dampen his corrections to the reference glide slope by making specific angular adjustments appropriate to recapturing the reference with the timeliness he desires. This damping is included in the flight-director command-bar mechanization, however, so that for the investigation reported here the flightpath angle bar provides auxiliary situation and monitoring information regarding the performance of the flight-director commands. While in MODILS coverage, the bar is free to move laterally according to an estimate of the aircraft drift angle computed from a resolution of the navigation filter ground velocities into aircraft coordinates. The display is registered with the perspective runway so that is presents the aim point of the current aircraft velocity vector relative to the intended touchdown point.

Path deviation window: The path deviation window, referenced to the central fixed aircraft symbol, provides lateral and vertical situation data for monitoring the net outer-loop tracking performance achieved along the reference trajectory in response to the flight director commands. It is not intended that the box play any direct role in the flight director control or path-tracking tasks, but it does fulfill the vital role of allowing the pilot to monitor system performance according to some set of operationally relevant criteria. Most important is the pilot's perception of position approaching decision height, where satisfactory positioning within a window of appropriate dimensions serves as a criterion, similar to current CTOL Category II regulations, for continuing the approach. The dimensions of the flight corridor chosen to be represented by this box decrease smoothly toward landing, as shown in figure 17. The vertical dimensions of the tracking box approaching

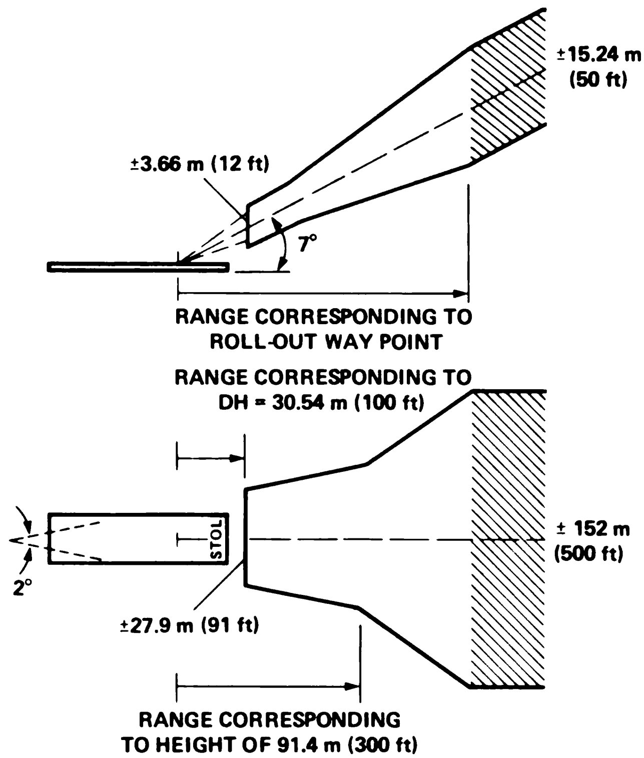


Figure 17.– Scheduled dimensions of path deviation window.

the decision height were chosen for purposes of initial evaluation to be those specified for CTOL Category II operations, that is, ±3.66 m (±12 ft) at 30.54 m (100 ft). The lateral dimensions were loosened somewhat from these standard criteria, however, to induce unanticipated lateral offsets at breakout, hence providing a more challenging final visual segment to the approach and landing task.

IV. FLIGHT DIRECTOR DESIGN FEATURES

The key element contributing to the feasibility of the curved, decelerating approach is the flight director. The flight-director software embodies mode selection, speed control, path guidance, control blending, trim management, and performance monitoring features, and presents command and status information to the pilot on an integrated primary display unit. Only the longitudinal design of the flight director will be described here. The lateral director design, which is relatively conventional, is adequately described in figure 18; its corresponding gains are indicated in table 3.

The functional design of the longitudinal flight director for the basic aircraft configuration is summarized in figure 19. It also applies to the backside or frontside speed-control SAS configurations before deployment of the nozzles for steep descent and automatic speed control. In addition to the basically conventional implementation of pilot-mode selection, and guidance and control position feedback laws, three unique design features were incorporated:

1. Means to smoothly handle the changing effectiveness of pitch and throttle controls, which occurs during transition to powered-lift, by means of configuration-dependent control blending coefficients.

2. Means to minimize the pilot action involved in setting the decelerating reference speed.

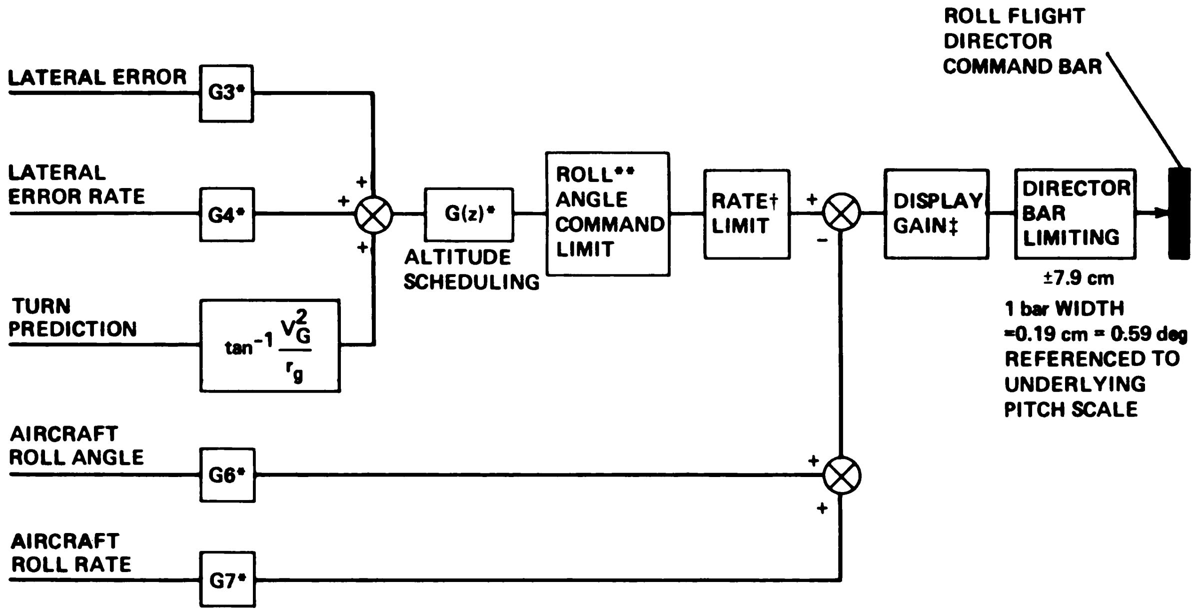
3. Mechanization of an additional director cue suggesting an appropriate setting for the third auxiliary control used for trim.

Pilot Mode Selection

As illustrated in figure 19, the pilot is able to select a full range of flightpath and speed references at his cockpit mode select panel, shown in figures 11 and 14. Although the flight director system developed for this investigation can be employed in any separate or combined path-speed modes shown, exclusive use is made of the R-NAV mode for generating the curved descending reference approach profile of these tests. As a minor detail, the system automatically converted from R-NAV curved-path tracking to the straight-in MLS tracking mode at way point 6, the rollout way point, with an associated inconsequential transient. No change in control laws was involved, although the means for determining the reference flightpath became substantially simplified in this final straight rectilinear flightpath segment. Use of the two available means for determining the speed reference is described next.

Speed and Deceleration Control Modes

Two methods for furnishing an airspeed reference to the system are available. One involves direct selection by the pilot through the airspeed reference slew knob located on the pilot's mode select panel (figs. 11 and 14). The pilot can select or hold any airspeed within the allowed flight envelope of the aircraft. The allowed flight envelope at any flap setting is typically determined in the high-speed region by the flap or airframe structural limitations, and in the low-speed region by aerodynamic safety margins; it can be interpreted as a deceleration corridor which is negotiated during the change from the aircraft's conventional cruise configuration to its STOL landing configuration. It would be undesirable, however, to require the pilot to manually select a lower airspeed (with the slew knob) each time that a configuration change (e.g., flap or nozzle angle setting) was made toward the final landing configuration. Consequently, a flap-dependent airspeed schedule is incorporated. The schedule allows the speed reference to automatically lower whenever more flap is selected, without further action by the pilot. To invoke this programmed schedule, the pilot has only to select a single Full Auto button (figs. 11 and 14), which starts the speed reference moving toward the final landing speed, subject to progressively achieving the landing configuration. The final landing speed is automatically determined (and temporarily displayed to the pilot in the airspeed reference window on the Mode Select Panel for 5 sec following his selection of Full Auto) after the desired landing flap configuration and current aircraft weight are entered at the pilot's keyboard, prior to entry to the terminal area.



NOTES:

*FOR VALUES SEE TABLE 3.

**±25° EXCEPT ±15° MLS, ±10° BELOW 250 m

†±6°/sec EXCEPT ±3°/sec BELOW 173 m

‡0.1 cm/deg ROLL ERROR

Figure 18.– Lateral flight director.

As shown in figure 20, the programmed speed reference lies somewhat above the minimum safe speed boundaries for the aircraft[1] and only just below the flap structural limits until the final landing configuration is achieved. Consequently, it should be interpreted as a deceleration schedule, suitable for all aircraft weights. It allows the aircraft to negotiate its deceleration corridor using highest practical approach speeds up to the point that airspeed must be reduced as much as possible in order to achieve the desired landing performance.

Logic is also included that increases the airspeed according to the programmed schedule should the pilot for any reason reduce the flap setting during the course of an approach or for go-around. Similarly, a speed reference that is above the structural boundary or below the programmed speed schedule cannot be selected by the pilot, and if the system is inadvertently first engaged outside of these limits the reference speed will slew to the appropriate boundary. These features ensure that an appropriate speed reference is always readily available in the system for both accelerating and decelerating maneuvers without significant pilot action.

[1] The minimum speed boundaries are based on the lift reserve available from angle of attack at constant power. A value of 0.69 g for flaps less than 30° blends linearly to a value of 0.4 g for flaps at 65°. The available envelope is enlarged during steep descent, relative to the level flight case, since the nozzle deployment associated with descent results in a higher power setting and a relative increase in propulsive lift, hence permitting a lower level of airspeed-dependent aerodynamic lift. For each descent configuration, the trim power setting is maintained relatively constant over a wide range of trim aerodynamic flightpath angles by suitably adjusting the trim nozzle angle. Consequently, the descent minimum speed boundary is relatively invariant with wind condition. These criteria for minimum speed were a conservative reflection of early experience with this aircraft. A more general and rational set of criteria to determine aerodynamic safety boundaries for powered-lift aircraft (that have since been applied successfully to this aircraft) are proposed in reference 4.

TABLE 3.– FLIGHT DIRECTOR GAINS

			Pitch director			Throttle director[d]		Lateral director[d]	
Description	Symbol	Units[a]	R-NAV level & alt. hold	R-NAV descent & MLS basic	R-NAV descent & MLS *F/S*	R-NAV level & alt. hold	R-NAV descent & MLS	R-NAV	MLS
Velocity error	G1	deg/knot	0.4	0.4	*b*	0.58	0.58	*b*	*b*
Acceleration damping	G2	deg/m – sec^{-2}	.075	.075	*b*	.11	.11	*b*	*b*
Path error	G3	deg/m	$18.24/V^c$	.3	0.3	$38.0/V^c$	.62	0.021	0.0312
Path-rate damping	G4	deg/m – sec	73.1	$89.0/V^c$	$89.0/V^c$	$152.0/V^c$	$186.0/V^c$	.42	.416
Nozzle-to-pitch crossfeed gain	G5	deg/deg	.085	.085	0	*b*	*b*	*b*	*b*
Control-position feedback	G6	deg/deg	1.0	1.0	1.0	.29	.29	.32	.32
Control rate damping	G7	deg/deg – sec^{-1}	.25	.25	.25	.14	.14	.08	.08
Path-error gain scheduling	G(z)		*b*	$z \geqslant 477$ m:1.0 $z \leqslant 152$ m:1.3		*b*	$z \geqslant 380$ m:1.0 $z \leqslant 152$ m:1.3	*b*	$z \geqslant 250$ m:1.0 $z \leqslant 117$ m:2.0
Nozzle-to-pitch crossfeed lag	LAG 1	sec	.2	.2	.2	*b*	*b*	*b*	*b*
Pitch-rate feed-back smoothing	LAG 2	↓	.2	.2	.2	*b*	*b*	*b*	*b*
Director bar smoothing	LAG 3	↓	.5	.5	.5	.33	.33	.33	.33
Control-feedback washout	WASH 1	↓	4.0	8.0	2.0	8.0	2.0	*b*	*b*

[a] Units of director bar deflection are quoted in degrees of displayed pitch scale – 1 deg = 0.3175 cm.
[b] Not applicable.
[c] *V KTS CAS.*
[d] 1 deg δ_T = 1.38% rpm.

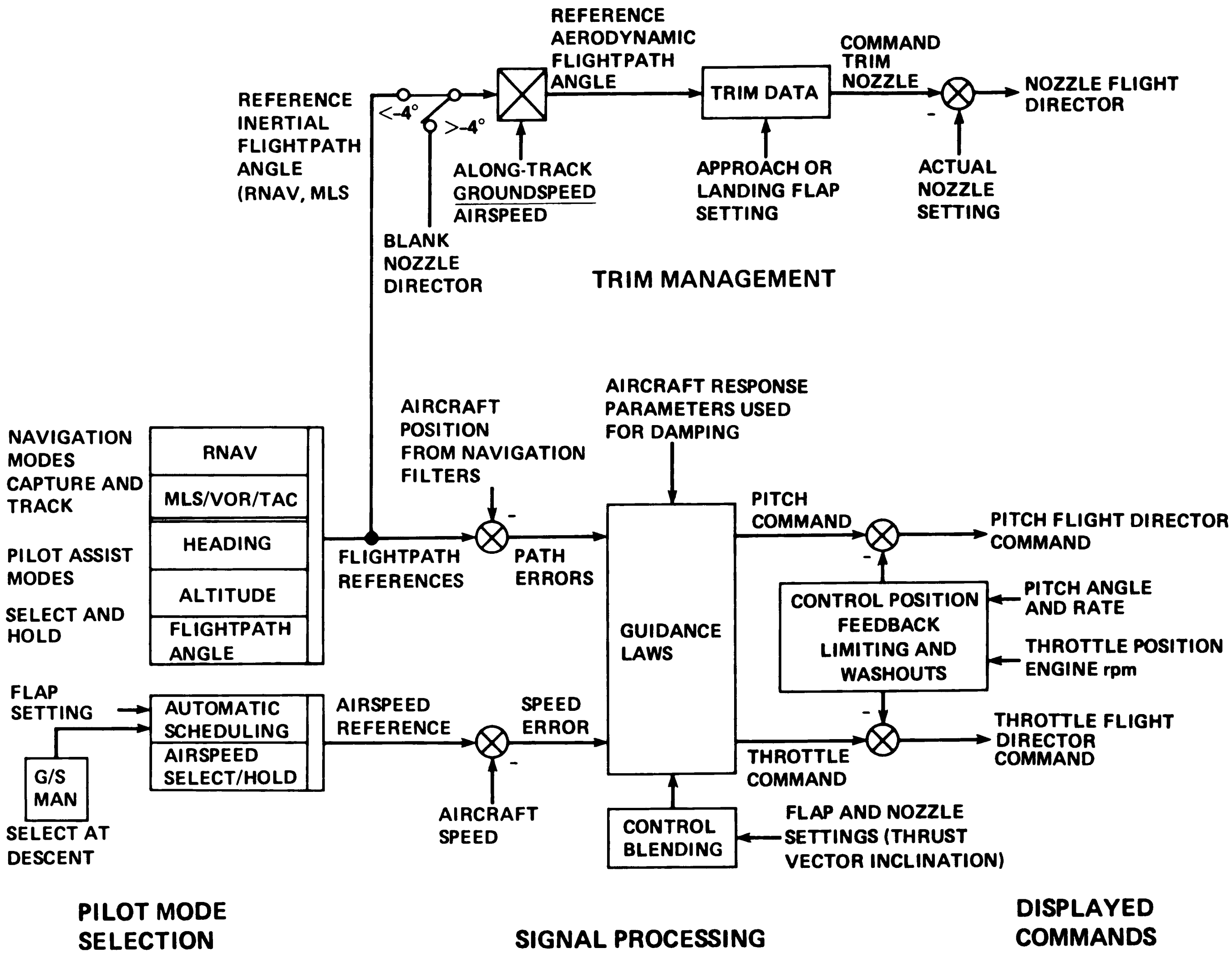
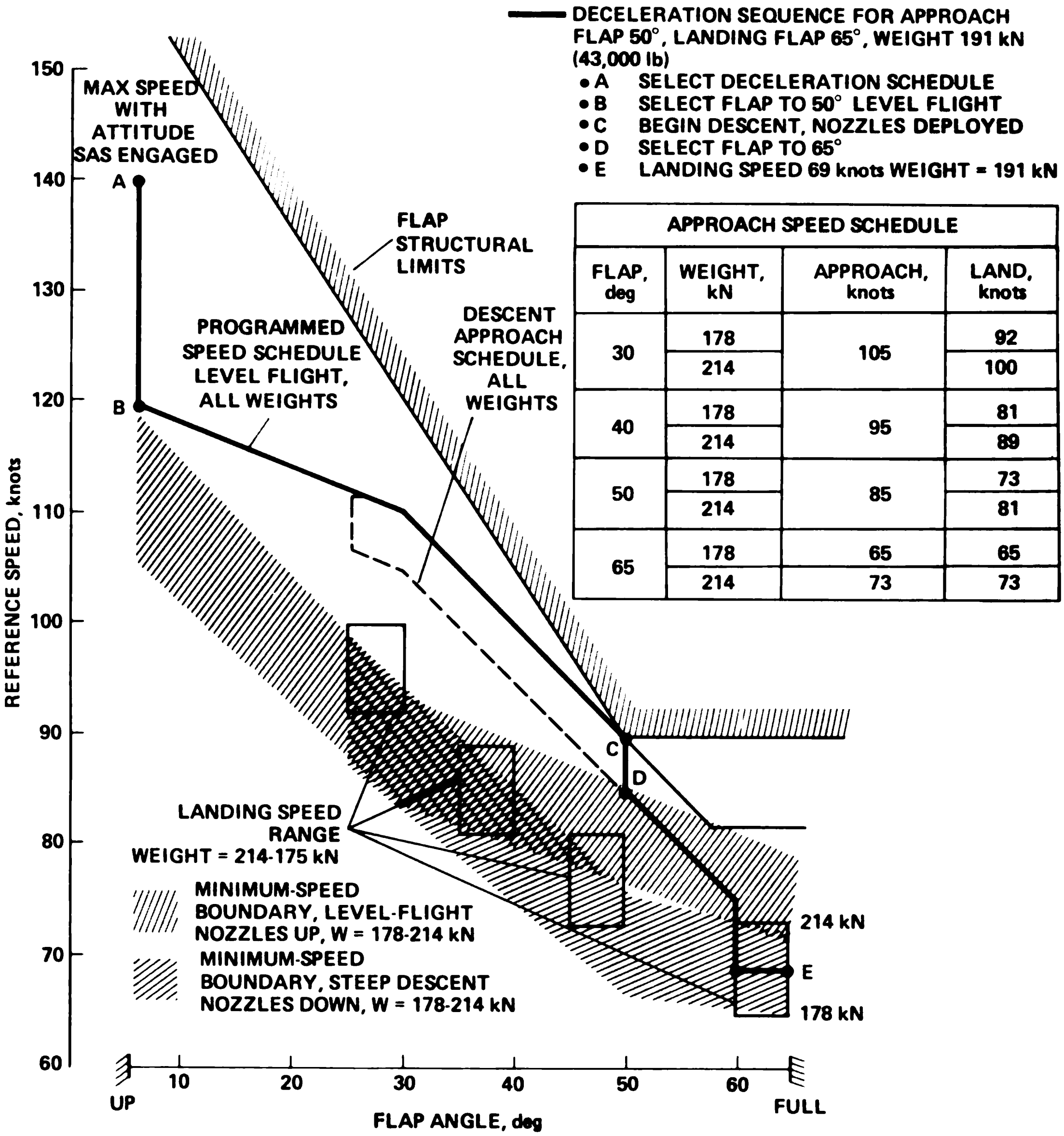


Figure 19.– Flight director functional design.



APPROACH SPEED SCHEDULE			
FLAP, deg	WEIGHT, kN	APPROACH, knots	LAND, knots
30	178	105	92
	214		100
40	178	95	81
	214		89
50	178	85	73
	214		81
65	178	65	65
	214	73	73

Figure 20. – Scheduling of the decelerating speed reference with flap and nozzle angles.

A typical deceleration is illustrated in figure 20. In the portion of the envelope above line *BC*, the pilot can select a reference velocity for terminal-area penetration and initial path acquisition through manual airspeed select actions at the flight director mode select panel (fig. 11). An initial airspeed of 140 knots is used for this example. At an appropriate point on the approach profile where he chooses to begin deceleration (nominally designated as way point 2 in fig. 1), the pilot relinquishes direct control of the speed reference to the flight director, and thereafter indirectly exercises control of the reference by means of successive flap deployments toward the preselected landing configuration. This is done by the single-action selection of the Full Auto button on the mode select panel causing the reference speed to slew at an appropriate rate (along *AB* in fig. 20) onto the deceleration schedule *BC*, where it holds pending flap deployment. In the case illustrated, flaps are progressively deployed at the pilot's discretion to an approach setting of 50° prior to commencing descent.

The rate at which the velocity reference is allowed to decrease in response to the initial deceleration to the scheduled boundary and subsequently in response to the increasing flap angle is restricted through a variable rate limit. This "deceleration reference" is designed to match the inherent deceleration characteristics associated with progressive configuration changes; it has the desirable effect of minimizing the amount of closed-loop control required to follow the slewing velocity reference. The slew-rate control employed was based on the control blending coefficient C_3, which is defined in the next section. This had the effect of limiting the maximum deceleration to $-0.6\ (C_3 + 1)$ knots per sec, where C_3 assumes values between 0 and 1, depending on configuration. This conservative deceleration limit of 0.03 g in the full powered-lift configuration serves also to preserve both speed-control authority and maximum downward flightpath angle capability as may be needed for satisfactory closed-loop control in the presence of atmospheric disturbances or maneuvering errors.

During glide-slope capture, the thrust vectoring associated with nozzle deployment from 6° to typically 80° results in substantial changes – of the order of 0.1 to 0.15 g – in propulsive lift and drag forces. To assist the coordination of the pitchover that is also required during this maneuver, a 5-knot speed reduction at a rate corresponding to one-half that just described is implemented (line *CD* in fig. 20). The decision of the pilot to deploy the nozzles as the aircraft intercepts the glide slope is signaled to the system by his selection of the Glide slope Manual button on his mode select panel (fig. 11). If the backside or frontside speed-control SAS is to be employed, and if it has been previously armed, that is, if the servos have been engaged, then this action will also cause the nozzles to deploy to a midrange setting prior to the control loops automatically closing to effect speed control. Since the safe specification of the final landing speed is predicated on the nozzles having been deployed, this direct pilot method of signaling the system serves as a safeguard to ensure that nozzle deployment has indeed taken place, allowing the speed schedule to shift to the lower descent and landing airspeeds. A more detailed description of the philosophy, flight director programming, and procedures employed during glide-slope capture is contained in a later section on pilot comments.

The initial portion of the descent is flown at point *D* in the illustration until flaps are set to the final landing setting of 65°, perhaps halfway around the final turn, as suggested in the pilot's approach profile chart. Five degrees prior to the flaps reaching their final setting, the velocity reference is allowed, subject to the rate limit, to fall away from the descent schedule into the landing speed range, finally reaching a value appropriate to landing weight (point *E* in fig. 20).

Prior to entering the terminal area, the pilot will have entered both the estimated landing weight and the selected landing flap configuration into the flight director computer. A longer runway or a "guaranteed" strong headwind might result in the choice of a landing flap configuration of 40°, for example, in which case the initial descending approach might be carried out with flaps at 30°. The airspeeds corresponding to the range of configurations available to the pilot are shown in figure 20. This feature allows for steep approaches even at high airspeeds, without encountering unacceptably low power settings, since in the test aircraft the nozzles can still be used independently to adjust the trim approach drag, even for reduced flap settings.

Control Blending Coefficients

Figure 21 illustrates how the control usage was blended according to changing aircraft configuration during conversion to powered lift. In the case of the normalized throttle coefficients C_3 and C_4,

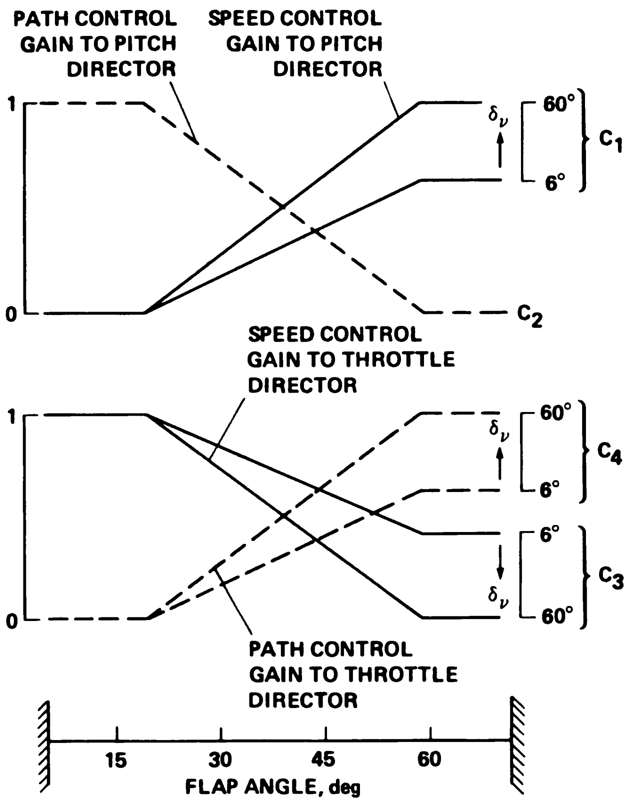


Figure 21. – Control blending coefficients.

these control effectiveness gains relate to the throttle control derivatives X_{δ_T}, Z_{δ_T}, reflecting the changing orientation of the incremental thrust vector as flap and nozzle are deployed toward full powered-lift settings. For example, when X_{δ_T} dominates over Z_{δ_T}, as is the case in conventional flight, the speed-control gain to throttle C_3 is correspondingly large. The crossover in pitch effectiveness is less directly related to the changing propulsion system aerodynamics, reflecting instead an appropriate and necessary blending toward the backside control technique as the only means, in the absence of independent longitudinal force modulation, of satisfactorily controlling airspeed. Nevertheless, this requirement is fundamentally brought about by the progressively more destabilizing influence of ever-increasing induced drag as powered lift is developed. This blending of control effectiveness is employed for nulling longitudinal path and airspeed errors, except when either version of the automatic speed-control SAS is used during steep descent, as discussed below.

Guidance and Control Feedback Laws

The control blending coefficients are used to govern the mixing of path and speed errors in the multiloop guidance laws driving the pitch and throttle director bars, as illustrated in figures 22 and 23. The pitch and throttle flight directors are configured in the single blended mode indicated for the basic aircraft unless on steep descent, where the configuration then conforms to whichever STOL control concept has been selected for evaluation; basic aircraft, backside speed-control SAS, or frontside speed-control SAS. The gains employed in the different modes are summarized in table 3 and were developed empirically in a fixed-base simulator as an extension of a previously existing automatic control system. The gains and structure differ somewhat from those suggested in reference 16, which were determined separately according to an analytical procedure embodying manual control theory for the research effort reported in reference 11. (Although these control laws provided the guidance that was required for this investigation, more detailed study and development of the control laws employed during the steep approach were carried out subsequent to the main flight program. This resulted in preferred control laws, the details of which along with limited flight-test results are contained in the appendix.) Displayed element sensitivities for the director bars are quoted in table 3 in degrees of bar displacement relative to the underlying pitch scale. The "Lag" and "Wash" functions shown in figures 22 and 23 represent simple first-order smoothing and washout signal processing implemented by difference equation algorithms. The washouts on the control position feedbacks are necessary to eliminate standoffs in the outer-loop path or speed-error parameters, achieving the same effect as a forward-loop integrator that would be employed in an automatic control loop. The path-tracking gains for the throttle and pitch flight directors, when used in support of the basic aircraft or backside SAS, or the frontside SAS modes, respectively, were scheduled with altitude as shown in table 3 in an attempt (later proved ineffective and detrimental to stability) to obtain improved tracking performance approaching decision height. Not shown in the figures are anticipation features, based on the current along-track ground-speed estimate, that provide appropriate lead for impending changes in lateral or vertical path segments.

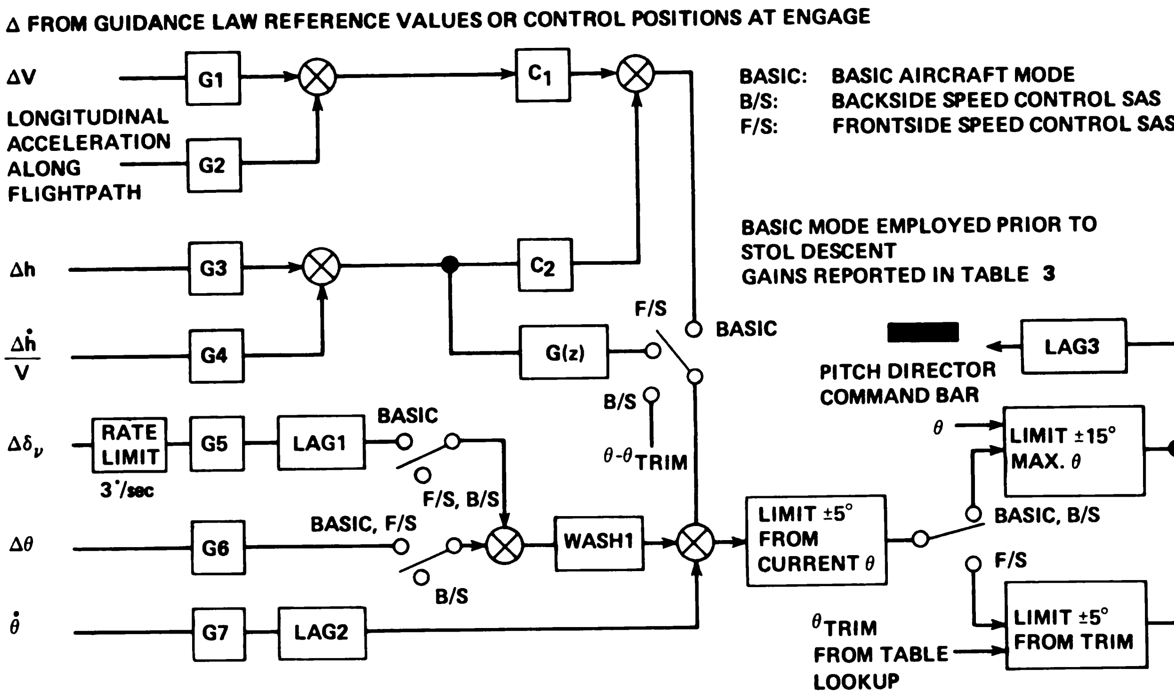


Figure 22. – Pitch flight director.

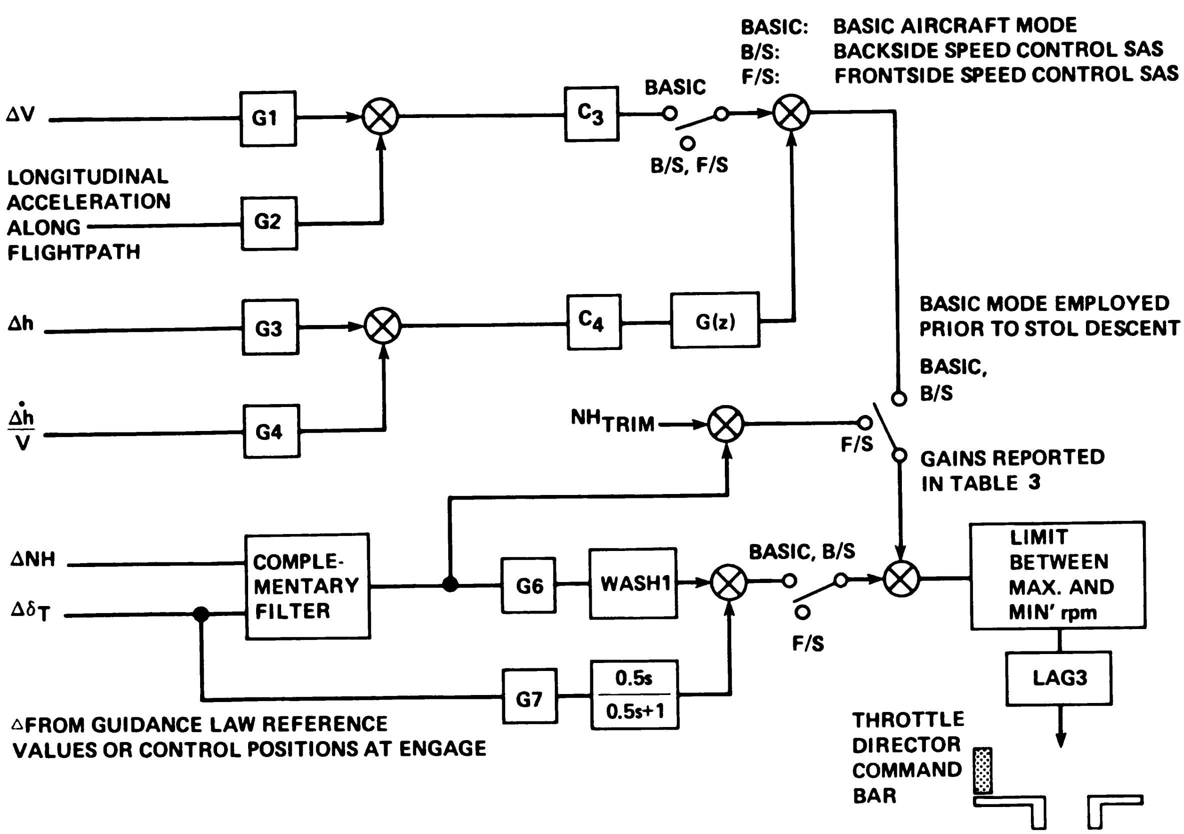


Figure 23. – Throttle flight director.

In the basic aircraft mode, which is used throughout for the level approach and initial deceleration segment, and during descent (if neither version of the speed-control SAS is selected), a feed-forward of nozzle angle into the pitch director is used to assist the pilot's coordination of pitch attitude necessary to maintain speed during minor adjustments of nozzle trim on descent. This feature also provides an appropriate crossfeed to pitch during glide-slope captures (and go-around), during which the path-error signal is temporarily suppressed while the new aircraft configuration is established. In the glide-slope capture case, the new configuration consists of nozzle deployment through typically 80°, for which a smoothly coordinated trim pitch change of about -6° is simultaneously required for satisfactory speed control. Greater detail on the programming incorporated for the glide-slope capture maneuver is contained in a subsequent section describing pilot procedures.

In the case of the throttle director, a combination of throttle position and engine rpm is used to provide the control position feedback signal. This contributes toward maximum bandwidth of control in the presence of significant engine response lags, and also overcomes the effects of a hysteresis existing in the linkage between the throttle lever handle and the engine fuel control unit.

In both throttle and pitch director laws, special care is given to appropriate limiting of the command signals. For throttle, reliable limiting of commanded throttle changes within the acceptable propulsion system operating range provides the pilot with the assurance that he may follow the flight director commands without separately monitoring the engine instruments. Similarly, reductions in throttle below levels that would result in excessive angles of attack are prevented by a configuration-dependent minimum thrust limit, likewise reducing the requirement for separate monitoring.

Limiting the commanded control correction in the pitch director to within ±5° relative to the aircraft symbol serves the conventional purpose of maintaining the director bar within view for all modes of use of the pitch director. For the frontside speed-control SAS mode an additional limiting of the pitch command to a range ±5° from the computed approach trim-pitch angle was incorporated to recognize the limited (but still substantial) authority of this control system. In addition, it was desired to conform somewhat with the tentative ±4° criteria proposed in reference 4 prescribing path control authority requirements thought acceptable for steep-angle operations in rough air. The ±15° limiting of the absolute pitch angle, used for the basic aircraft mode pitch director, serves to preclude excessive attitudes during climbout.

The flight director control and feedback laws just described were used in the course of collecting the performance, control and pilot opinion data presented subsequently in the body of this report. However, during the flight evaluation of these control and feedback laws, certain deficiencies became apparent that could not be remedied within the time constraints of the flight program. A subsequent effort to rectify these deficiencies, which resulted in significantly improved control laws for the glide-slope tracking segment of the approach profile, is reported in the appendix.

Trim Management

The continuously changing and generally uncertain nature of the ambient mean wind field, because of its significant effect on control authorities and safety margins, may be a source of major additional workload to the pilot of a powered-lift aircraft on a steep curved approach. The flight director was designed to provide the pilot with a cue from stored trim data for positioning the third auxiliary or redundant control so as to maintain satisfactory authority and safety margins associated with the active utilization of the other two controls. In addition to this stored knowledge of aircraft characteristics, the key computational feature of the director in assisting the pilot with this control function is its on-line estimate of along-track groundspeed, and hence aerodynamic flightpath angle, obtained from the navigation filters.

The trim nozzle data used to support the basic aircraft mode are shown in figure 24; they apply satisfactorily to all approach and landing flap angles because of the relative independence of hot-thrust vectoring from the high-lift aerodynamics in all practical approach configurations. Since ample safety margin exists at the higher speeds corresponding to the approach descent schedule shown in figure 20, there is no need to direct an increase in nozzle angle in tailwind conditions, for the consequently lower power setting is easily tolerated. The directed reduction in nozzle angle in headwind conditions is required on both approach and landing schedules, however, in order to prevent excessive thrust settings. Any difference between the system-determined trim setting and the current nozzle

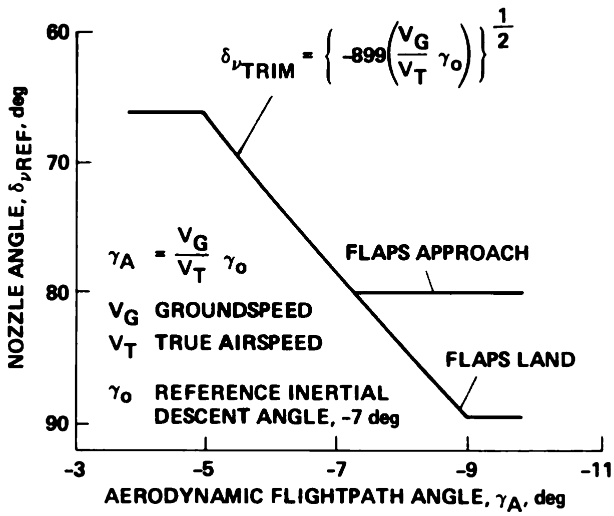


Figure 24.– Trim nozzle calculation.

setting is presented to the pilot via the central nozzle director window on the EADI, shown in figure 16, hence prompting an incremental correction.

Determining the trim settings for the backside and frontside speed-control SAS modes is more complex. Data are stored for a range of weights and aerodynamic flightpath angles for each approach and landing flap setting, and table look-up and interpolation are used to provide a continuous computation of trim pitch and power setting as flap is deployed on descent. The calculation changes to separate data appropriate to the final landing speed 5° before the prespecified landing flap setting has been achieved. Figure 25 presents the approach and landing trim data for flaps at 50° and a weight of 191 kN (43,000 lb). A further correction of

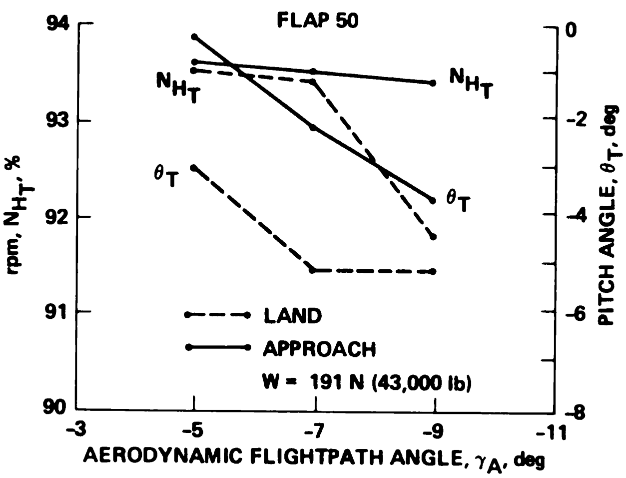


Figure 25.– Trim pitch and rpm tabulation.

+1.5% rpm increment is universally incorporated for the frontside mode where chokes are employed in order to furnish the offsetting lift requirements not allowed for in the stored trim data. In the backside mode, trim direction is displayed by the pitch-flight director bar as indicated in figures 22 and 16; the throttle director bar is used for presentation of required changes to trim throttle in the frontside mode. The stored trim data are calculated on the basis of the nozzle trim curve of figure 24, and, under ideal conditions, establishing the directed trim position for the third auxiliary control will also result in nominal positioning of the other two controls. Supporting these automatic speed control modes is the presentation of current averaged rpm in the central EADI display window in place of the nozzle angle director which is not applicable to these configurations.

The trim management feature of the director is also used during glide-slope capture, where the philosophy employed was to first establish the trim aircraft configuration appropriate to the new aerodynamic flightpath angle, and gradually resume closed-loop path tracking thereafter. The procedure involved the use of three controls by the pilot: first a computed trim throttle was set at the beginning of the capture maneuver, then the nozzles were manually deployed to their computed trim position, while the pilot also followed the nozzle-to-pitch crossfeed director to an appropriate trim pitch attitude. After the aircraft was established close to the desired glidepath using this procedure, the path-tracking loops would gradually take over, and the pilot could select either mode of the speed-control SAS, if desired. An alternative capture mode was also tested for the speed SAS modes that would provide automatic nozzle deployment at a suitable rate to the initial trim position, prior to smoothly establishing closed-loop velocity control.

V. FLIGHT TEST RESULTS AND DISCUSSION

Test Conditions and Procedures

The data reported here were obtained from approximately 60 approaches carried out in the test aircraft. The test site was the Crows Landing Naval Air Facility, California, where a STOLport defined according to the specifications of FAA Advisory Circular 150/5300-8 had been established on one of the CTOL runways. The runway environment and definition of navigation coordinates are shown in figure 26. Detailed documentation of the specific geometry and relative accuracies of the navigation facilities is contained in reference 17. Three research pilots, each with broad experience in low-speed handling-qualities programs, evaluated the three available STOL control-director concepts by flying hooded approaches to a decision height of 30.54 m (100 ft). Each approach was completed by a final visual segment during which the pilot's objective was to accomplish the best possible touchdown within the prescribed touchdown zone, also removing lateral offsets as may exist at breakout. The touch-and-go landing was followed by a climbing turn to intercept the profile for another approach. During any single flight the pilot generally evaluated only one control-director configuration; as many as 6 evaluation approaches were possible in the course of a 40-min flight. The pilots were provided with an approach profile chart, shown in figure 27, to assist with preflight briefings.

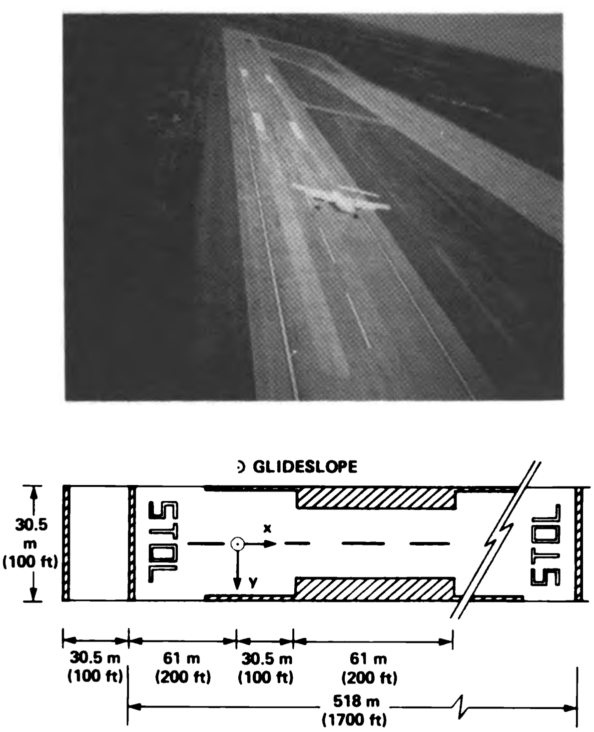
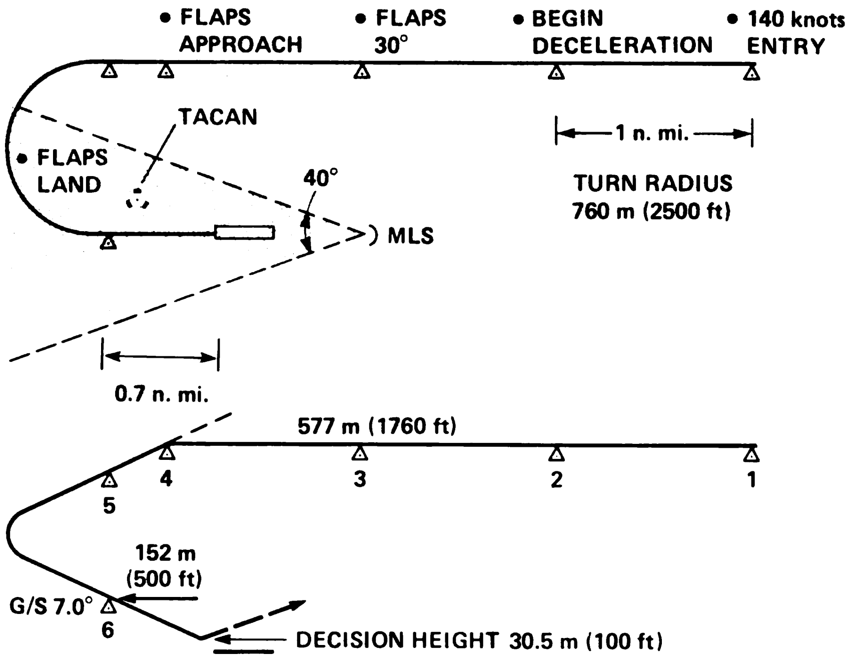


Figure 26. – Crows Landing Test Facility, STOL runway and coordinate system.

The decelerating curved-approach task was recognized as a two-pilot operation. The copilot deployed flaps at the pilot's command; monitored the flight director, approach progress, aircraft systems, and the aircraft trim state relative to changing winds during the approach; and performed usual communications tasks. In addition, the copilot made the required computer entries, using the keyboard shown in figure 14, specifying the landing flap configuration, estimated landing weight, as well as which of the three STOL control and flight-director concepts was to be evaluated.

A moderate range of wind conditions was encountered during the course of the flight-test program; however, turbulence was consistently light or negligible. It was a general objective during all flights to increase pilot awareness of potential control difficulties that might be caused by winds. For example, in order to operationally deal with the varying wind conditions, four reference approach trajectories were available to the pilot. They offered a choice of rollout altitude at the final straight approach segment of either 152 m (500 ft) or 213 m (700 ft) and a choice of turn radius of either 762 m (2500 ft) or 914 m (3000 ft). Information about probable winds during approach was furnished to the pilot during preflight briefings. The wind data were obtained by weather balloons launched from the STOLport. In addition, an on-line readout of estimated wind in runway coordinates obtained from the on-board navigation and air data systems was displayed for pilot reference on the MFD cockpit display. These sources augmented the reports of surface winds at the STOLport and together simulated the probable availability of comprehensive wind information to support future commercial STOL operations.

Twenty-two approaches were carried out in moderate wind conditions, that is, in winds ranging from 15 to 20 knots on final approach. In nearly all of these cases, the wind directions at turn altitudes were unfavorable to the left-hand descending turn, steepening the descent at initial turn roll-in and tending to drift the aircraft outside of the turn and across the localizer at rollout. All of these approaches utilized the wider turn radius in order to reduce these effects. In addition, 10 approaches were flown in these stronger wind conditions using an approach flap setting of 40° for the initial descent and a flap setting of 50° for landing. The nominal configuration used for all other approaches used approach and landing flap settings of 50° and 65°, respectively.



APPROACH SPEED SCHEDULE			
FLAP	WEIGHT, kN	APPROACH, knots	LAND, knots
40	178	95	81
	214		89
50	178	85	73
	214		81
65	178	65	65
	214	73	73

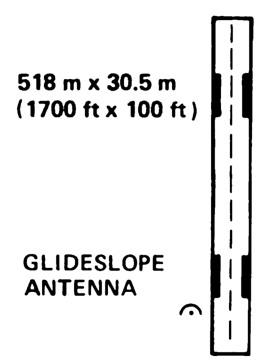


Figure 27. – Pilot's approach profile chart.

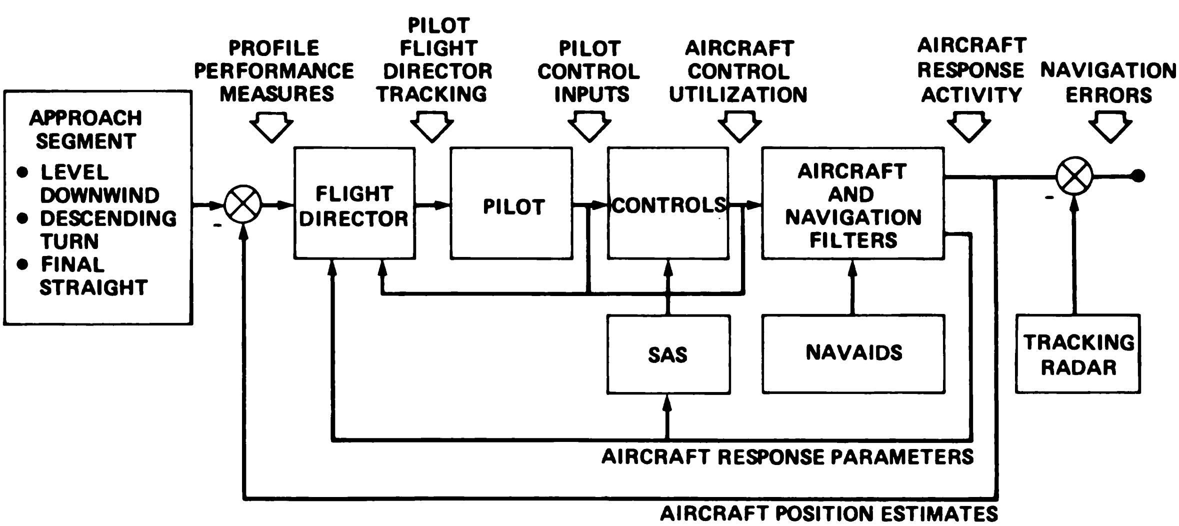
Data Measurement Philosophy and Organization

The unusually comprehensive nature of this investigation makes available a wide range of data which are likely to be of interest to a variety of individual disciplines. Figure 28 defines the outer- and inner-loop performance and control quantities and navigation system errors that are the subject of this section. Outer-loop performance measures describe the net profile performance achieved by the system based on its own position estimates obtained from the navigation filters. Presented as lateral and vertical position errors from the desired approach profile, these parameters are also referred to as guidance errors or flight technical errors; they reflect all sources of system error exclusive of navigation errors. Generally, these guidance errors are the same errors that are displayed to the pilot via the EADI tracking box, the aircraft position symbol on the MFD, and his electromechanical HSI. As shown in figure 28, navigation errors are defined as the difference between the estimated position of the aircraft (as determined in flight by processing navaid signals in the navigation filters) and the actual position (as measured by a ground-based tracking radar). These data describe the accuracy and qualities of the basic navigational facilities and environment, reflecting as well the design characteristics of the navigation filters. The inner-loop quantities shown in figure 28 describe the action of the pilot and the use of controls to achieve the outer-loop profile performance measures. While the flight director tracking errors and associated pilot control inputs provide measures perhaps pertaining to pilot workload, the control utilization data furnish information on the amount of control needed to achieve the measured profile performance. When interpreted in conjunction with the aircraft aerodynamic and control characteristics shown in figures 5 and 6 and with other information available in references 2 and 7, these data can be reduced to more general approximations of control power requirements, should such be desired for design purposes.

For purposes of data analysis and presentation, the approach task was subdivided into level-downwind, descending-turn, and final-straight approach segments. For each segment the parameter class measures just discussed are presented. There is a further subdivision, where appropriate, of data according to the three STOL control concepts during the descending segments. Also presented in this section are data related to performance criteria and control utilization at decision height and during the landing maneuver. The reader may choose to focus on only those data of interest to him in this section.

The minor variations in the four available approach profiles previously described did not produce any significant differences in performance data, so that all profiles contributed to the aggregate data base. Data from approach profiles having higher rollout altitudes, which were flown early in the program during the course of navigation filter developments, contributed to control and handling data bases, but not to the navigation and guidance data aggregates.

Consistent with the task-oriented emphasis of this work, this breakdown by approach segment provides the general framework for the presentation of system performance data to follow. Pilot comments, pilot opinion data, and discussion of the data from the points of view of handling qualities and pilot workload considerations are reserved for a following section.



DATA TYPES
OUTER LOOP PARAMETERS:
- PROFILE PERFORMANCE MEASURES – VERTICAL AND LATERAL PATH, SPEED ERRORS

INNER LOOP PARAMETERS:
- PILOT FLIGHT DIRECTOR TRACKING – PITCH, ROLL, THROTTLE DIRECTOR BAR ERRORS
- PILOT CONTROL INPUTS – PILOT'S COLUMN FORCE INPUT, WHEEL ANGLE
- AIRCRAFT CONTROL UTILIZATION – ENGINE rpm, NOZZLE ANGLE, PITCH ANGLE, ROLL ANGLE
- AIRCRAFT RESPONSE ACTIVITY – PITCH AND ROLL RATES, SINK RATE, GLIDEPATH ERROR RATE

NAVIGATION SYSTEM PARAMETERS:
- ACROSS-TRACK, ALONG TRACK, VERTICAL NAVIGATION SYSTEM ERRORS

Figure 28.– Data measurement philosophy.

Level-Downwind Segment

Net profile performance– Figure 29 illustrates in a macroscopic sense the net profile performance realized for approaches flown along one of the four available reference approach paths. The data were obtained from measurements by a ground tracking radar referred to the same coordinate system shown in figure 26. The net error from the desired profile accomplished by the system is a combination of navigation and guidance errors. The source of navigation errors during the downwind segment has been discussed in an earlier section; the guidance errors reflect pilotage, the suitability of the guidance control laws, and, to a large extent, the details of how the pilot chose to initially intercept the profile. These constituents of the net crosstrack error for the same approaches as represented in figure 29 are illustrated in figure 30. The day-to-day variations in TACAN navigation quality, which are evident in the upper chart of figure 30, are seen to be reflected in the guidance errors; this is particularly so during large transients, such as changeover to MODILS navigation during the turn. The effect of these external navaid disturbances and error sources on the dynamic system performance is a subject for separate study. Although occasionally apparent to the pilot, navaid error phenomena did not affect the approach task to any significant degree during this primarily handling-qualities oriented flight investigation.

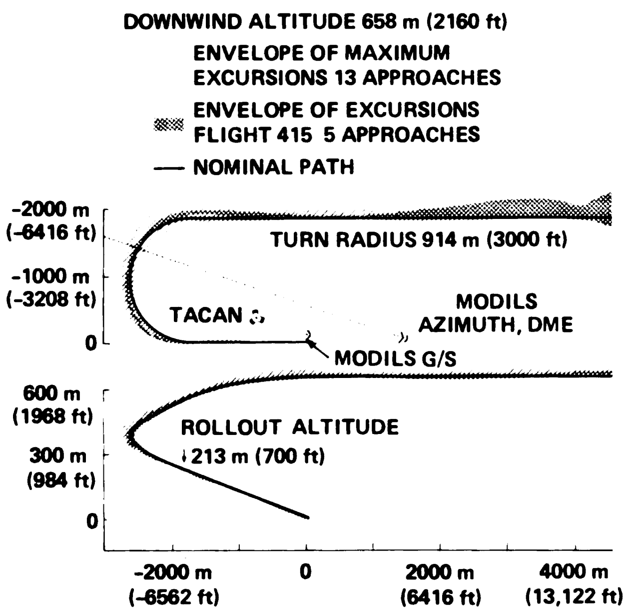


Figure 29.– Envelope of approach performance, flightpath 2.

Despite the nonstochastic nature of these errors, an indication of the crosstrack performance likely to be achievable in an environment similar to that of this investigation is represented by the probability density functions of figure 31. These histograms simply represent normalized tabulations of crosstrack navigation and guidance errors that fall within discrete error bands during the downwind segment for all flightpaths between way points 2 and 4, as illustrated in the lower chart of figure 30. Also interpreted as the percentage of samples (or time) among all approaches that errors fell in certain ranges, this form of data presentation is used extensively in this report.

Level deceleration and conversion to powered lift– Of greater interest during the downwind segment are considerations associated with longitudinal control of the aircraft. A typical set of time histories describing the deceleration from 140 knots to the initial approach speed of 90 knots is shown in figure 32. The modest levels of pitch- and throttle-control activity required while effecting the conversion to powered lift represent the low pilot workload involved in this maneuver, particularly during this early segment of the approach where except for the desire to delay deceleration as long as possible to conserve fuel, the performance requirements are relatively unconstrained.

The reader should note the characteristics of the inner-loop parameters – flight-director errors, pitch-control input activity levels, and frequencies – for later comparison with similar data during the final stages of the approach. It should be recalled that the maximum blending of the multiloop flight director occurs during this segment when flaps are generally deployed to 50°. This blending requires both pitch and throttle controls to be used to null any speed or path error; however, no problems in managing the two controls at roughly the same frequency requirements are evident.

The aggregate of pertinent longitudinal performance and control utilization measures during this segment of the approach task are shown statistically in the form of probability density functions in figure 33. This means of data presentation has been chosen to more graphically illustrate the amplitude distribution characteristics of the performance and control parameters of interest; representative time histories are presented as before to illustrate the

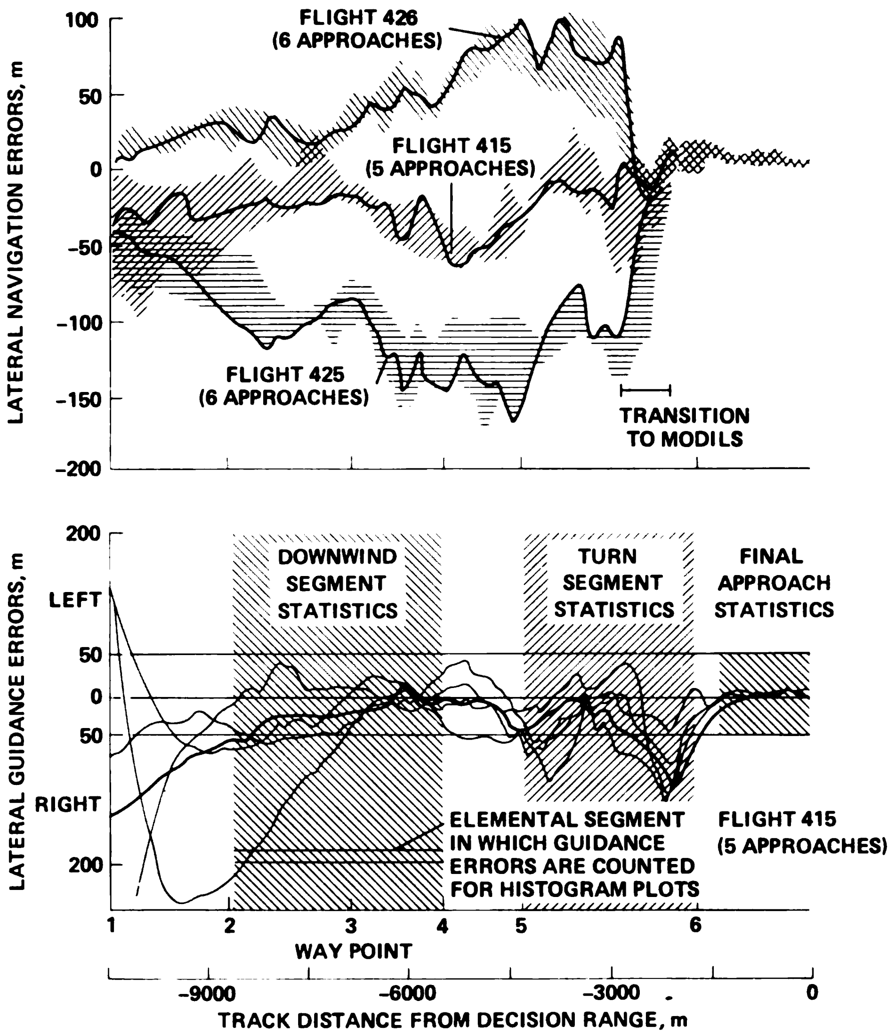


Figure 30.– Typical crosstrack navigation and guidance errors.

frequency characteristics of the data. These tabulations are not necessarily meant to imply statistical significance, so that sample means and variances are generally not emphasized except in cases where meaningful comparisons can be made. However, the shape and breadth of these histograms provide useful quantitative data on the relative amplitude and frequency of occurrence of the variables of interest. The histograms of flight-director tracking errors shown in figure 33 can be interpreted as a direct measure of pilot performance in a compensatory (error nulling) tracking task, where director bar widths in the case of the pitch director, and degrees of throttle director displacement measured against the background attitude scale are typical and directly calibrated measures that the pilot can use to judge his

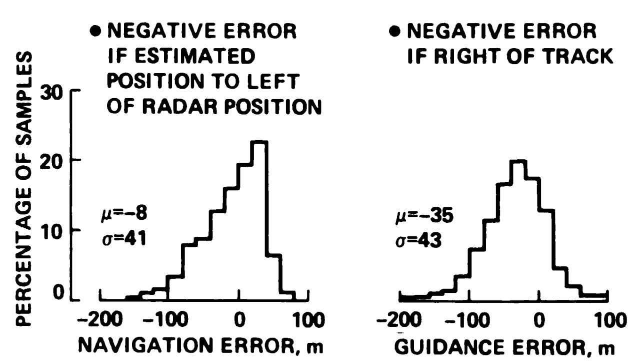


Figure 31.– Crosstrack navigation and guidance errors during level downwind segment (data from 34 approaches).

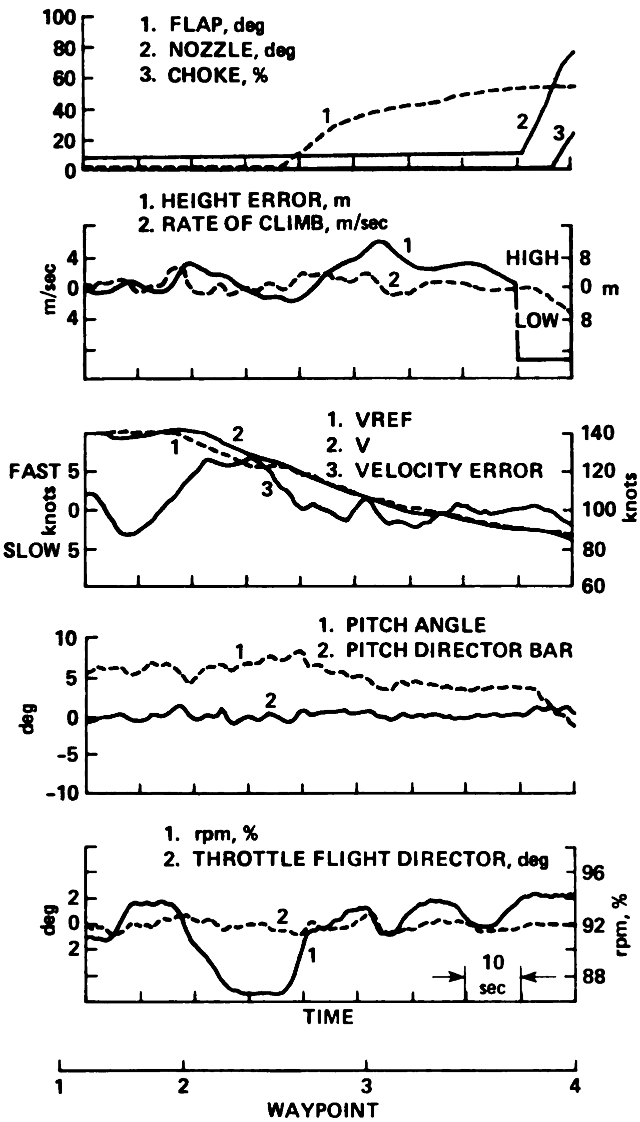


Figure 32.– Time histories of a typical initial level deceleration.

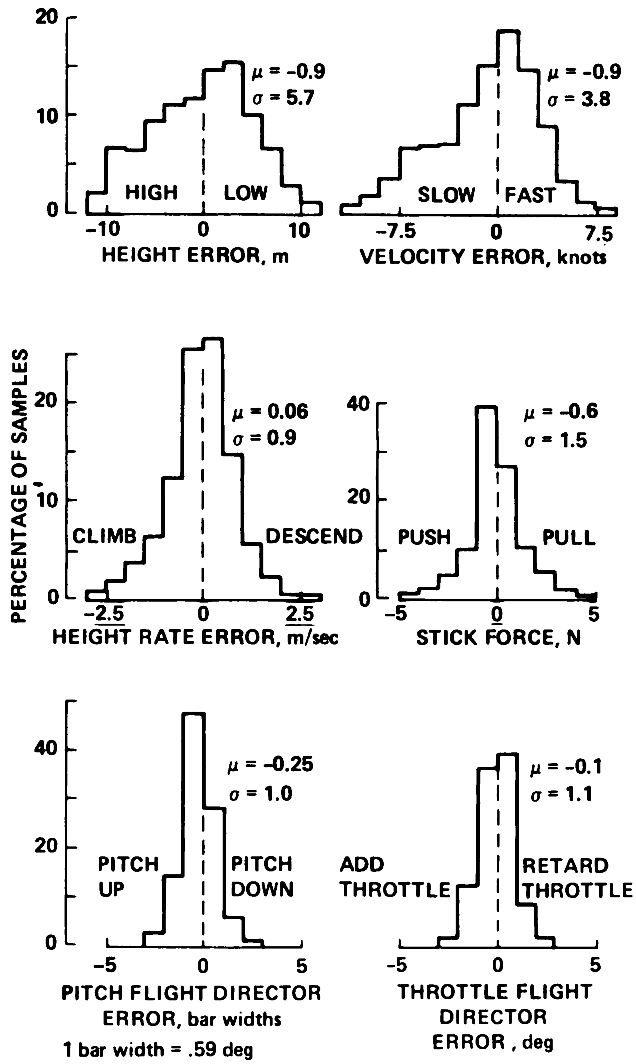


Figure 33.– Amplitude distributions of longitudinal performance and control parameters during level downwind deceleration segment (data from 34 approaches).

own performance. Alternatively, the director tracking errors also reflect, via the flight-director gains (table 3), the outer-loop tracking errors, or errors in control positions necessary for good outer-loop control.

Descending Turn Segment

Profile performance measures– Navigation and guidance errors during this segment are presented in figures 30 and 34. The horizontal discontinuities associated with the transition into the MODILS zone are encountered during this segment, making the probability density function of figure 34 more a tabulation of errors encountered, rather than suggesting any particular statistical significance. It is generally true that crosstrack navigation errors of sizes represented by the extremities of the histogram have their source while still in the TACAN region. They are presented to the system for elimination during this segment once transition to MODILS guidance is accomplished.

The magnitude of the navigation transient injected as a result of the change in navaid source from TACAN to MODILS is better indicated in figure 35. The figure summarizes the across- and along-track navigation errors existing at the on-board navigation filters, transformed to R-NAV track coordinates, at

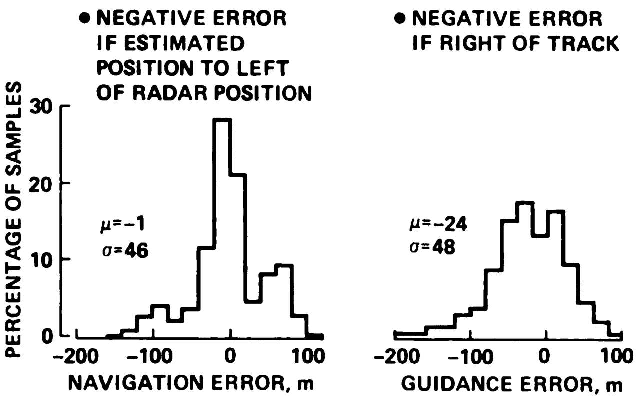


Figure 34. – Crosstrack navigation and guidance errors during turn segment (data from 34 approaches).

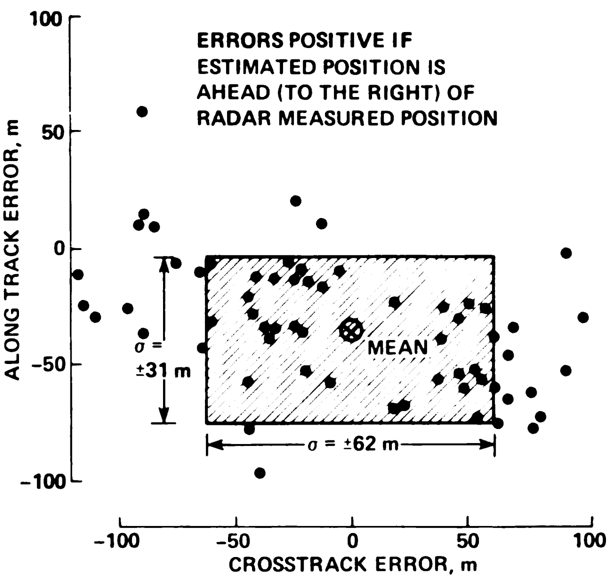


Figure 35.– Navigation errors at time of changing from TACAN to MODILS.

the time just prior to navaid switching. (Switching was generally implemented manually by the copilot at a position halfway around the turn, although under operational circumstances, automatic switching would be used.) The sources of these errors are primarily the transmission-reception characteristics of the TACAN DME and bearing information that can vary daily and with different units or adjustments of ground or flight equipment. The geometry of the navigation environment is such that the crosstrack error at the point of switching is largely a result of TACAN distance measurement errors, while the along-track error is mostly a result of bearing errors. Neglecting additional errors arising from the complementing function of the on-board inertial sensors, and assuming relatively error-free MODILS navigation data, this figure suggests two of the three dimensions of the probable TACAN-to-MODILS delivery zone. The effects of a typical transition are represented by the pertinent lateral time histories of figure 36, illustrating the controlled navigation filter transients in both runway and track coordinates, and their effect on the guidance and control parameters. The lateral control correction required to remove the TACAN error is without the larger transient which would otherwise exist had the position transient been allowed to propagate through the navigation filters affecting the velocity damping term.

Roll control during turn– The utilization of roll angle during the turn is presented in figure 37, comparing on the same axes the actual and commanded roll angle used to achieve the crosstrack performance typified by figure 34. Also shown for purposes of later comparison are amplitude distribution data describing flight-director following and the pilot's roll-control input characteristics. The data contain the effect of selecting an approach profile of lesser or greater turn radius for the wind conditions of the day and the approach speed employed in order to maintain the nominal turning bank angle nearer to 15°.

Longitudinal control data and final deceleration– Typical time histories of longitudinal control parameters are shown in figure 38 for the three STOL control concepts that were investigated. The final deceleration from approach to landing speed was usually accomplished during this segment by deploying the final landing flap as illustrated. Additionally, moderate winds during the approach would require small trim adjustments of the third auxiliary control as the turn progressed, which were in addition to those appropriate to assuming the final landing flap and speed configuration. The final straight approach segments included in this figure are discussed later.

Pertinent aggregates of longitudinal control data in the form of probability density functions are shown in figure 39. The relative contributions of the velocity error (from the reference speed) and glidepath error performance measures for each of the three STOL control concepts evaluated are illustrated in the cumulative aggregates. No such breakdown is included for the flight-director tracking measures, however, since these considerations will be addressed in the following section.

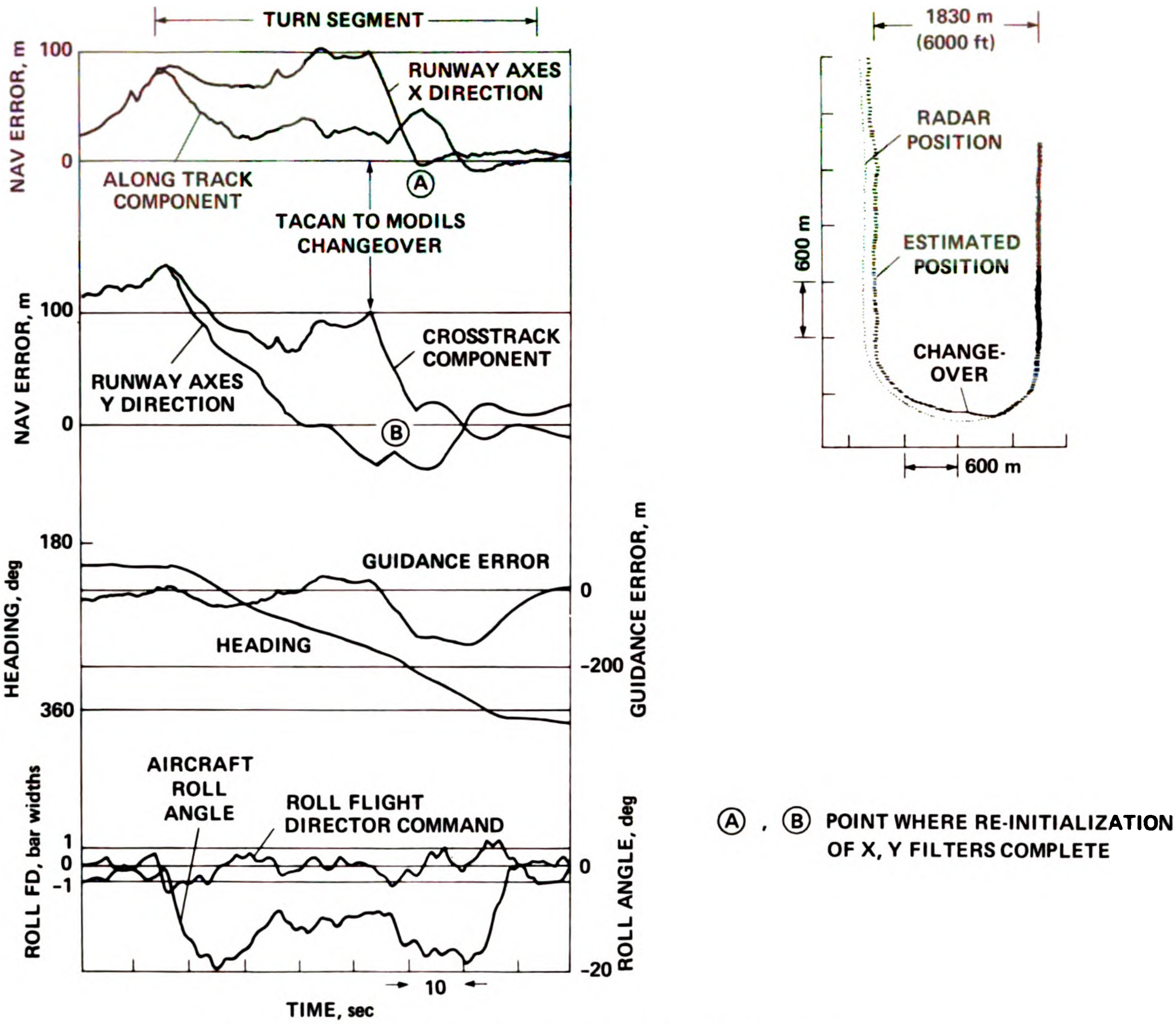


Figure 36.– Typical lateral transient due to NAVAID switching.

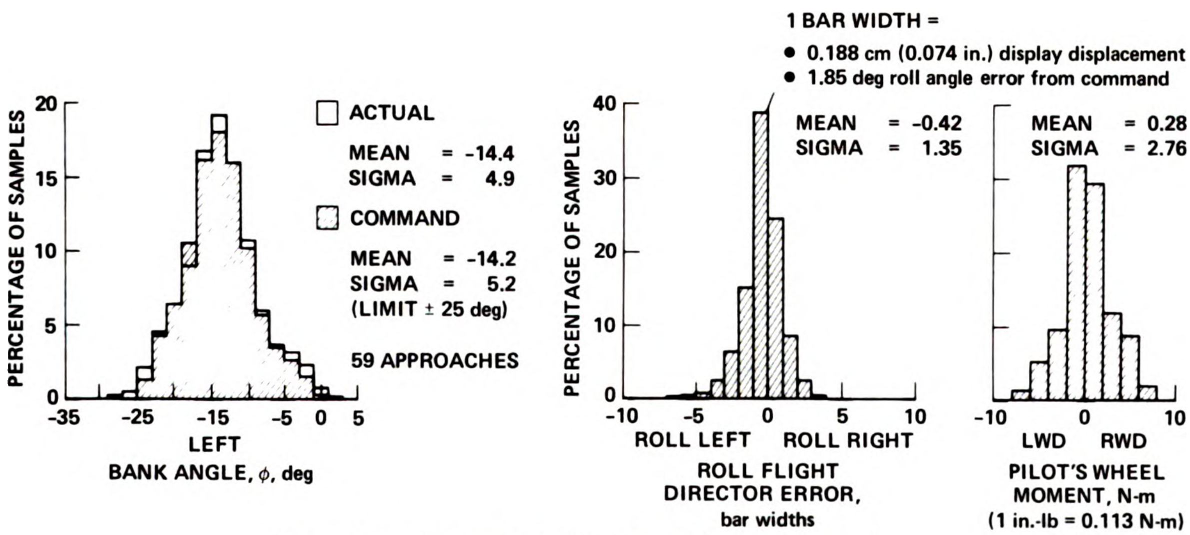
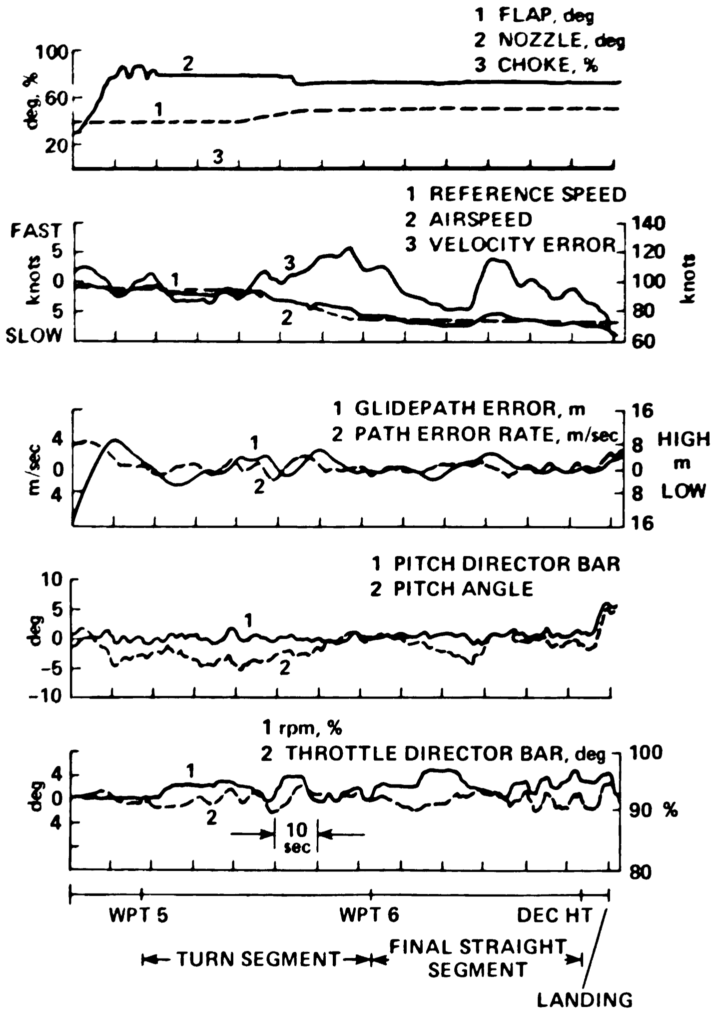


Figure 37.– Roll control utilization during turn segment.



(a) Basic aircraft.

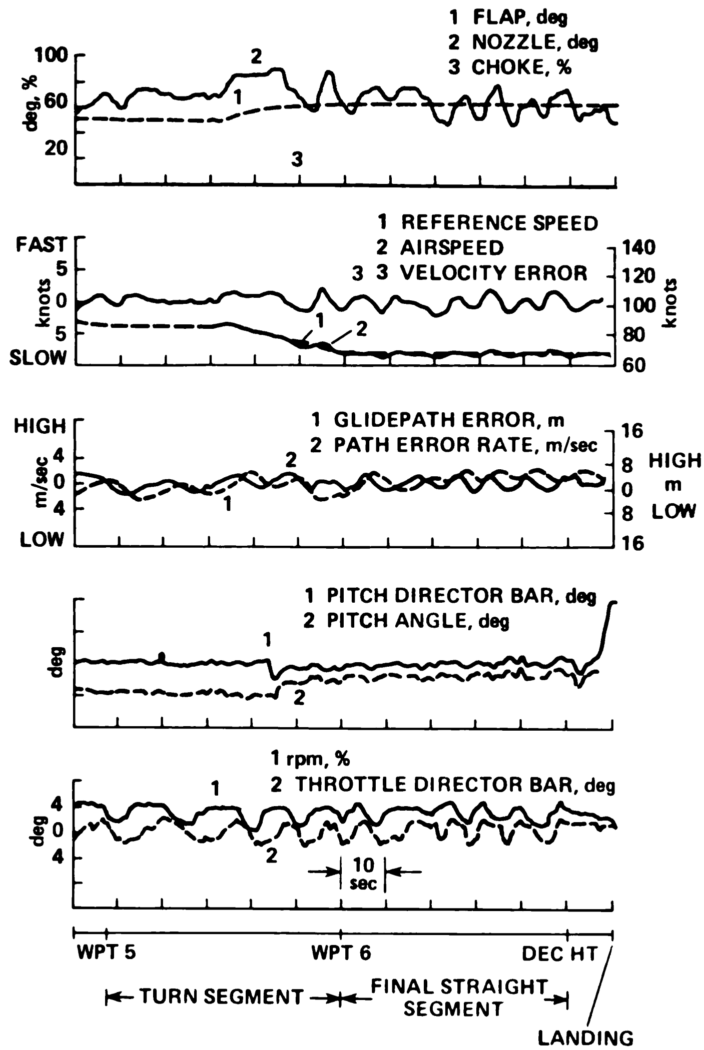
Figure 38. Time histories of longitudinal parameters during turn and final straight segment.

Final Approach Segment to Decision Height

General The final straight-approach segment following turn rollout provides the best opportunity to evaluate factors relating to the three STOL control concepts that were studied during this investigation. Interest is concentrated in the final 30 sec, approximately 122 m (400 ft) prior to reaching decision height, since any larger errors resulting from turn rollout and final deceleration have generally been corrected by this stage of the final segment.

Operationally, transition from instrument to visual flight conditions can occur any time prior to the nominal 30.5-m (100-ft) decision height chosen for this investigation. Consequently, some consideration is given in the data presented to performance measures that are averaged over the two 30.5-m (100-ft) altitude intervals prior to reaching decision height, as possibly providing a more representative indication of system performance than the instantaneous measures occurring at breakout. The latter are also reported.

Navigation errors– The navigation quality of the MODILS guidance aid used in this experiment is illustrated in figure 40 for the two 30.5-m (100-ft) altitude intervals just prior to decision height. Although the vertical navigation was of consistent quality over 13 flights and 61 approaches represented by the data, the lateral navigation occasionally showed daily variations in azimuth alignment in a direction that typically placed the aircraft to the right



(b) Backside SAS.

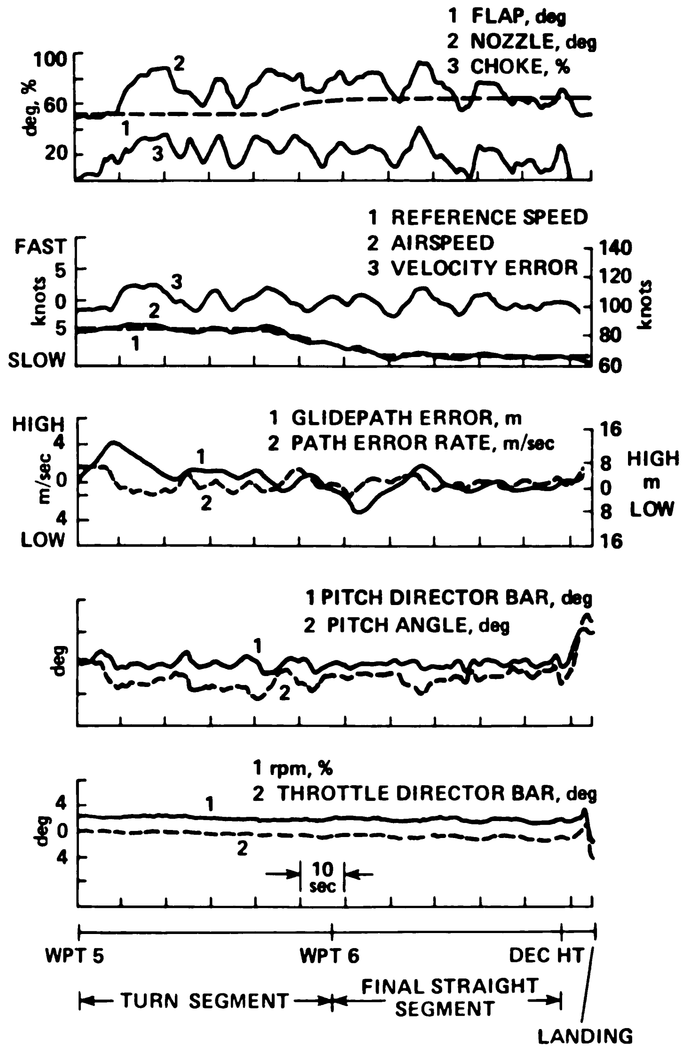
Figure 38.– Continued.

of its estimated position. Lateral navigation was further degraded by the 1.22-m (4-ft) resolution used in the lateral navigation filter shown in figure 12, which provided the error signal for localizer tracking. Despite high complementary filter gains prevailing in this region, it is considered that the poorer-than-desired lateral performance achieved during this segment can be partially attributed to this coarseness.

While the amplitude distribution functions of figure 40 provide averaged measures of navigation quality in the two 30.5-m (100-ft) altitude intervals above decision height, the actual combinations of vertical and lateral navigation errors existing at the decision range plane (the range corresponding to the decision height of 30.5 m (100 ft) when precisely on glidepath) are shown in figure 41.

These data summarize only some of the pertinent navigation qualities of the MODILS guidance aid used in this investigation. It was not an objective to document in detail the performance of this system; further details of the system are given in reference 17.

Performance and control data– Consistent with the navigation data just presented, the corresponding glidepath and localizer guidance errors in the altitude segments 91.5 to 61 m (300 to 200 ft) and 61 to 30.5 m (200 to 100 ft) are shown in figure 42 for all three STOL control concepts combined. The actual



(c) Frontside SAS.

Figure 38.– Concluded.

combinations of vertical and lateral guidance errors existing at the decision altitude of 30.5 m (100 ft) are shown in figure 43. The left-of-center bias which is apparent in the lateral data arises as a result of persisting small vertical gyro bias errors generated during the final turn during which the roll-angle erection feature has been automatically disabled. The flight-director gains are such in this altitude region to cause a 4.8-m (16-ft) lateral standoff for a 1° roll-angle error. These data will be discussed further in a subsequent section which considers issues associated with breakout and landing.

A comprehensive set of time histories of the pertinent longitudinal performance and control data for the three STOL control concepts evaluated is shown for typical approaches in figure 38. The purpose of this figure is to illustrate the basic nature of the different control concepts, whose performance and control aggregates are next summarized as probability density functions. The reader will note the oscillatory character of the throttle-control activity, which influences glidepath error for both the basic aircraft and backside SAS modes, and which also couples into the speed-control loop for the backside SAS mode. These characteristics were later rectified with improved control laws as reported in the appendix.

Aggregates of glidepath error, glidepath error rate, and approach speed error over the final 30 sec prior to decision height are presented in figure 44 for the

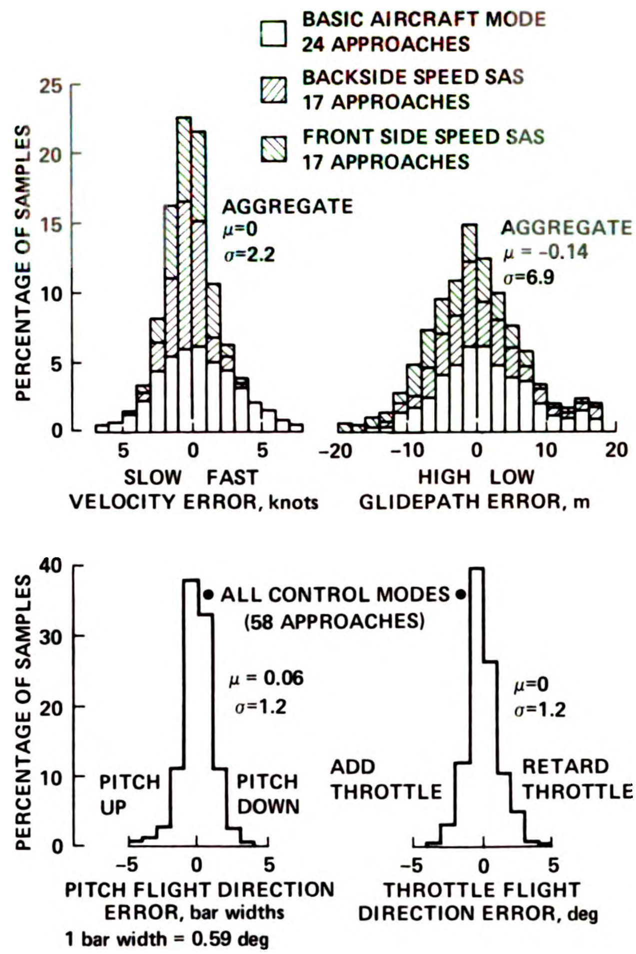


Figure 39.– Longitudinal performance and control parameters during turn segment.

three STOL control concepts that were evaluated. Somewhat greater dispersions in these quantities are evident for the basic aircraft configuration; however, none of the differences is significant to the 90% confidence level. The data are presented to furnish quantitative boundaries to tracking dispersions and to provide a quantitatively based feeling for differences in the STOL control concepts. For example, it might be felt that slower correction of glidepath errors is a characteristic of the frontside SAS control concept. However, presented in this way, the data do not support this conjecture. On the other hand, the improvement in speed control provided by both speed SAS modes is strongly evident, as is a speed bias on the slow side for the basic aircraft mode. It could thus be inferred from these latter data that even the facility of a pitch flight director does not fully induce the pilot to assume the unconventional control technique of pitching down when adding power to correct up to path, particularly at lower altitudes.

The control utilization characteristics involved in achieving the longitudinal performance data just discussed are summarized in figure 45. The controls are categorized for each STOL control concept as primary, secondary, or trim, as was outlined in an earlier section and summarized in table 2. A further separation of the data for light and moderate headwind components is necessary in order to properly account for the effect of differing trim aerodynamic flightpath angles affecting the mean value of configuration parameters other than power. It should be recalled that the objective was to maintain power settings in all control modes which were basically independent of wind. This was achieved by controlling trim drag directly by setting a specified appropriate trim nozzle angle (basic aircraft mode), setting a specified pitch attitude, which would

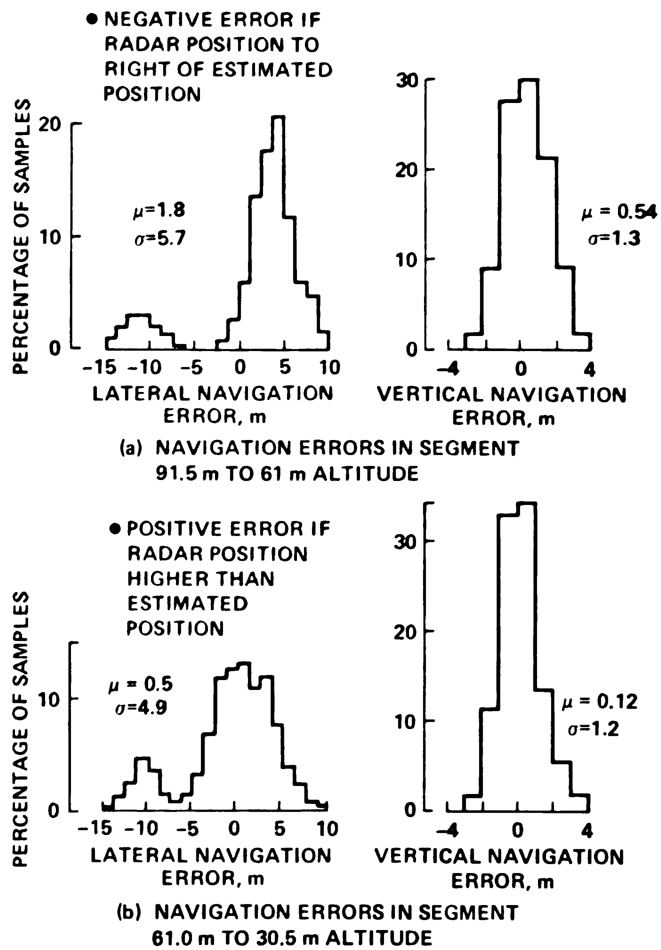


Figure 40. – Navigation errors during final approach segment (data from 61 approaches).

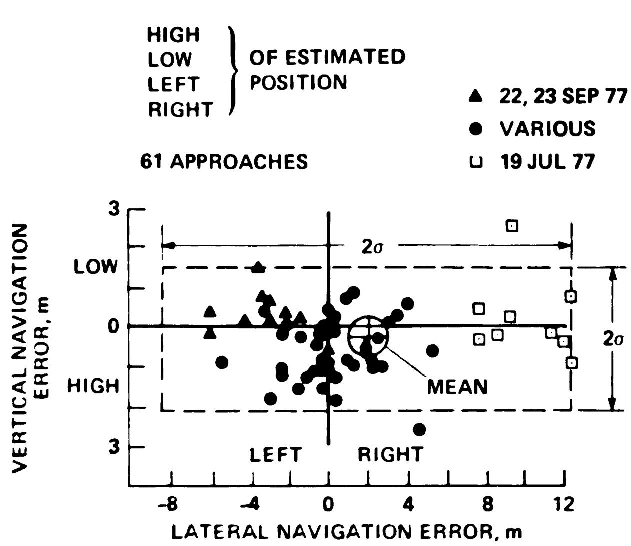
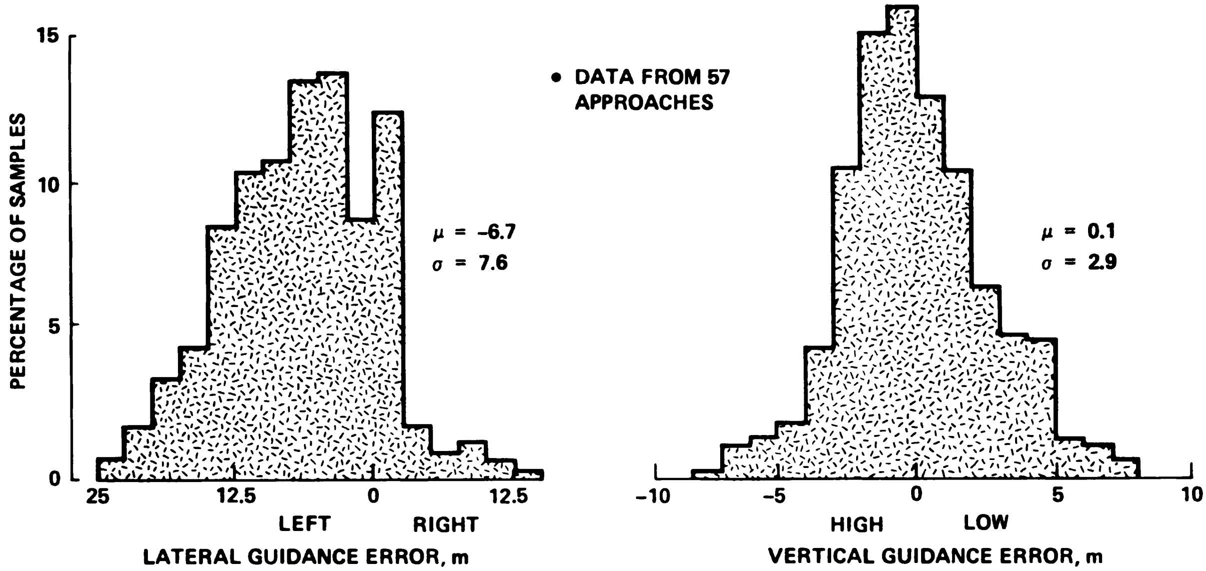
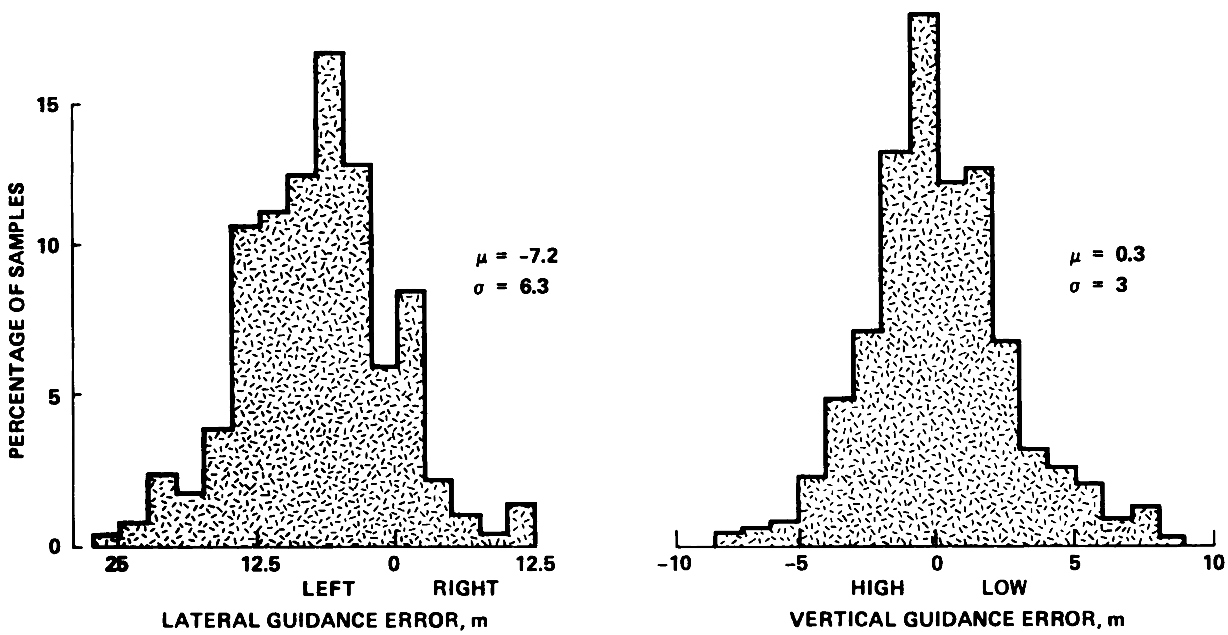


Figure 41. Navigation errors at decision range plane.

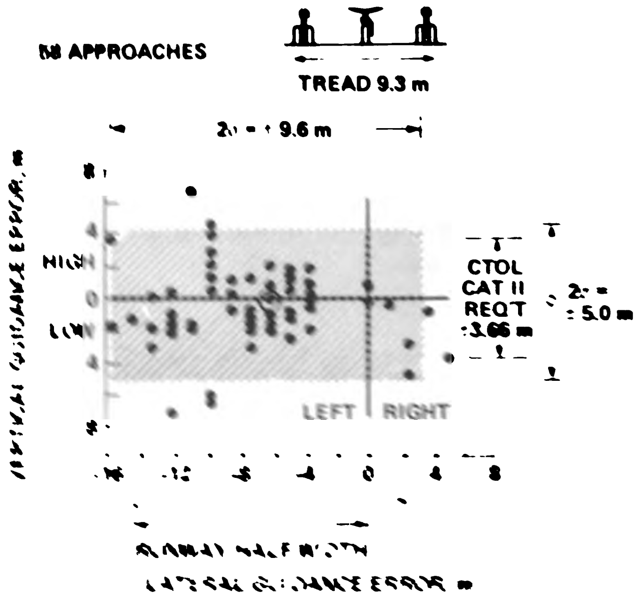


(a) GUIDANCE ERRORS IN SEGMENT 91.5 TO 61 m ALTITUDE INTERVAL



(b) GUIDANCE ERRORS IN SEGMENT 61 TO 30.5 m ALTITUDE INTERVAL

Figure 42.– Guidance errors during final approach segment.



TREAD 9.3 m
HIGH
LOW
CTOL
CAT II
REQ'T
±3.66 m
± 5.0 m
LEFT
RIGHT
-16
-12
-8
-4
0
4
8

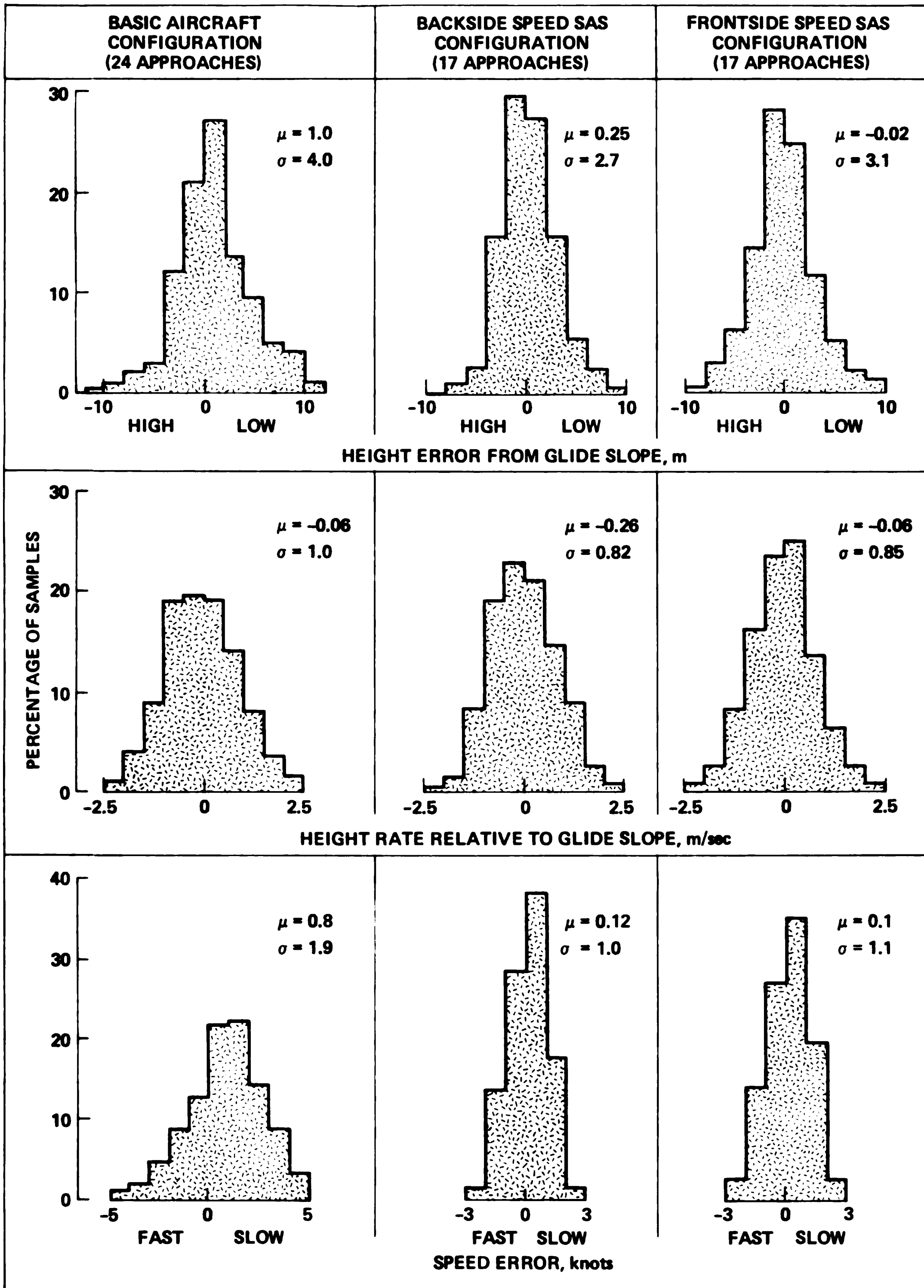


Figure 44.– Longitudinal performance measures during final straight segment.

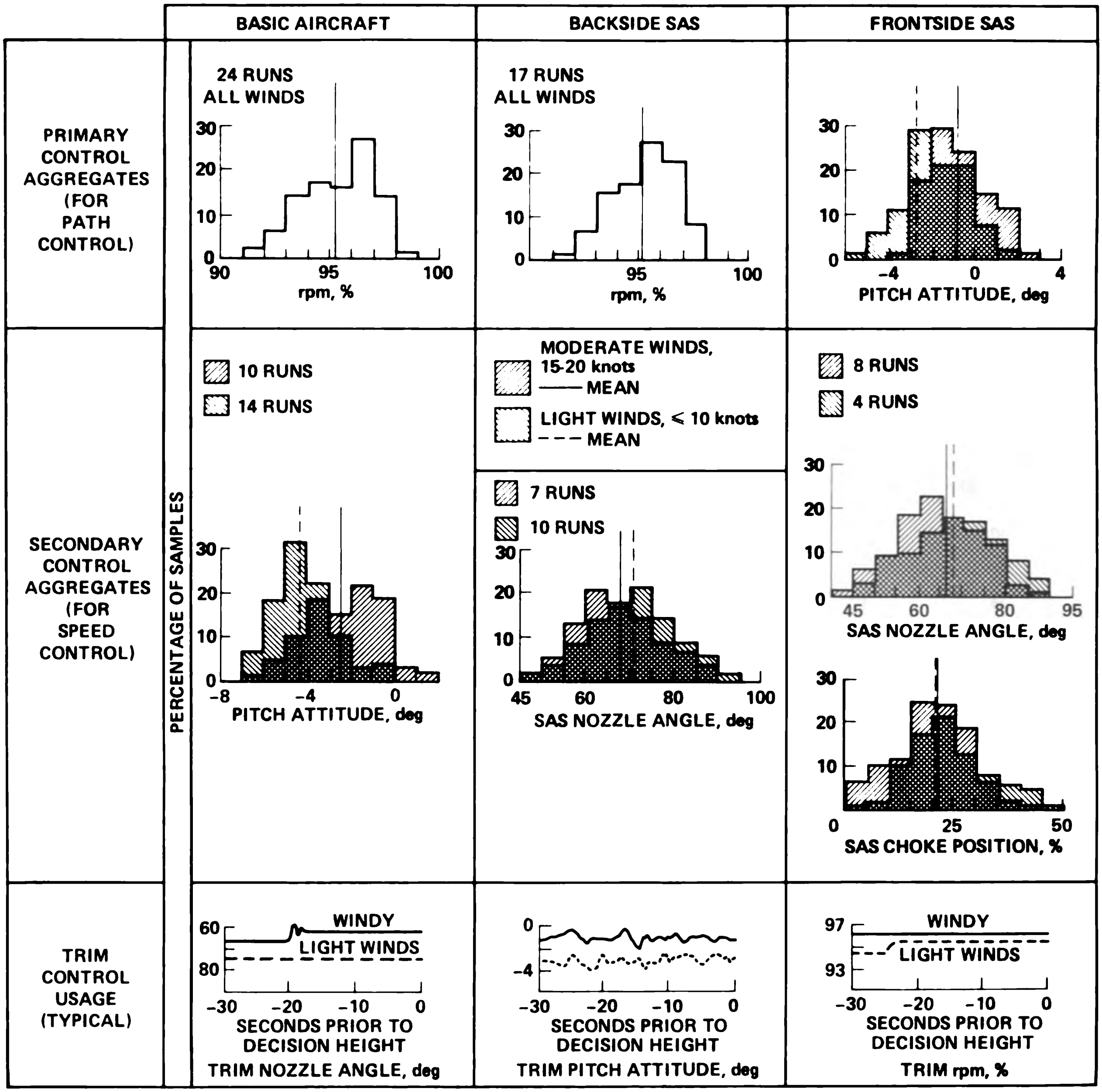


Figure 45.– Summary of control utilization data during final 30 sec of approach.

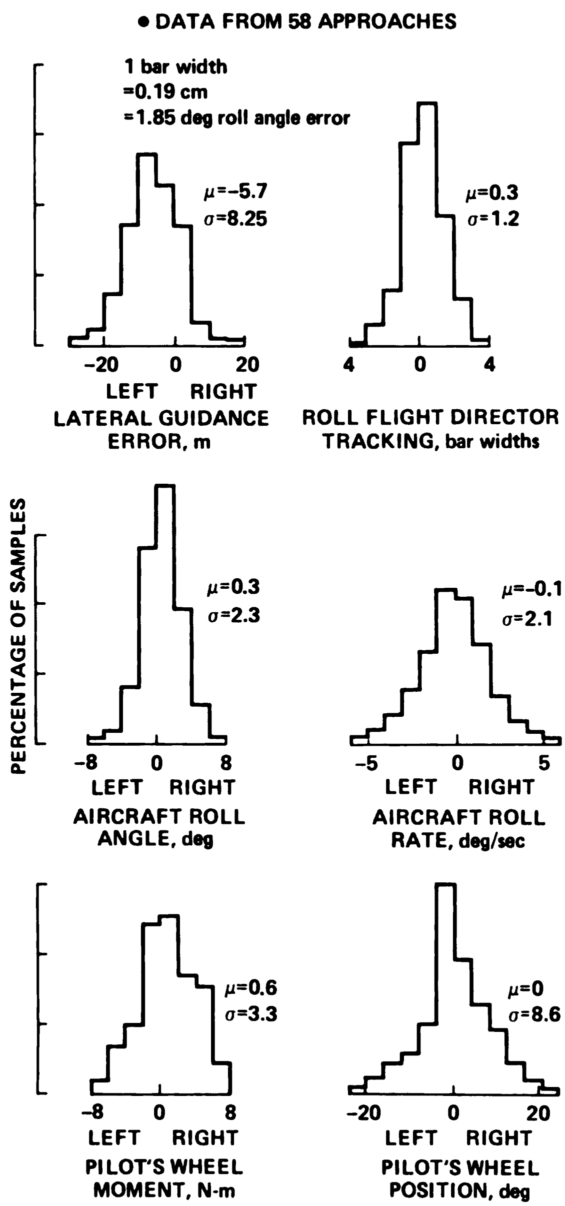


Figure 46.– Lateral performance and control parameters during final 30 sec of approach.

inputs in order to meet the stringent lateral performance requirements during the turn and final approach segments, which inevitably contaminate even a perfect pitch-attitude hold SAS. In addition, it is important to note that despite this rather theoretical assignment of relative control function noted above, the physical fact remains that pitch attitude retains a singular control significance for the pilot, not only because of the dominating nature of the associated kinesthetic feedback cues, but also due to the usual linkage of pitch control to the physically primary cockpit column control. In consequence, it might well be inferred that the pilot's most familiar, and perhaps most effectively designed and instinctive control, is thus misused in a pure backside mode of operation, being used to assist attitude stabilization, but not for any form of useful flightpath control.

The qualitatively similar shapes of the histograms presented in figure 47 also suggest that the inner-loop control and performance measures used are evidently insensitive to tracking either the essentially fixed trim pitch attitude of the backside SAS mode or the low amplitude, slowly varying secondary (speed control) pitch attitude tracking task of the basic aircraft mode. At least in the latter case some useful control is achieved in addition to attitude stabilization. However, as presented earlier in figure 44, the outer-loop speed performance is notably better in the former case due to the speed-control SAS.

Proceeding to the next level of pitch-control utilization, the frontside speed-control SAS mode seeks to take advantage of the good speed control provided by the speed SAS, while realizing a primary control function from pitch attitude. This results in the visibly different pitch control measures of figure 47, which nonetheless fail to pass 90% significance tests on the sample variances. However, the fundamentally different nature of control is greater than perhaps is quantitatively evident. The control concept is characterized by undeniably increased pitch activity in amplitude and frequency, with a corresponding increase in nozzle activity brought about by the speed-control SAS. Were it not for the albeit performance-penalizing inclusion of the augmentor chokes to provide direct lift control augmentation and compensation of lift losses due to nozzle retraction in this system, this pitch-control activity would be even greater. Although influenced by the effective heave damping in the short term, the pitch activity is primarily a kinematic phenomenon associated with low approach speeds, and might be argued to represent an excessive utilization of pitch control, particularly if rapidity of path response is demanded. Yet some significant advantages accrue from this mode of operation, particularly for designs similar to the test aircraft where adequate glidepath control response and authority can be achieved under normal circumstances without the need to modulate power. However, the many design-related considerations associated with the three STOL control concepts investigated here are beyond the scope of this report.

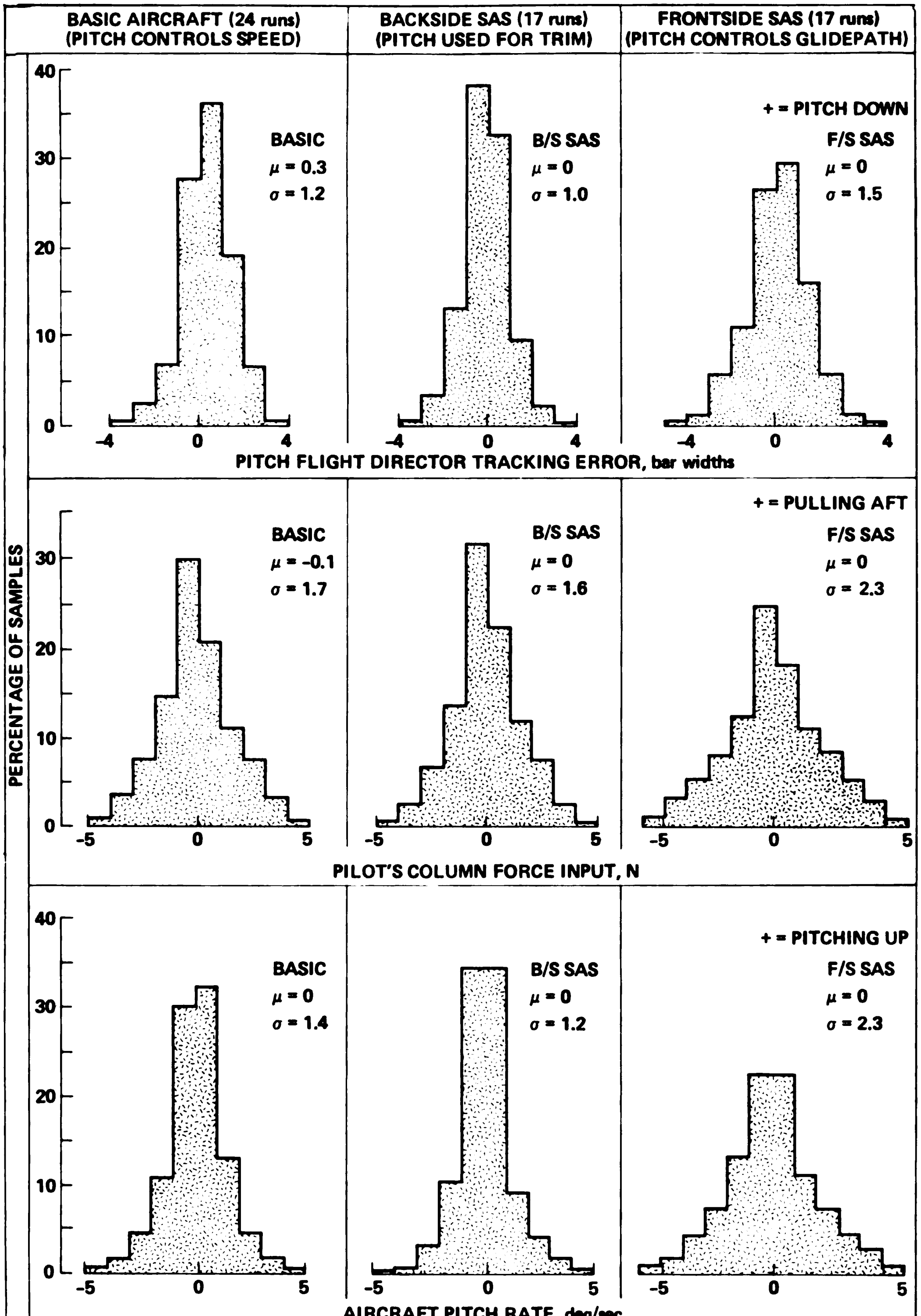


Figure 47.– Summary of pitch control characteristics during final 30 sec of approach.

Decision Height, Breakout, and Landing Transition

General– For purposes of initial evaluation, the nominal Category II decision height of 30.54 m (100 ft) generally applying to CTOL operations was used as the altitude at which the pilot removed his blind flying hood and proceeded with the objective of landing the aircraft within the prescribed touchdown zone. It was recognized that design-related considerations associated with engine-out or missed-approach performance might well restrict the achievable decision height to a higher altitude; however, these factors were not addressed. In addition, the nominal 7° glide-slope angle chosen for the tests bordered on the steepest limit which is probably acceptable for instrument approach operations, since a nominal 69-knot approach speed resulted in a sink rate of 4.36 m/sec (860 ft/min), providing only a nominal 7 sec for the landing transition. As discussed in reference 18, it is generally regarded that an upper limit of 5.1 m/sec (1000 ft/min) exists as a maximum acceptable sink rate during typical corrections or disturbances, at least when operating to these altitude limits. It should be emphasized that this research did not seek to define satisfactory decision heights and associated performance requirements, but merely to provide some background data which could be useful for a more exhaustive future study.

The navigation and guidance errors existing at decision height have been reported earlier in figures 41 and 43. These data are relative to the electronic centerline which was in reality displaced (because of physical placement of the transmitting antenna) 5.2 m (17 ft) to the left of the actual centerline of the 30.5-m (100-ft) wide STOL runway used for landing. The more pertinent measures of net positioning errors required to be adequately taken out by the landing maneuver are the actual displacements of the aircraft when passing decision height, relative to the actual centerline. The combined navigation and guidance errors existing at the pilot's decision height as measured by the tracking radar are summarized in figure 48, and will be discussed separately for their vertical and lateral considerations.

Glidepath corrections near breakout– A consideration of the geometry and kinematics of low-speed steep angle approaches suggests that it is particularly important to have small errors in both vertical position and rate relative to the glideslope at decision height, the objective being to allow the

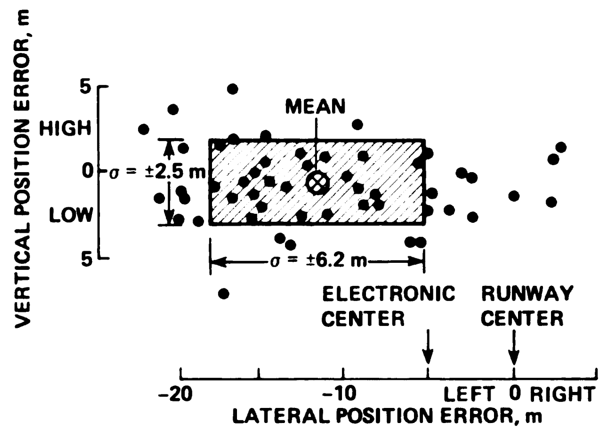
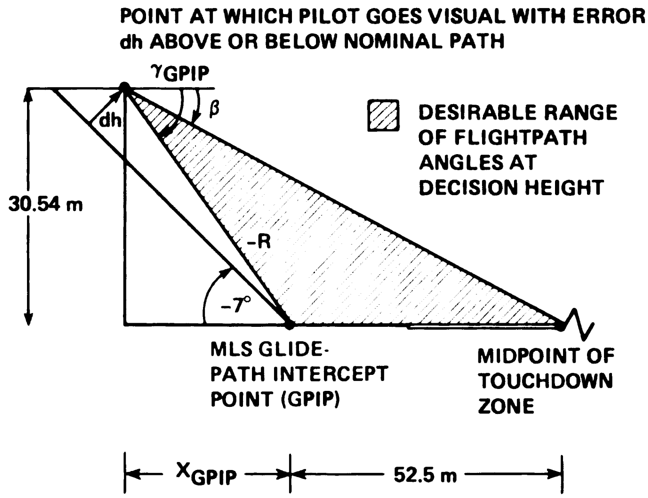


Figure 48.– Net position errors at pilot's decision height.

aircraft to carry on toward an acceptable vicinity of the touchdown zone with minimum requirement for maneuvering by the pilot, except to flare. This becomes especially important in cases where visual cues may be marginal just prior to decision height, and degraded afterward as the pilot seeks improved visual orientation for flare and landing. More specifically, if the aircraft is low just prior to reaching the decision height, for example, the pilot is perhaps more inclined to make a correction that will result in an inertial flightpath angle directed toward the glidepath intercept point. The correction made by the pilot might be altogether different (probably much less severe) than that induced by the flight-director command law. (In this investigation, the flight-director command law was ignorant of these considerations.) This information is appropriately presented, however, by the inertially referenced flightpath angle bar relative to the inertially calculated perspective runway display. Both are features of the electronic attitude director indicator described in an earlier section. This display feature was evaluated only during a few approaches, however, and not by all pilots.

Recognizing the importance of both flightpath error and the direction of the longitudinal velocity vector (i.e., inertial flightpath angle) just prior to and at breakout, the simple analysis shown in figure 49 suggests how acceptable combinations of these parameters might be determined. The assumption is made that the desirable range for pointing of the longitudinal flightpath vector at decision height is no steeper than the electronic glidepath intercept point, and no shallower than one-half of the distance into the touchdown zone. Furthermore, flightpath angles should be restricted to within ±2° of the



LIMIT ENSURING NO SHORTER THAN GPIP:

$$\tan \gamma_{GPIP} \doteq \frac{30.54}{(30.54 - dh)} \tan 7.0$$

LIMIT ENSURING NO LONGER THAN MIDPOINT OF TD ZONE

$$\beta = \tan^{-1} \frac{30.54}{52.5 + R \cos \gamma_{GPIP}}$$

Figure 49.– Definition of desirable conditions at breakout.

nominal path in order to conform to some of the considerations presented in reference 4.

The resulting envelope of optimum combinations of vertical path error and flightpath angle at breakout, based on small-angle approximations, is shown in figure 50, on which are plotted the measured data from the 56 approaches of this investigation. The data from the cases for which the perspective runway was employed are separately identified, although no correlation with this thesis seems to exist. The objective of this figure is to suggest the nature of the longitudinal maneuvering required following breakout in order to position the aircraft for flare and landing, and to imply that programmed constraints on flightpath angle excursions approaching decision height may be desirable. These considerations were addressed in the improved glidepath control laws that were developed after completion of this flight program as reported in the appendix.

The longitudinal touchdown performance achieved in these tests is summarized in figure 51 for 62 landings. Touchdown dispersion data were obtained from both radar and photo measurements and have an estimated accuracy of ±5 m (±16 ft) longitudinally. The touchdown sink rates were obtained from a third-order complementary filter that combined radar altimeter data with normal accelerometer data; the sink rates are thought to be accurate to within 0.5 m/sec (1.6 ft/sec). Strut compression was used to signal touchdown. It is worth noting that both short touchdowns, identified as *A* and *B* in figure 50, were also at the higher sink rates, and that these two landings correlated with lower and steeper conditions at breakout, as shown. Both occurrences drew pilot comments about too little time to appreciate the visual situation and react to it adequately. The longest landings tended to be low floaters for which the pilot could have safely accomplished earlier touchdown had it been necessary to do so in order to realize stopping distances. No attempt to gather field length data was made in this program, since the flights consisted of touch-and-go landings between multiple approaches. Although the three STOL control concepts tested represented rather widely varying piloting techniques for flare and landing, little reliable correlation of touchdown data with control mode appears to be evident, a result consistent with similar investigations presented in reference 11.

Lateral maneuvering requirements– The lateral position errors at breakout shown in figure 48 were

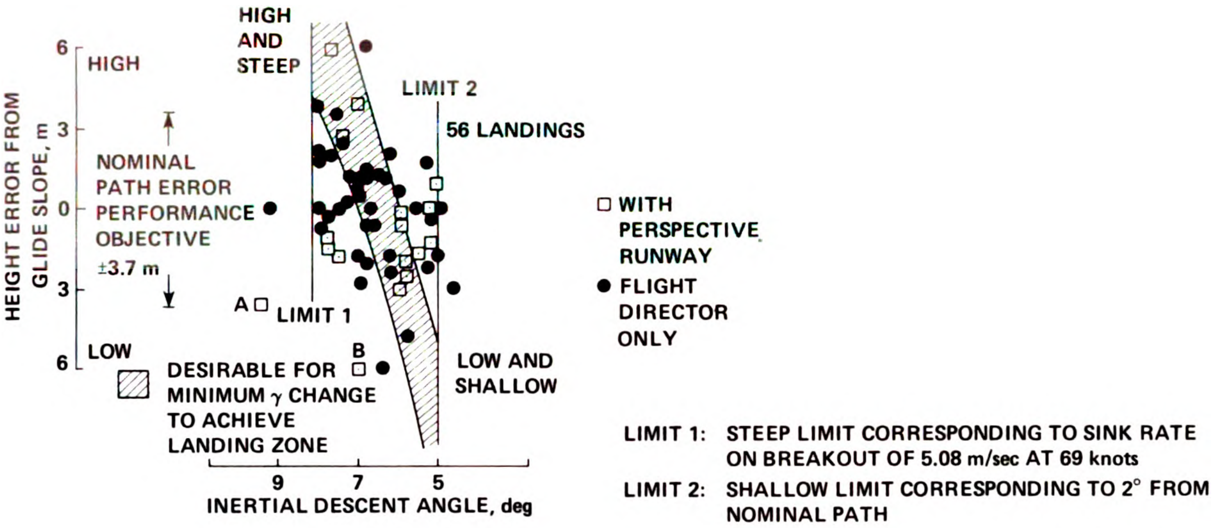


Figure 50.– Glidepath error, inertial flightpath angle combinations at breakout.

useful in creating a lateral-directional control task following breakout to landing. The magnitude of error shown in the figure was contributed to by several factors which were in addition to the intentional 5.2-m (17-ft) lateral offset resulting from the physical location of the MODILS electronic guidance centerline relative to the actual runway centerline. To review, these factors were (1) the relatively low sensitivity of the localizer raw data tracking box; (2) the unusual coarseness of the MODILS azimuth signal (see table 1); (3) the less-than-required resolution of the lateral position error signal feeding the guidance laws; (4) the persistence of a small control-law feedback bias from the roll angle gyro following rollout from the final turn; and (5) the day-to-day MODILS azimuth alignment errors shown in figures 40 and 41. Although all these factors would require improvement for an operational system, the desirable result for this investigation was to surprise the pilot with at least the magnitude of lateral correction required after breakout, the direction thought to be less important in the artificial environment of superb visual scene available. The left-to-right correction typically required also occurred in the presence of left crosswinds which created a challenging combination of maneuver demands to correct position and also accomplish suitable decrab to land.

The range of lateral maneuver demanded by the situation is summarized for all approaches in figure 52. The probability density tabulations of roll-angle and roll-rate utilization during the task

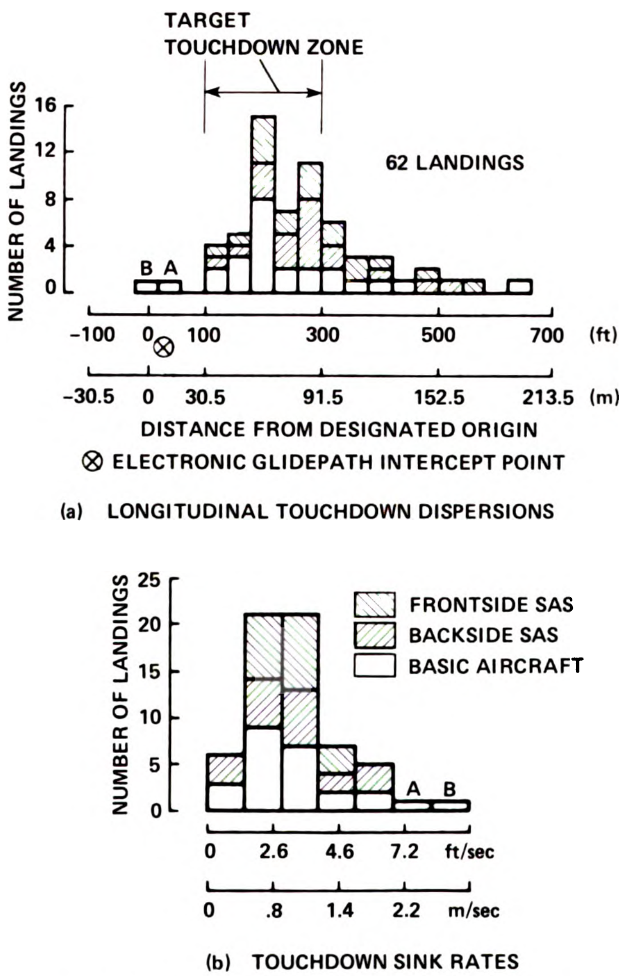


Figure 51.– Longitudinal touchdown performance.

segment for breakout to landing provide an initial measure of roll- and yaw-control utilization requirements for these maneuvers. It should be noted that there were no rejected landings because of unacceptable positioning at breakout for any approaches flown.

The lateral touchdown dispersions achieved are shown in figure 53; they have an estimated accuracy of ±2 m (6.6 ft).

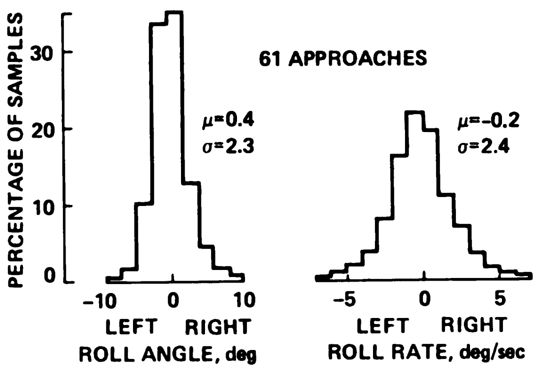


Figure 52.– Roll control utilization during maneuver to land following breakout.

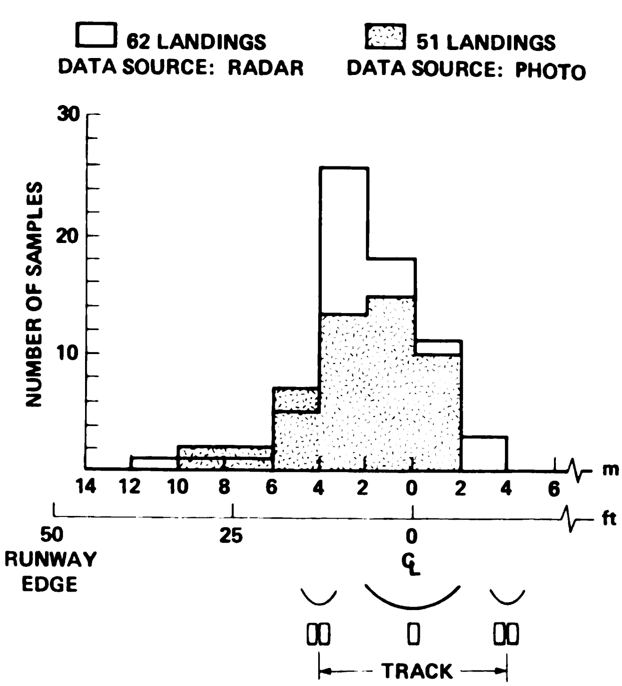


Figure 53.– Lateral touchdown dispersion.

VI. PILOT COMMENTS, HANDLING QUALITIES AND PROCEDURES, AND DISPLAY CONSIDERATIONS

General

The comprehensive approach task reported here provided the opportunity to assess a wide variety of factors involved in the potential feasibility of constrained terminal-area approach profiles for powered-lift STOL aircraft. Workload and performance considerations, handling qualities and control considerations, and cockpit display requirements are perhaps the more significant for discussion from a piloting point of view. As discussed in this section, they serve to complement the flight-test data just presented.

Three research pilots (the authors of this report) with broad experience in low-speed handling qualities programs and in various terminal-area approach and landing programs evaluated the approach task of this investigation. Pilots (A) and (B) were from NASA and pilot (C) was from the National Aeronautical Establishment, Ottawa, Canada. Each had already acquired considerable experience in the test aircraft, and each was well acquainted with the technical and operational considerations of powered-lift STOL aircraft. In addition, the two NASA pilots had recent flight experience in two other STOL aircraft that employed different powered-lift concepts; they also had broad simulation exposure to a variety of STOL handling qualities. One of the NASA pilots (B) also had considerable experience in V/STOL aircraft and helicopters, as well as conventional aircraft; the other (A) had an exclusively conventional aircraft background prior to his STOL research. The experience of the third pilot (C) was primarily in conventional jet aircraft, light STOL aircraft, and helicopters (including extensively variable stability helicopters), although he had some experience in a V/STOL aircraft.

One of the more significant aspects of this experiment being the electronic cockpit displays, each pilot was able to be adequately familiar with the display features and their use from other programs being conducted on the research aircraft, or through use of the fixed-base laboratory simulation prior to flight evaluation. The same prior in-flight experience existed in the basic handling characteristics of the three STOL control concepts that were evaluated. In consequence, the work reported here benefits from rather extensive prior familiarity with essentially all of the constituent elements on the part of all the evaluation pilots.

To encourage a more consistent approach to the many pilot-related aspects of the approach task, a questionnaire was developed which presented those considerations thought relevant to the evaluation. The questionnaire, which was completed after each flight, was particularly useful in establishing consistent criteria for making pilot comments and assigning pilot ratings for each task segment. The constraint was imposed that a pilot rating be averaged over the number of approaches flown in a like control configuration during a particular flight.

This section summarizes the more significant pilot comments by segment, and presents the pilot ratings.

Level-Downwind Segment

The procedural requirements during the level-downwind segment consisted of selecting the deceleration schedule (a single button-pushing action determined by progress relative to way point 2) and subsequent initial flap deployment to the approach flap setting. For both requirements, copilot assistance was required to back up the appropriate selection of deceleration, often modified to a point in advance of reaching way point 2 if winds were moderate, and to monitor the slowly moving flaps (2°/sec) to the required settings since the available mechanical flap lever selection detents were not generally appropriate to the settings used. Despite the rather significant thrust vectoring associated with this initial flap deployment, the only apparent longitudinal control annoyance was a conventional nosedown trim requirement to prevent the ballooning that was associated with the very first few degrees of flap deployed at 120 knots.

The flight-director command bars were smooth and easy to follow in this segment, requiring little enough attention to allow adequate progress monitoring and wind display monitoring on the MFD in anticipation of deceleration and descent, and to monitor the flap settings. Display monitoring, cockpit procedure, and control management workload levels were generally light to moderate. There was no tendency for the changing functions of the pitch and throttle directors to confuse the pilot during this segment of increasingly blended multiloop control laws, nor were the relatively similar control frequencies of the pitch and throttle commands that were generated in response to any altitude or speed errors in any way difficult to control. Although there was some concern initially that inattention to one of the pitch or throttle director commands could lead to sustained and possibly confusing errors in altitude and speed (a potential problem area with multiloop control laws), no such situations were encountered during extensive simulation and flight trials of this concept.

Performance achieved during this segment generally met the pilot's objectives, the slight ballooning associated with initial flap deployment being of mild annoyance. Speed control was quite acceptable, the only major control input associated with following the decelerating reference that was obvious to the pilot being the initial throttle reduction required to slow from 140 to 120 knots. Thereafter, the deceleration profile to the initial approach airspeed was nicely tailored to that inherent in flap deployment, allowing nearly constant throttle while pitch was adjusted to maintain constant altitude.

Descent-Capture Segment

The philosophy adopted for glide-slope capture reflected well-established techniques for CTOL aircraft. Typically, some appropriate configuration change (undercarriage or flap lowering) is effected which results in the aircraft assuming the nominal glide slope with little or no change in throttle setting. The glide-slope capture maneuver is thus essentially a transition between trim states, and for steep approach angles involves a change in configuration drag which is approximately twice that for CTOL aircraft on more shallow approaches. In powered-lift STOL aircraft these large drag changes are usually accomplished through the mechanism of thrust vectoring. In the test aircraft used in this investigation this was realized by setting the nozzle angle from 6° to about 80°, relative to aircraft datum, while the throttle setting was maintained at about 93% rpm. Associated with this nozzle deployment is the requirement for an approximate 6° reduction in pitch angle (to about -4°) in order to establish the trim descent configuration at the desired airspeed. The greater magnitude of these trim configuration changes significantly affects control law design.

The flight director was programmed with open-loop control position commands during glide-slope capture that would result in the aircraft's assuming its descent trim condition appropriate to the initial approach configuration and the system-estimated initial aerodynamic flightpath angle. From its estimate of groundspeed, the flight director would anticipate intercepting the glide slope and would remain in this effectively open-loop glide-slope capture mode for about 15 sec or until appropriate convergence had been established on the descending path before transitioning to the glide-slope track mode. At glide-slope capture, the raw data tracking box would jump to the top of the EADI display to indicate transition to the upcoming descending segment, and the throttle director would revert from its closed-loop altitude-speed control laws, used during the level downwind segment, to a mode that commanded the descent trim rpm. After setting this value (typically little change was needed) the pilot had to manually deploy the nozzles to a position that would null the nozzle angle director, which appeared on the EADI at this time. Since the flight director frequently entered the glide-slope capture mode somewhat early due to erroneous groundspeed estimates (that were caused by TACAN DME errors affecting the navigation filters as the aircraft passed nearly overhead the station), the pilot often had to modify his timing of nozzle deployment in order to effect a better capture. He could base his decision on the rate of convergence on the EADI tracking box, which would begin to move from the top of the display toward the aircraft symbol; the procedure was similar to that used for instrument approaches without the aid of a flight director. Since a positive signal had to be provided to the flight director that nozzle deployment was indeed being effected (as described in a previous section on deceleration scheduling) the pilot first selected the Glideslope Manual button on his mode select panel prior to setting the required nozzle angle, an action which also allowed the speed reference to reduce by 5 knots. Finally, the pitch flight director was programmed with an appropriate direct crossfeed from nozzle angle to assist in coordinating the attitude change required with nozzle deployment from the attitude existing at capture entry to an appropriate descent trim value, typically -4°. In consequence, the entire glide-slope capture maneuver was essentially open loop, except that after practice the pilot could judge the best initiate time and rate of manual nozzle deployment to end up in the new trim condition on the proper descent path. However, if the pilot undertook any closed-loop control on his own, it was preferable to give priority to controlling the speed error, since the speed-control SAS modes, if used, could be engaged more smoothly. This was accomplished after setting the nozzles by selecting the Speed SAS switch on the pilot's mode select panel (fig. 14). Alternatively, if the speed-control SAS were to be used on descent in either its frontside or backside configurations, it could be "armed" in advance on the downwind leg (by selecting the Speed SAS switch) and the nozzles would automatically deploy when the pilot selected the Glideslope Manual button for descent. The nozzles would move to a setting of 70° at a fixed rate of 20°/sec where the speed-control loops would slowly close. This procedure closely resembled the usual case for CTOL aircraft where a single-action configuration change is effected to begin descent.

The pilots felt that these procedures were appropriate and comparable to techniques for CTOL aircraft. Since glide-slope capture coincided with a more or less major transition in control technique relative to that used on the level downwind segment, the discrete and basically open-loop nature of the event was considered appropriate. It was considered somewhat cumbersome to (1) set the throttle levers at the beginning of capture, (2) select Glideslope Manual, (3) set the nozzle levers, simultaneously pitching down to -4°, and finally, (4) return to the throttles as the glide-slope track mode was entered. An integrated propulsion system control lever incorporating control over both throttle and nozzle was recommended as a possible means of simplifying the procedure. The automatic nozzle deployment for the Speed SAS modes using the Glideslope Manual button was preferred. Additional cues that the director had indeed entered the capture mode were considered necessary, and could be easily incorporated by mode annunciation, using the EADI bezel lights (or other means), as shown in figure 16. (These annunciators were employed for this investigation only at way point 6, where the final straight segment was captured.) Finally, the approach profiles that were flown provided an altitude change of approximately 100 m (330 ft) in which to accomplish the initial descent, before entering the final turn. This was considered by the pilots to be the minimum acceptable when specifying the approach profile geometry in order to permit adequate stabilization in the descent configuration before commencing the turn.

Descending-Turn Segment

Partly as a consequence of the still relatively loose glidepath tracking requirements during the descending-turn segment of the approach, the major effort required of the pilot at this stage of the approach was toward ensuring good lateral performance. This required close concentration on the roll director bar to avoid delay in responding to the turn entry command, and thereafter, close attention had to be paid in order not to overlook small errors in the roll bar. The requirement to monitor approach progress on the MFD in order to call for the final flap setting also provided the possibility of some additional lead toward ensuring a good rollout. In this regard, the raw lateral position data available from the EADI tracking box and the data presented on the MFD in conjunction with the aircraft track prediction vector (fig. 15) were both useful and not mutually exclusive.

Two pilots commented on an occasional tendency toward a mild pilot-induced oscillation in roll appearing during this segment, reflecting the higher pilot gains on roll-flight-director error just discussed, and possibly contributed to by small nonlinearities in roll-control sensitivity. The net result of shortcomings in roll-director tracking, ambient winds, and also TACAN to MODILS navigation errors was generally to allow the aircraft to drift outside during the turn. However, the performance levels achieved were not considered to be unacceptable, mainly because any resulting localizer overshoot at turn rollout seldom exceeded 100 m (328 ft) and was well within the ±152-m (±500-ft) lateral dimensions of the EADI tracking box.

The consensus on longitudinal performance was that it was adequate at this stage of the approach, there never being any concern about the ability to achieve the more stringent performance requirements during final approach and at decision height. The realistically lesser constraints on vertical path performance up until turn rollout (the tracking box had dimensions ±15.3 m (±50 ft)) allowed concentration on other longitudinal requirements, namely selection of flap to the landing setting, dealing with the associated deceleration, and adjusting longitudinal trim with the auxiliary control as necessary in the changing relative winds. It was found that the copilot occasionally had to provide a reminder that the approach progress was such that final flap should be deployed in the latter half of the turn. In most circumstances, the effects of this final deceleration were scarcely noticeable. However, on a few occasions when an associated downside path correction compounded the effect, the pilot became aware of a temporarily lower power setting and associated higher angle-of-attack situation for the basic aircraft mode. Similarly, although the automatic nozzles were generally adequately removed from their full down limits during deceleration, they could sometimes be forced onto the stop if correcting down to path while also decelerating in either of the speed-control SAS modes.

The dynamics of the longitudinal flight director were thought to be fairly reasonable during this segment, the throttle and pitch bars having suitable gains. The speed-error thermometer scale could be easily interpreted against either a fixed or reducing speed reference, which, were there any doubt as to its current value, could be quickly obtained from a glance at the reference speed annuniator window on the mode select panel. After practice, however, it was a simple matter to cross-check the displayed speed error against the digital airspeed presentation immediately above. Although the digital format is deficient in effectively displaying rates of change to the pilot, the analog pointer against the thermometer scale was effective, if observed, in presenting gust information, shear information, or maneuver rate errors.

Despite the widely accepted need for the nozzle director function for trim management in the basic aircraft mode, the display format that used the central digital EADI window was considered unsatisfactory for both its digital and compensatory features. The pilot usually had to make several small reversals with the quite awkward nozzle levers (located on the overhead console) in order to confirm the direction of the correction being requested, and then to find the correct setting. This problem was compounded by approximately 5° of hysteresis which existed in the aircraft nozzle-control mechanism. In addition, changes in the digitally displayed error from trim were not compelling enough to attract attention to a developing error, which frequently had to be pointed out by the copilot. In contrast, the assignment of this display element to averaged engine rpm for both the backside and frontside SAS modes was of relatively little utility. For these control modes, the pilot was able to observe and respond to small changes in commanded pitch angle or throttle setting, respectively, as flaps moved from the approach setting to the landing setting. Small changes caused by wind effects were less obvious, but were apparently effective in maintaining satisfactory trim conditions during the descending turn.

Combined workload levels during this segment were considered light to moderate; the trim adjustments required and the deceleration characteristics were considered acceptable for the atmospheric conditions of the tests. Despite the possibility, advanced by one pilot, that provided flight director errors were kept small, the turning approach might be acceptable without the availability of the MFD, using instead a conventional horizontal situation indicator (HSI), it is not considered that this flight investigation was structured to assess this possibility. Typically used in the heading-up orientation mode at maximum sensitivity, the MFD was found to furnish readily interpretable situation information throughout the approach, especially during the turn. Approach progress relative to deceleration-configuration change way points, descent, and turn entry-exit way points was quickly available with minimum effort. Although the HSI was programmed with distance and bearing to next way point and the track bar provided across-track deviation data relative to a piecewise rectilinear path, this display was seldom referenced; thus, the comparable information would have been more difficult to obtain. None of the pilots found the necessity to use the HSI at all during the approach, even for heading information which was adequately available as an error from desired track from the pictorial MFD presentation. However, a more precise measure of heading was frequently obtained when approaching decision height from the heading display on the HSI, in order to better anticipate the maneuver and decrab requirements during the landing transition. This information could alternatively be indirectly obtained on the EADI from the orientation of the perspective runway display, if used. Consideration to directly presenting heading on the EADI was also suggested.

Final Approach to Breakout

Having achieved the final stabilized landing speed and flap configuration by turn rollout, the pilot was left with the task of meeting the increased performance objectives established for the assigned decision height. Both the flight-director path-tracking gains and the displayed sensitivity of the raw-data tracking box were increased in this segment as previously described. The associated increase in the pilot's flight-director tracking gains revealed some oscillatory glidepath control tendencies in all three STOL control concepts evaluated; these tendencies were experienced to varying degrees by all pilots. Most significant was the tendency to overcontrol the throttle input in response to the flight-director throttle-command bar for the basic aircraft and backside SAS modes of operation. The pilots generally found themselves using some lead compensation in order to suppress or reduce this difficulty, contributing to what was assessed as a moderate to high workload during this segment. The same characteristics, but of lesser degree, were noted for the control law gains employed in the work reported in reference 11. That effort assessed the utility of a flight director for improving the straight-in instrument approach task in comparable aircraft configurations, and employed a constant EADI tracking box sensitivity of ±15 m (50 ft). Although this alternative configuration (which was evaluated by the same pilots) exhibited reduced oscillatory tendencies, no glidepath-tracking or decision-height performance data are reported in reference 11; thus, the two systems cannot be fully compared. In addition, some tests were carried out using different tracking box sensitivities which suggested that the pilot's tracking dynamics could be influenced by his perception of performance; the higher box sensitivities were often associated with more oscillatory behavior without any change in director law gains. A more detailed study of the flight-director control laws that led to significant improvements is reported in the appendix.

The corresponding tendency to overcontrol in pitch for the frontside SAS mode was experienced more by pilot A than the other two pilots. In this mode, the director gains were essentially the same as those also used in reference 11, except for the same difference in the sensitivity of the EADI tracking box mentioned earlier. It was generally felt that this control mode yielded a less crisp response for the small precise glidepath corrections which were often desired as the vertical dimensions of the path-tracking box reduced to ±3.66 m (±12 ft), at least for the amount and rate of pitch-control input used. All pilots indicated their greater restraint in using aggressive pitch control inputs to accomplish the glidepath control corrections that might, under some circumstances, be commanded by the flight director. In this regard, the physically different nature of throttle and pitch-control inputs should be kept in mind. In the latter case, the glidepath response is achieved through exercising the pitch dynamics, a mechanism of which the pilots (and passengers) are strongly aware through visual and motion cues. In the former case, however, the pilot is able to achieve the desired glidepath change through mechanisms from which he is usually much more detached: throttle position changes, engine dynamics, and aerodynamic circulation effects. In consequence, the pilot is inclined to make throttle-control inputs that are more aggressive and steplike than is the case for pitch; this is evidenced by the time-history control input data of figures 38 and 63. Of course, the pitch dynamics do not permit step inputs in any event, hence contributing to the pilot's notion of apparently slower response relative to his relatively unconstrained throttle inputs. Even with the augmentation of heave response to pitch that was incorporated, all pilots felt that pitch-control activity could become objectionable in more demanding flight conditions, such as moderate or severe turbulence. The glidepath tracking-control laws that were developed subsequent to these flight trials addressed the need for rationally constrained but still effective pitch-control commands, also suppressing any oscillatory characteristics. These details are reported in the appendix. These difficulties with glidepath control laws notwithstanding, the pilots generally reported that the glidepath tracking performance that was achieved met their objectives, despite occasional excursions beyond the displayed limits of the EADI tracking window.

Speed-control considerations varied according to the control concept being evaluated. One pilot (C) felt that the adverse power-speed coupling manifested in the basic aircraft mode by the requirement to pitch down when adding power was significantly less objectionable when the pilot was induced to do so by the flight director, than was the case when flying the basic aircraft visually or on instruments without the flight director when this unnatural coordination needs to be consciously remembered. Another pilot (A) considered both situations equally objectionable, admitting, however, to improved speed control with the flight director. The speed-control SAS modes generally provided good control. There were no particular considerations regarding authority limits for the backside SAS mode. However, nozzle authority limiting at 45° or 105° could be induced for large path corrections made in the frontside SAS mode. Since the pilot was not directly monitoring SAS nozzle position, this saturation generally became apparent by an associated temporary speed error visible at the speed-error thermometer display and degraded glidepath control characteristics. It was felt that some better means should be incorporated to indicate this occurrence to the pilot, as well as suggesting to him a course of action that could alleviate the problem. For example, it might be desirable to program a recognizable change in the mode of the throttle director bar from its normal trim function to a path-control augmentation function. This would have the effect of temporarily assisting the glidepath change being sought, thus unloading the speed-control SAS.

The trim management aspect of the flight director was well accepted by all the pilots during this segment where its importance was primarily associated with maintaining adequate safety margins on the approach and with ensuring adequate "flareability" for the impending landing maneuver. Without the flight director, the pilot is generally inclined to carry out a more lengthy straight-in approach from an altitude of at least 300 m (1000 ft) in order to establish an appropriate trim approach configuration, even in visual flight conditions. The significant improvement in capability realized here stems from the combination of relatively tighter speed and glidepath control, and the suitability of the director-induced setting of the auxiliary control used for trim. Only for the case of the basic aircraft mode was the additional action required of the pilot in setting this control (nozzle angle) of any consequence. For the atmospheric conditions encountered, this infrequent requirement to reposition the nozzles was considered acceptable by the pilots. The reality of the situation was that the relatively short final approach segments tested did not allow the pilot time to be burdened with the significant mental workload otherwise associated with trim strategy. He was virtually committed to accepting or rejecting the situation existing, and, in all cases, this turned out to be within acceptable limits. Partly because of these trim considerations, it was generally agreed that 122 m (400 ft) above decision height constituted the lowest acceptable rollout altitude for these tests, and that rolling out at 183 m (600 ft) above decision height provided a noticeably more comfortable opportunity to establish stabilized conditions by decision height. Use of a precision terminal-area navigation device having wider coverage might allow a somewhat lower rollout altitude since the trajectory could be stabilized sooner than in the present case, where some trajectory perturbations still remained from the TACAN to MODILS navigation transition even after rolling out on the final straight segment.

The oscillatory tracking difficulties mentioned earlier for the longitudinal flight director were much less significant in the lateral channel. Despite an occasional tendency to excite a small short-lived control oscillation in roll (described in the previous subsection), it was agreed that the lateral-directional characteristics of the aircraft had no significant bearing on the approach and landing task. The lateral performance that was achieved easily met the pilot's objectives, although this judgment was to some extent intentionally preconditioned by what may be a less-than-required flight-director control law gain and insufficient tracking-box lateral sensitivity for operations to a 30.5-m (100-ft) wide STOL runway.

Some comments on the EADI display symbology and format indicated that there was a tendency for the raster-generated display elements, such as the tracking window, to overlay the director symbols, thus reducing the pilot's awareness of small errors. On the other hand, the stroke-generated elements, particularly the perspective runway display, had adequate definition and brightness to preclude any confusion among frequently coincident symbols. The pilot who evaluated the perspective runway display commented on its utility for (1) anticipating turn rollout as it moved in smoothly from the left edge of the display, (2) reinforcing his perception of drift angle or heading errors on final, and (3) increasing his awareness of the approaching decision height. One pilot commented that the flight director null reference was insufficiently defined to allow precise centering of the director bars. All pilots thought they would have felt more comfortable with the throttle director bar located to the right of the display in closer analog with the actual throttle position in the cockpit – perhaps removed from behind the wing of the aircraft symbol. No adverse comments were received about the three-cue nature of the director, nor was the fourth cue, that is, the nozzle director in the case of the basic aircraft mode, criticized for other than its previously mentioned display format deficiencies.

Decision Height, Breakout, and Landing Transition

Some of the issues associated with the longitudinal flight conditions that prevailed when decision height was being approached were discussed in conjunction with the data presentation in a previous section. Pilots B and C particularly expressed concern over the direction of the longitudinal velocity vector at breakout, resulting in the need for their occasional compensation of the flight-director commands just prior to reaching decision height, generally in the altitude interval of 61 to 30.5 m (200 to 100 ft). Pilot B was able to use the perspective runway display element in conjunction with the inertially referenced flightpath angle bar; pilot C did not evaluate this display feature; instead, he made his own estimates about desirable flightpath angles for the existing path errors. Emphasizing the importance of this consideration, the nature of the blind flying hood used required the pilot to temporarily remove his hands from the overhead throttles in order to raise the hood, which even in the frontside SAS mode resulted in essentially no control for the first second or so following breakout. This might be considered in a rudimentary way to simulate a visual transition delay in more realistic visibility conditions.

Pilots B and C expressed reluctance at reducing throttle in either the basic aircraft or backside SAS modes just prior to or just following decision height, for fear of generating excessive sink rates. It was more acceptable to pitch over in order to correct downward, if necessary in order to make the touchdown zone, and this of course was better suited to the frontside SAS control mode. Pilot A was more consistent in being able to pass through decision height with nearly nominal conditions, which was also reflected in more consistent touchdown performance. He felt that 30.5 m (100 ft) was a comfortable decision height for this simulated instrument approach task. All pilots stated that their confidence in the aircraft trim state at decision height was such that full concentration could be placed on the maneuvering requirements for landing, without need to reference parameters in the cockpit or to regain safety margins while also maneuvering to land. Such might not be the case in the presence of adverse atmospheric disturbances, however.

The lateral "S" turn requirement during the landing maneuver was thought effective in making the landing transition task more realistic. Although the pilot knew that some lateral maneuvering would be required at breakout, the extent of the correction required was often somewhat of a surprise, even if it was generally in the same direction. A significant number of approaches required moderate lateral maneuvering efforts from the pilot in order to achieve the touchdown zone.

Pilots B and C, who experienced more varied dispersions at decision height than did pilot A, considered the 30.5-m (100-ft) decision height to be too low for operational use for the nominal sink rates characteristic of this experiment. The 7° approach angle, in combination with the approach speeds used, resulted in typically 8 sec in which to accomplish the landing transition; this was considered too short a time under realistic circumstances, given the relatively large variations in flightpath angle which might be expected before and after breakout. These reservations regarding decision height are primarily related to kinematics and may well be alleviated through improvements in flight-director guidance laws and cockpit display features (see appendix). On the other hand, it was felt that the aircraft handling qualities that were represented by the three STOL control concepts which were evaluated were satisfactory to deal with conditions encountered at these low decision heights, a finding consistent with the research of reference 11. A thorough study of decision heights appropriate for powered-lift STOL aircraft requires more detailed consideration of these and other factors.

Landing performance did not always meet with the pilot's approval. The qualification most frequently given was insufficient recent practice with the significantly different flare techniques required for each of the three STOL control concepts evaluated.

Pilot Opinion Ratings

Numerical pilot ratings, determined in accordance with the standard scale shown in figure 54, were assigned to each segment. The results are shown in figure 55; they represent the range of ratings assigned by all pilots on all evaluation flights for the three different STOL concepts evaluated. To complete the data, the single control configuration, which was evaluated during the initial deceleration segment while downwind, received consistent ratings between 2.5 and 3.5, primarily determined by the less than optimum lateral performance arising from navigation deficiencies in this region.

These data require interpretation in the context of the atmospheric conditions of the tests, the limitations of the simulated instrument environment, the choice of reference approach angle, and the navigation and runway environment employed. It is noteworthy that the approaches flown during days of moderate winds which employed landing flap settings of 50° in combination with higher approach airspeeds did not receive any particular comment nor change in rating from the pilots, lending potential to the possible use of this procedure to minimize pilot workload and fuel and airspace requirements.[2] Further, it should be emphasized that the comprehensive nature of the evaluation task presented many aspects for consideration in arriving at a pilot rating, ranging across navigation, guidance, control, display, and procedural factors. In consequence, no significant differences show up in the ratings segregated according to different control concepts.

For purposes of comparison with a more widely recognized terminal approach task, the pilots considered the task of this experiment to be more acceptable (assuming resolution of the throttle director oscillation problem in the final straight segment) than a conventional straight-in ILS task flown on raw data, without a flight director, in a CTOL aircraft at jet approach speeds. It was recognized, however, that the decelerating curved approach task was more prolonged in terms of precision performance requirements in the initial stages of the approach than the conventional situation. The conventional ILS approach involves much less constrained terminal-area maneuvers, often under radar vectors, and involves aircraft configuration changes which are normally accomplished well in advance of reaching decision height. On the other hand, the STOL task evaluated here was considered more demanding than the conventional CTOL task when performed with the aid of a flight director, although

[2] Subsequent to this main investigation, each pilot was able to better evaluate the potential of this procedure during straight-in approaches flown in strong quartering headwinds of 25-35 knots. Both the basic aircraft and the frontside speed-control SAS configurations were flown on 7° approaches, using landing-flap angles ranging between 30° and 65°. The associated airspeeds were as tabulated in figure 27. All pilots preferred the higher approach airspeeds for their more nominal sink rates and reduced durations of precision tracking, as well as the reduced decrab requirements for landing. Although the control blending gains used in the basic aircraft flight director were not well tailored for the 30° flap configuration, all other characteristics of the flight director, including the programmed trim settings, appeared satisfactory. As expected, the control activity requirements at the higher airspeeds were noticeably reduced. Although it was agreed that this would be a useful feature during straight-in or dogleg approaches in very strong winds, its feasibility during 180° turning descending approaches may become limited by the descent capability of the aircraft and the higher bank angles involved during the initial portion of the turn.

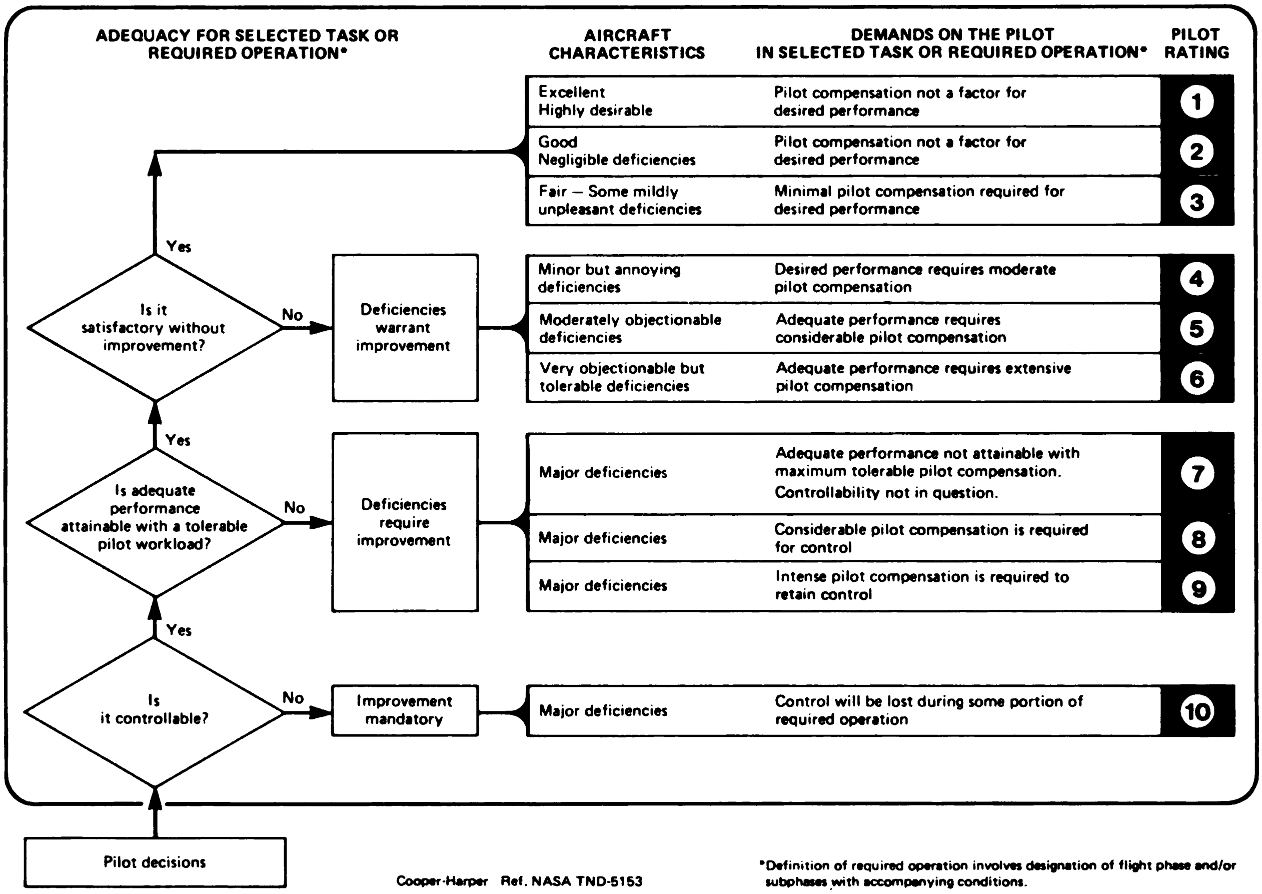


Figure 54.– Handling qualities rating scale.

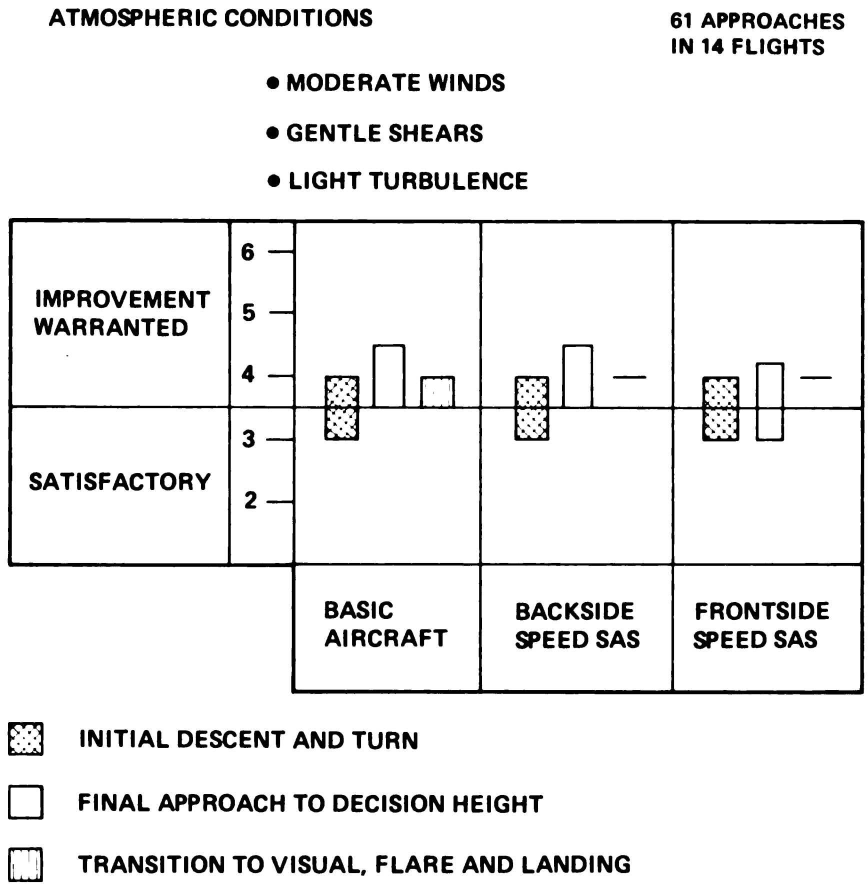


Figure 55. – Range of pilot ratings assigned to three segments of the decelerating curved approach task.

the added workload did not manifest itself in proportion to the number of additional director commands to be tracked.

Of greater significance was the totally new capability, provided chiefly by the area navigation system and the flight director, to perform with repeatable precision such tight, turning, and decelerating approaches to the STOLport. Although the body of experience in operating this aircraft is extensive (represented by more than 2000 STOL approaches), this capability surpasses that which has previously been possible even in visual flight conditions. This superior performance is a measure of the improvement in mission capability that can be achieved. The single control-related feature contributing most to this capability is the trim management function of the flight director, relieving the pilot of the otherwise burdensome task of assessing and determining lift-drag trim strategy. The most significant navigation feature providing the tight turning approach capability is the indication of the appropriate point at which to begin descent, made possible by the three-dimensional curvilinear R-NAV system which was available.

VII. CONCLUDING REMARKS

Summary of Results

A flight director concept, which provides a potentially feasible means for carrying out manually flown decelerating curved approaches in a powered-lift STOL aircraft, has been developed and evaluated. The flight tests were carried out in a realistic navigation environment, and included various STOL control concepts. Although the handling qualities of powered-lift STOL aircraft have been separately studied in previous research, the objective of this work was to consider these characteristics in the context of an operationally relevant and demanding terminal-area curved descending approach task, such as may be required if these aircraft are to realize their full potential.

Data have been presented describing net outer-loop performance achieved, inner-loop pilot tracking performance measures, and associated control utilization characteristics for the conditions encountered during these tests. The initial data base provided by this work should be expanded to include flight in more significant levels of atmospheric turbulence and wind shears, and in the presence of failures in various systems during approach. At the same time, rectification of deficiencies in the system evaluated here and reviewed later in this section should result in improved performance measures.

Notwithstanding these limitations, the following conclusions are drawn.

1. Curved decelerating approaches with moderately low rollout altitudes to final approach do appear to be feasible for instrument flight operations in powered-lift STOL aircraft from a pilot acceptance point of view, when provided with an appropriate flight director.

2. Incorporation of a capability such as the one demonstrated can, in addition, lead to more efficient terminal-area operations in visual flight conditions by providing guidance for curved descent paths and configuration trim management.

3. Differences in pilot acceptance, workload, and performance are not widely separated for the various STOL control concepts evaluated, at least in the atmospheric conditions of light turbulence and weak shears which were encountered by the three evaluation pilots who participated in this investigation.

4. The characteristics of the navigation environment, particularly the precision with which the terminal-area R-NAV profile can be located, and the volume of coverage of the MLS facility, will be important factors influencing the approach profiles that may be authorized.

5. It was found important to incorporate an automatically computed trim position for the third auxiliary control, primarily to relieve the mental workload associated with evaluating and determining satisfactory longitudinal lift-drag trim states. While the flight director performed the necessary computation, the pilot had merely to occasionally reposition the auxiliary control in response to a displayed command, and to monitor the trim state that resulted.

6. Changing the pilot's control technique from frontside to backside, accomplished by blending in a multiloop flight director, did not constitute a difficulty for the pilots.

7. The equivalent of Category II decision heights and performance criteria for manual powered-lift STOL operations may differ from those now employed for CTOL aircraft. However, developments in director control law concepts and the use of new electronic cockpit displays should permit this class of aircraft to achieve similar performance criteria as currently demonstrated with CTOL aircraft. The handling qualities of the three STOL control concepts that were evaluated were not considered limiting in potentially achieving low decision heights.

Recommendations for Improvement

Deficiencies in the system employed here became evident during the course of the evaluations; however, it was not considered that they compromised the main conclusions of the investigation. The major areas requiring improvement are reviewed here.

Navigation– It is significant that discontinuities and inaccuracies in the navigation environment did not prove limiting during these tests from a pilot acceptance point of view, once sufficient development had been carried out. Yet, more accurate navigation during the initial stages of the approach in the region requiring reliance on enroute nonprecision navaids (VORTAC) is likely to be required from airspace control considerations. An important area for improvement, however, and one peculiar to the system used here, is the lateral resolution and sensitivity employed during the final straight segment. A separate high-resolution (about twice that used here) localizer track filter, utilizing some combination of higher-gain guidance laws and greater sensitivity in the lateral tracking box dimensions, is warranted. Although the lower values employed here usefully served to induce a lateral maneuvering task at breakout, a preferable technique would have been to incorporate appropriate random biases in the electronic centerline, thus providing the same lateral offsets in a more controlled fashion. Use of a microwave landing system having the higher resolution azimuth characteristics shown in Table 1 would also improve lateral performance.

A secondary deficiency in the navigation system was its inability in the TACAN region to provide adequate groundspeed and wind estimates while on the downwind leg in the presence of rapidly changing bearing and range geometries. Although this particular problem is unique to the navigation environment used for the tests, it highlights the general need for accurate groundspeed (and wind) measurements in order to support constrained terminal-area approaches by low-speed aircraft.

Flight director control laws– Further development of the flight-director control laws for the STOL configuration is required in order to suppress the oscillatory tendencies noted, particularly in the throttle mode. Some improvement can be realized by gain adjustments and changes to the vertical sensitivity of the tracking box as was demonstrated in reference 11, but a requirement was also identified for a more rationally scheduled control law that constrains corrections in flightpath angle appropriate to both the existing path error and the proximity of the aircraft to decision height. These latter comments apply particularly to guidance laws for glidepath control; however, the same requirements exist, though less severely, for lateral guidance. An alternative glidepath control law that meets these requirements was developed subsequent to this investigation and was evaluated briefly in flight. The details are reported in the appendix.

Display and control– Although the basic display format and symbology received little criticism during the tests, the deficiency of the central digital window in adequately displaying errors in nozzle position from computed trim was noted. The implication is that a fourth director cue for trim control positioning may be quite acceptable, if properly implemented. With developments in colored electronic displays proceeding as rapidly as they are, it would seem that satisfactory presentation of the display features necessary for this type of operation will be possible at reasonable cost.

An associated area of criticism was the particular layout of thrust (throttle) and thrust-vector (nozzle) control levers, and suggests the importance of judicious design in the pilot's propulsion system management controls. The manipulation of these two controls did not prove unacceptable in the conditions of these tests (for the basic aircraft mode where it was required), but it was felt that more appropriately designed propulsion system controls, perhaps integrating both functions at the same control handle, would warrant consideration.

Deceleration optimization– In this investigation the pilot actions necessary to accomplish deceleration had to be initiated by the pilot in compliance with a standard procedure suggested on his approach profile chart. Since the copilot occasionally had to remind the pilot of the need for a further configuration change, it might be desirable to incorporate a prominently located alphameric display to annunciate the currently appropriate aircraft configuration. This philosophy would be in the direction of wholly computer-stored approach and landing procedures. In reality, however, the locations of these configuration change way points were often modified by the pilot as a result of his own perception of ambient wind effects (and sometimes other factors reflecting how conservatively he might wish to carry out the approach). More effectively, if an adequately reliable estimate of the wind profile during approach were somehow provided to the system, then the location of the nominal points for configuration change actions could instead be computed, resulting in more rational energy management along the approach profile. This could lead to improved efficiencies in fuel consumption as well as reduced potential for control problems arising from inadequate anticipation of wind effects by the pilot.

Approach profile variations– Although prestored R-NAV profiles were employed in this flight experiment, use could be made of some procedure to optimally synthesize approach profiles from any point in the terminal area, such as the one proposed in reference 6. Similar guidelines to those evolved here governing the pilot's use of controls, and definition of an acceptable approach procedure, would have to be established in order to limit the range of acceptable approach trajectories. The results of this investigation could be applied directly to this more flexible situation to the extent that the fixed paths flown here lie within the range of acceptable synthesized trajectories.

Application to Other Aircraft

The two major issues involved in curved-decelerating STOL approach profiles, such as were investigated in this work, are navigation and control. The results of this work have suggested that given acceptable navigation, the control considerations associated with the particular powered-lift aircraft configurations used for these tests show potential for operational acceptance on the profiles tested. These control considerations were presented in an introductory section as being common to all powered-lift concepts (including V/STOL aircraft) in varying degrees, and are most significantly manifested by the trim management problems associated with the redundant control peculiarities. However, the particular means of dealing with these requirements are strongly configuration-dependent. Similarly, the importance of appropriately scheduling the changeover in control effectiveness during conversion to powered-lift, and of tailoring the deceleration schedule in accordance with inherent lift, drag, and thrust changes, also require specific configuration-dependent design. Nevertheless, some of the major control considerations likely to be of general concern to the pilot for this kind of operation have been identified. At the other end of the scale, it is considered that operations on these approach profiles with low-wing-loading STOL aircraft, or RTOL aircraft, present substantially fewer control considerations, and mainly require an adequate navigation, profile computation, control authority, and cockpit display environment for their operational implementation.

Ames Research Center
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Moffett Field, California 94035, July 29, 1980

DESIGN AND EVALUATION OF ALTERNATIVE FLIGHT-DIRECTOR CONTROL LAWS

Introduction and Review of Deficiencies

Although the flight-director laws which were employed for the work reported in the body of this report provided the guidance required for the investigation, they were empirically developed in a fixed-base piloted simulation without reference to any analytical design procedure, such as the one proposed in reference 19. Although certain objectionable deficiencies were exhibited by the control laws, these deficiencies were tolerated to the extent that they were considered not to significantly compromise the major objectives of the flight investigation. These objectives were oriented toward systems integration and operational feasibility considerations in the real flight environment, rather than addressing specific design requirements for the many subsystems involved. Nevertheless, an effort to improve the control laws and to rectify some of the deficiencies exhibited by the glidepath tracking control laws in the STOL approach configuration was undertaken subsequent to the flight-test program; these alternative control laws along with some limited flight evaluation data are reported here.

The oscillatory nature of the flight director-pilot-aircraft closed-loop glidepath tracking system was illustrated in figure 38, and pilot comments on this objectionable feature have been discussed in the main body of this report. A more severe example of this problem as experienced by pilot A is shown in figure 56. This characteristic was particularly apparent in the basic aircraft and backside speed-control SAS configurations, where throttle is used to control glidepath (the backside control technique). This problem can arise when the pilot is required to provide excessive compensation, usually in the form of lead generation or to adjust his gain precisely, in order to rectify dynamic deficiencies in the controlled element – in this case the throttle flight-director bar.

An additional deficiency in the glidepath control laws was the absence of suitable gain scheduling with height, in effect requiring the same performance at all altitudes during approach. (The control laws were based on linear, not angular, deviations from the desired glide slope.) This implementation may be appropriate from the point of view of providing time-invariant gains and dynamics for the closed-loop tracking system, a design approach particularly suited to an automatic pilot. However, the suitability of this design approach for manual flight control can be seriously questioned since there is ample

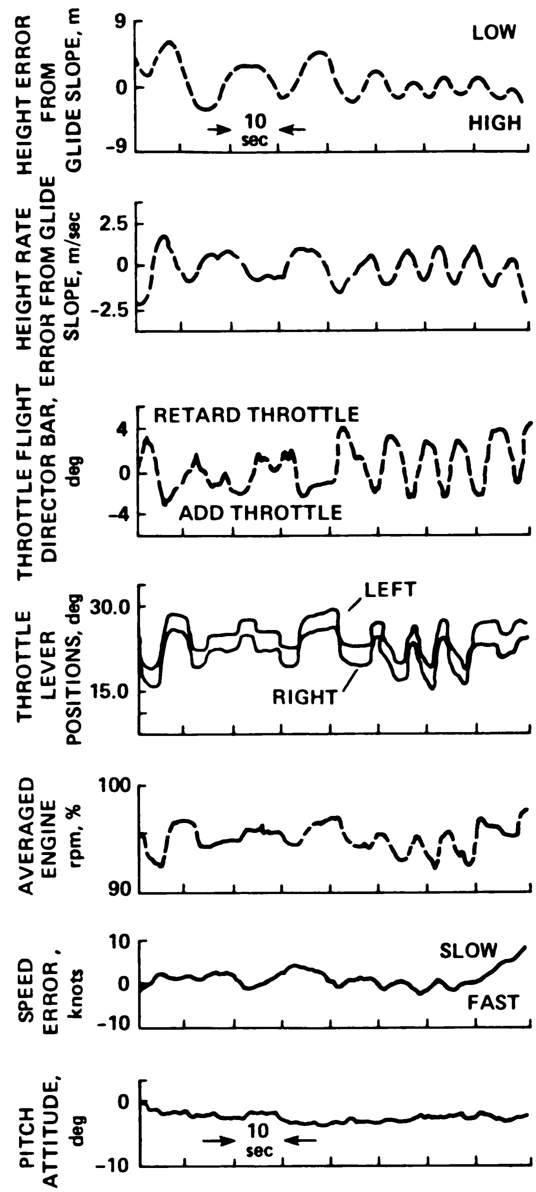


Figure 56.– Glidepath tracking characteristics, basic aircraft configuration. Throttle control laws of main investigation – Pilot A.

evidence to suggest that the human pilot performs very well using a scheduled control law, at least to the extent that the effects of changing gains are not great. In the first place, the pilot routinely carries out visual approaches, even to precision landings, that are essentially based on his perception of angular (not linear) error from the desired glide slope. Secondly, conventional instrument approaches, both with and without flight director assistance, have been conducted routinely for many years using the same (but more precise) angular deviation information obtained from the instrument landing system. Although the linearly increasing sensitivity of angular error to linear displacement, as touchdown is approached, inevitably requires some gain compensation, this problem appears to become significant only at very low altitudes, as reflected by the incorporation of "beam softening" in CTOL Category II flight directors in the region 60 to 30 m (200 to 100 ft). Despite the fact that these glidepath control laws, based on perceived or measured angular deviation from the desired glidepath, may reflect the particular capabilities of their respective sensors, a useful and significant result of this design approach is to rationally schedule glidepath performance toward the standards required at decision height, hence avoiding unnecessarily high pilot workload during early stages of the approach.

In the work reported in the body of this report, a limited amount of gain scheduling was incorporated (see figs. 22 and 23, and table 3) in an attempt to alleviate the initial glidepath performance requirements and to obtain improved performance at lower altitudes. However, this scheduling was not based on angular glidepath deviations and was proved to be ineffective, in fact, contributing to the oscillatory tracking characteristics noted earlier. Also lacking with these control laws was any ability to constrain corrections to the glide slope as decision height was approached, in order to prevent excessively shallow or excessively steep flightpath angles at breakout. This was identified by the pilots as an important consideration which sometimes resulted in their altering their response to the flight-director control laws in this region in order to prevent such undesirable conditions.

The data and results reported in the body of this report were obtained using flight-director control laws with the deficiencies just reviewed. A subsequent brief effort to develop improved control laws is reported in this appendix. The engineering basis for the control law is first described, followed by a rationalization of the design with modern manual control theory. Limited flight-test results are reported along with pilot comments on the effectiveness and suitability of the control laws.

Description of Alternative Control Laws

A new glidepath tracking control law was developed that emphasized angular rather than linear deviations from the desired glide slope, thereby embodying inherent gain scheduling with range or altitude to the electronic glidepath intercept point. As will be described, gain compensation is included that prevents excessive sensitivity at low altitudes while also serving to constrain angular corrections near decision height to practically desirable values.

The control law commands a corrective flightpath angle γ_{cmd} such that

$$\gamma_{cmd} - \gamma = 0 \tag{A1}$$

where γ is the instantaneous inertial descent angle of the aircraft and

$$\gamma_{cmd} = \gamma_o - K_{\Delta_\gamma} \cdot (\gamma_o - \beta) \tag{A2}$$

In this expression, γ_o is the desired nominal glide-slope angle, $-7°$ for this investigation, and β is the depression angle (negative) of the electronic glide-slope intercept point below the horizon, as measured by the MLS glide-slope receiver. (This particular mechanization does not lend itself directly to use during the descending curved segment of the approach profile.) A control law gain, K_{Δ_γ}, of 3.6 deg/deg was chosen, so that, for example, an error of 1° below the glide slope is corrected by a flightpath angle which is initially 3.6° more shallow than the nominal path. This control law represents the exponential correction of a glide-slope error of $(\gamma_o - \beta)$ degrees within a parametric distance which is $1/K_{\Delta_\gamma}$ of the remaining distance to touchdown. A limit of ±4° is placed on the corrective flightpath angle relative to the nominal path, $K_{\Delta_\gamma}(\gamma_o - \beta)$, to maintain flightpath angle and associated control input excursions within acceptable bounds, and to reflect the probable minimum requirements for satisfactory control in rough air conditions that are proposed in reference 4.

To reduce the rapidly increasing sensitivity of angular path deviation per unit of linear path error which occurs at low altitudes, and to constrain the amount of commanded path correction nearing decision height, the control law gain $K_{\Delta\gamma}$ was scheduled with computed slant range to touchdown in the following manner:

$$
\begin{array}{lll}
R > R_1 & K_{\Delta\gamma} = 3.6 & \\
R_1 > R > R_2 & K_{\Delta\gamma} = (3.6) \cdot (R/R_1) & \text{(A3)} \\
R_2 > R & K_{\Delta\gamma} = 1.0 &
\end{array}
$$

At ranges less than R_2, the control law gain of 1.0 commands corrections that will direct the longitudinal velocity vector γ toward the electronic glideslope intercept point, hence recognizing the changing glidepath control objectives when approaching decision height that were reflected in the body of this report. In the limited evaluation of these control laws contained in this appendix, R_2 was chosen as the range corresponding to the decision height of 30.5 m (100 ft) with the result that gain reduction on $K_{\Delta\gamma}$ begins at an altitude of 110 m (360 ft). This gain scheduling results in a stationary control law at ranges beginning at R_1 to the range corresponding to decision height.

The control law just described pertains only to the outer loop glidepath tracking requirement and is equally applicable to the frontside or backside glidepath control techniques that were evaluated in the main body of this report. Since the problems with the original control laws were more pronounced for the backside technique, using throttle to control glide slope, it is this application which is emphasized here. Application of these control laws to the frontside control technique which uses pitch attitude for glidepath control is described in a following section.

Incorporation of the basic glidepath control law (A1) into the throttle flight director involves feeding back an inner control loop consisting of washed-out throttle position, as shown in figure 57.

$$\delta_{TFD} = K_\gamma \cdot (\gamma_{cmd} - \gamma) - \frac{K_{\delta_T} s \delta_T}{s + (1/T_{WO})} \qquad \text{(A4)}$$

where K_γ and K_{δ_T} are display sensitivity gains per degree of flightpath angle error and per unit of throttle displacement, respectively. The control law calculates for the pilot the amount of throttle input necessary to null any error from the commanded flightpath angle. The long-term throttle control effectiveness for glidepath angle changes (modified to account for the effect of winds) determines the ratio of display gains K_{δ_T}/K_γ, while the washout time constant T_{WO} reflects the aircraft time constant for glidepath response to throttle, as modified by the engine response characteristics. Any control law error, presented as a flight-director command, can be immediately nulled with a throttle position input scaled in terms of the desired inertial flightpath angle change. This initial control input washes out to be replaced in a complementary way

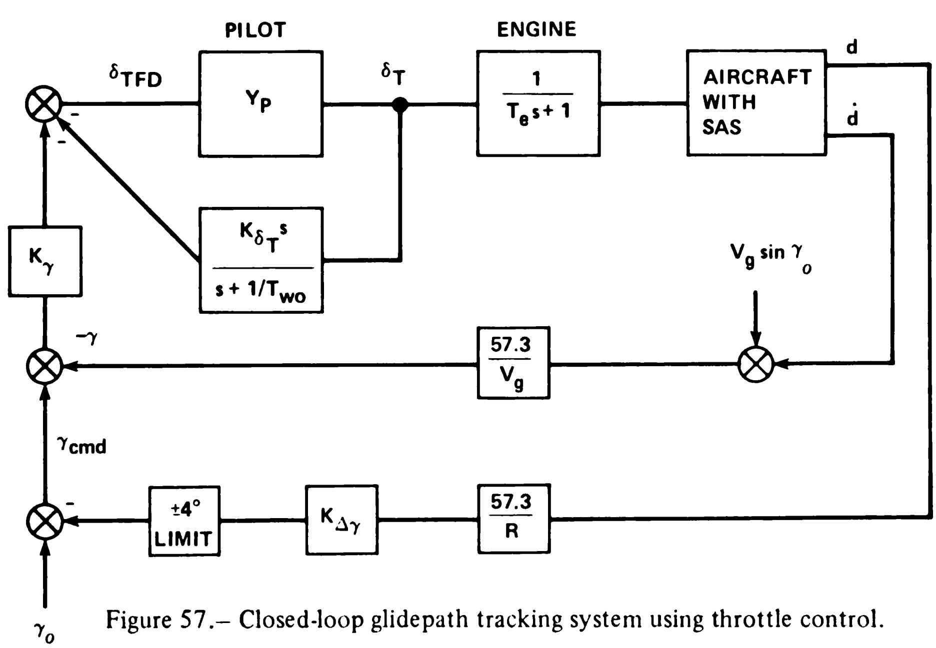


Figure 57.– Closed-loop glidepath tracking system using throttle control.

with the developing flightpath response. This control law was implemented directly as shown in equation (A4), after modifying the vertical complementary filter to a third-order mechanization, thereby eliminating the effects of any bias in the normal accelerometer on the inertial flightpath angle used for feedback. Use of the inertially referenced flightpath angle, requiring a relatively accurate measurement of groundspeed, ensures proper accounting for wind effects. Corrections were also employed to account for the conical nature of the MLS elevation signal, the origin of which was offset from the runway centerline, hence ensuring consistency in all parameters at low altitudes.

Analysis of Throttle Flight Director Dynamics

The engineering approach to the throttle flight-director control laws just described results in nearly constant gain dynamics for the controlled element δ_{TFD}/δ_T in the frequency range of pilot control. This reflected the preference expressed by the pilots for immediate nulling of any displayed error by a consistent and predictable amount of throttle lever input, frequently accomplished in a step-like manner. After nulling an error, attention could be temporarily diverted to other areas of the cockpit or display before the next correction was required. A disadvantage of these controlled element dynamics is their sensitivity to spurious higher frequency pilot control inputs as well as to atmospheric disturbances and system noise. (The abnormally high wing loading of powered-lift STOL aircraft serves to effectively filter the aircraft response to vertical gust encounters. Still, the dynamic analysis presented here should be extended to include a formulation of the effects of atmospheric disturbances, including windshears.) In the implementation employed here, first-order smoothing at 5 rad/sec was applied to the displayed throttle flight-director bar to suppress these effects with satisfactory results.

The design approach just outlined departs somewhat from generally accepted manual control display theory for flight-director systems that usually recommends a K/s shape for the controlled element in the bandwidth of pilot control, typically 0.1 to 10 rad/sec. The rationale for this theory is discussed in reference 16 and in greater detail in references 19-21; briefly, however, it stems from a large body of experimental evidence that shows the pilot always attempts to equalize the controlled element dynamics to a K/s shape at the crossover frequency, providing lead or lag as necessary, or preferably (it is assumed) acting as a simple amplifier of appropriate gain. (Considerations associated with the pilot's transport time lag, due to neuromuscular and scanning delays, are ignored for lower-frequency operation.) Provision of controlled element dynamics that maintain a simple K or K/s form over a wide frequency range, say 0.1 to 10 rps, allows the pilot to adjust system bandwidth without varying his own dynamics, except for gain, in the process. Alternatively, controlled-element dynamics which do not exhibit simple K or K/s forms in the frequency range of control usually result in the pilot's locating the frequency of operation where he can most easily provide whatever compensation is necessary to produce the K/s shape, while also, it is hoped, achieving the necessary standards of performance. However, this situation usually results in poorer pilot ratings and possibly unsatisfactory control characteristics, such as the tendency for oscillatory behavior exhibited by the control laws of the main investigation. This short discussion of manual control theoretical factors is included to provide a basis for documenting and interpreting the specific flight-director control laws employed in the course of this investigation.

An analysis of the controlled-element dynamics for the alternative throttle flight-director laws described in equation (A4), carried out with reference to their equivalent closed-loop small perturbation formulation illustrated in figure 57, produces the expression:

$$\delta_{TFD} = \frac{K_\gamma}{T_e(s+1)}\left(\frac{57.3\,\dot{d}}{V_g} + \frac{57.3}{R}\quad K_{\Delta_\gamma} d\right) + \frac{K_{\delta_T} s\delta_T}{s + (1/T_{WO})} \qquad \text{(A5)}$$

The engine response is modeled as a first-order lag with time constant T_e and the unit of throttle displacement is chosen as equivalent percent engine rpm. The aircraft response in linear glidepath error rate, $\dot{d}$, to a unit change in engine rpm is simplified to

$$\frac{\dot{d}}{\delta_T} \doteq \frac{-Z''_{\delta_T}}{(s/-Z_w) + 1} \qquad \text{(A6)}$$

where Z_W represents the damping in heave due to changes in vertical velocity. This is a valid approximation for the backside speed-control SAS, or for the case of the basic aircraft where the trim nozzle angle is not too large, hence resulting in negligible speed changes to throttle inputs.

The results of this analysis are shown in figure 58, illustrating that the control law is nearly stationary with reducing range to touchdown. The gain scheduling discussed earlier appears to be effective in avoiding adverse effects that would otherwise occur at the lowest altitudes near decision height. Also shown is the effect of a 0.2 sec first-order smoothing function which was applied to the displayed director element in the course of implementing these control laws for evaluation. This was required to suppress some of the pilot's high-frequency control inputs that were typically uncorrelated with a director command signal.

For purposes of comparison and documentation, similar representations of the throttle director bar dynamics are shown in figure 59 for the backside flight director employed in the main body of this report, and in figure 60 for the throttle flight-director control laws reported in reference 16, which provided the basis for those flown in reference 11, also shown.

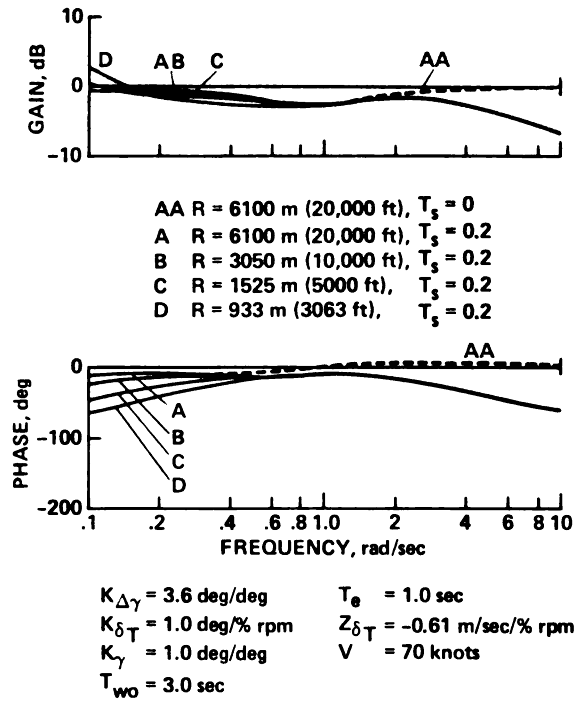


Figure 58. – Controlled element dynamics for alternative throttle director control laws.

Application to Pitch Flight Director

The glidepath control law described in equations (A1), (A2), and (A3) is employed in a nearly identical way when pitch is used for glidepath control (the frontside control technique). Because the test aircraft was rather highly augmented (with both a rate-command attitude-hold pitch SAS and an automatic speed-control system, the analysis of the pitch flight director characteristics is quite simple. Analogous to equation (A4), the pitch flight director control law is

$$\delta_{PFD} = K_\gamma(\gamma_{cmd} - \gamma) - \frac{K_\theta s\theta}{s + (1/T_{WO})} \qquad \text{(A7)}$$

where, as before, K_γ and K_θ are display deflection gains per unit of flightpath angle and attitude change, respectively. To preserve "face validity," a term employed in references 19 and 21 that refers in this case to the real pitch attitude change corresponding to a command displayed by the pitch director, the gain K_θ should be 1° of pitch-bar displacement, measured relative to the underlying attitude scale, per degree of pitch-attitude feedback. Consequently, the gain K_γ represents the inverse of the steady-state

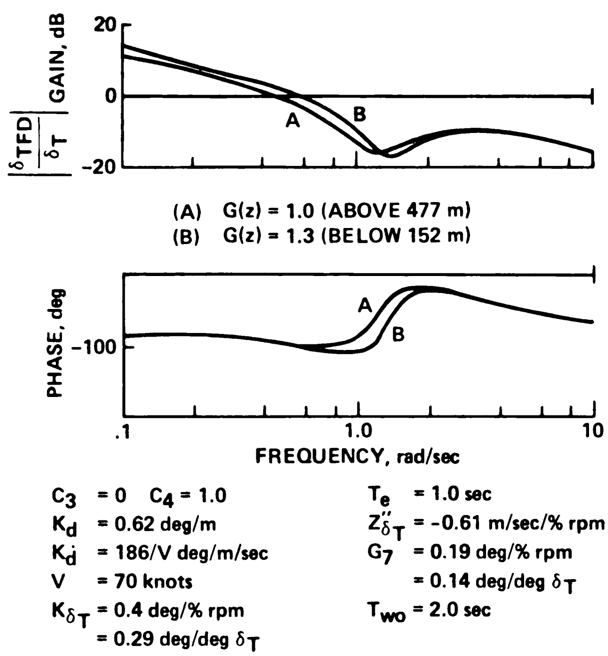
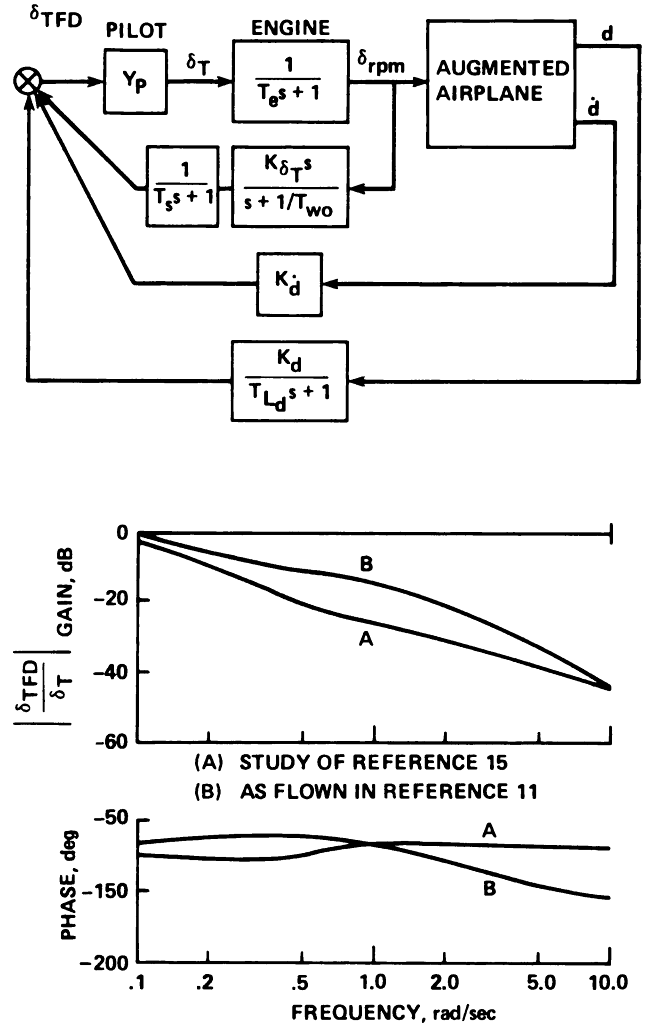


Figure 59.– Controlled element dynamics for throttle flight director of main investigation.



K_d = 0.12 cm/m
$K_{\dot{d}}$ = 0.3 cm/m/sec (A)
= 0.6 cm/m/sec (B)
T_s = 0 (A), 0.33 (B)
K_{δ_T} = 0.074 cm/% rpm (A)
= 0.127 cm/% rpm (B)
T_{wo} = 2.0 sec
T_e = 1.5 sec (A)
= 1.0 sec (B)
Z''_{δ_T} = −0.61 m/sec/% rpm
Z_w = −0.5 sec
V = 60 knots

Figure 30. – Throttle flight director implementation for study of references (11) and (16).

inertial flightpath angle change resulting from a unit change in pitch attitude

$$K_\gamma = \frac{1}{\left|\frac{\Delta\gamma_{air}}{\Delta\theta}\right|_{ss} \cdot \frac{V_A}{V_g}} \qquad \text{(A8)}$$

where the effect of winds that may be a large percentage of the approach airspeed is contained in the factor V_A/V_g.

The closed-loop formulation of the control laws for the pitch director is obtained from figure 61, resulting in the following expression (analogous to eq. (A5)):

$$\delta_{PFD} = K_\gamma\left(\frac{57.3\,\dot{d}}{V_g} + \frac{57.3}{R}\,K_{\Delta_\gamma}\dot{d}\right) + \frac{s\theta}{s + (1/T_{WO})} \qquad \text{(A9)}$$

With a perfect speed-control SAS, the aerodynamic flightpath angle response of the aircraft to a pitch-control input is nearly first-order:

$$\frac{\Delta\gamma_{air}}{\Delta\theta}(s) = \frac{\left|\frac{\Delta\gamma_{air}}{\Delta\theta}\right|_{ss}}{(s/-Z_w) + 1} \text{ deg/deg}, \quad \Delta\gamma_{air} = \frac{57.3\,\dot{d}}{V_A} \tag{A10}$$

where, as before, Z_w represents the effective heave damping of the aircraft but now includes the augmentation provided by the chokes. The factors affecting the value of $|\Delta\gamma_{air}/\Delta\theta|_{ss}$ were discussed in the body of the report. A value of 1.0 was used for this analysis, with $V_A = V_g$.

Finally, the relationship between the director feedback parameter θ and the actual pilot control input F_s is approximately

$$F_s = Ks\theta \tag{A11}$$

for the high-gain attitude SAS that was employed on the test aircraft.

The resulting dynamic characteristics of the controlled element δ_{PFD}/F_s are shown in figure 62.

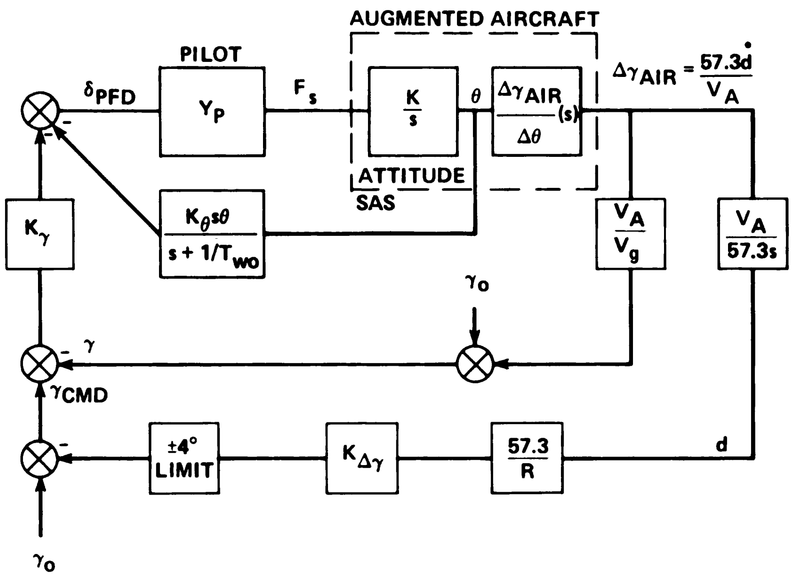


Figure 61.– Closed-loop glidepath tracking system using pitch attitude control.

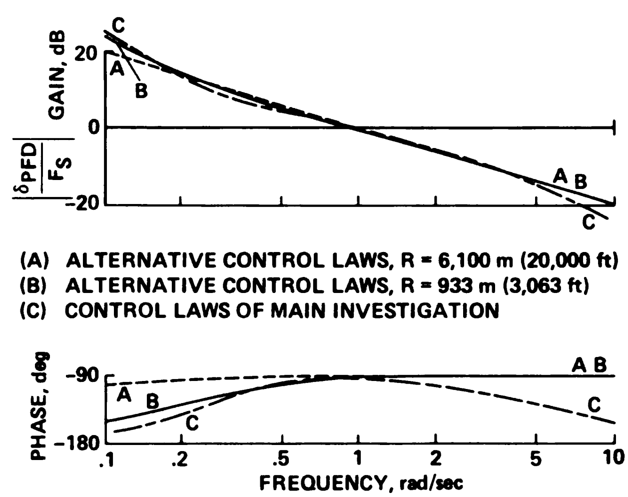


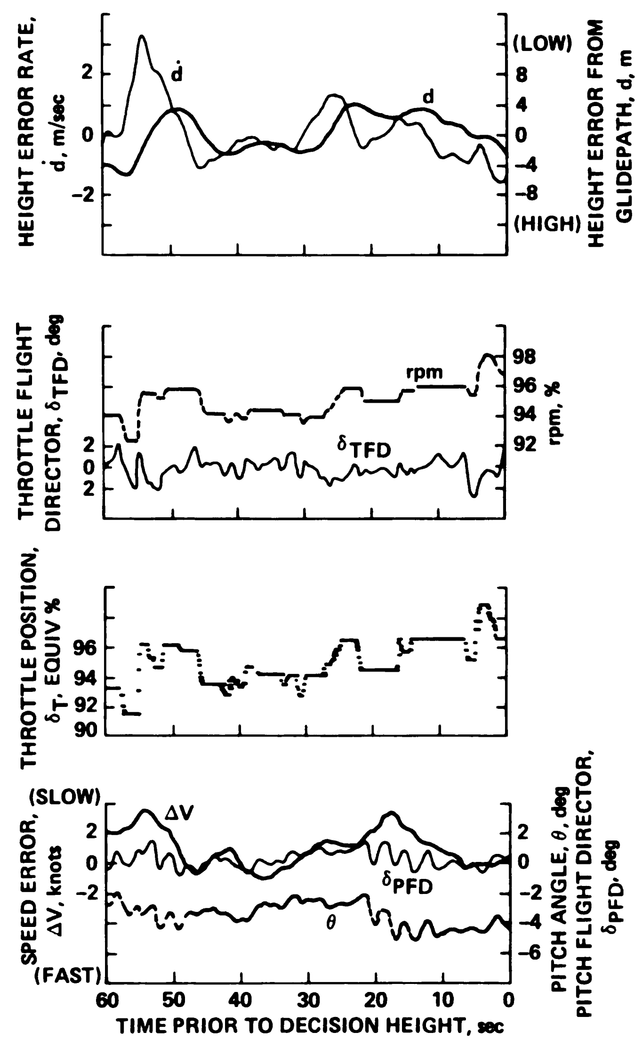
Figure 62.– Controlled element dynamics for pitch flight director.

As expected, it exhibits K/s characteristics over a broad frequency range with the same minor variations with reducing range to touchdown as exhibited by the nearly constant gain throttle director. For the pitch director, no final smoothing was employed on the displayed element, the implementation used being exactly as represented in equation (A7). For comparison, the dynamic characteristics of the pitch flight director employed in the main investigation are also shown in figure 62.

Pilot Evaluation of Improved Control Laws

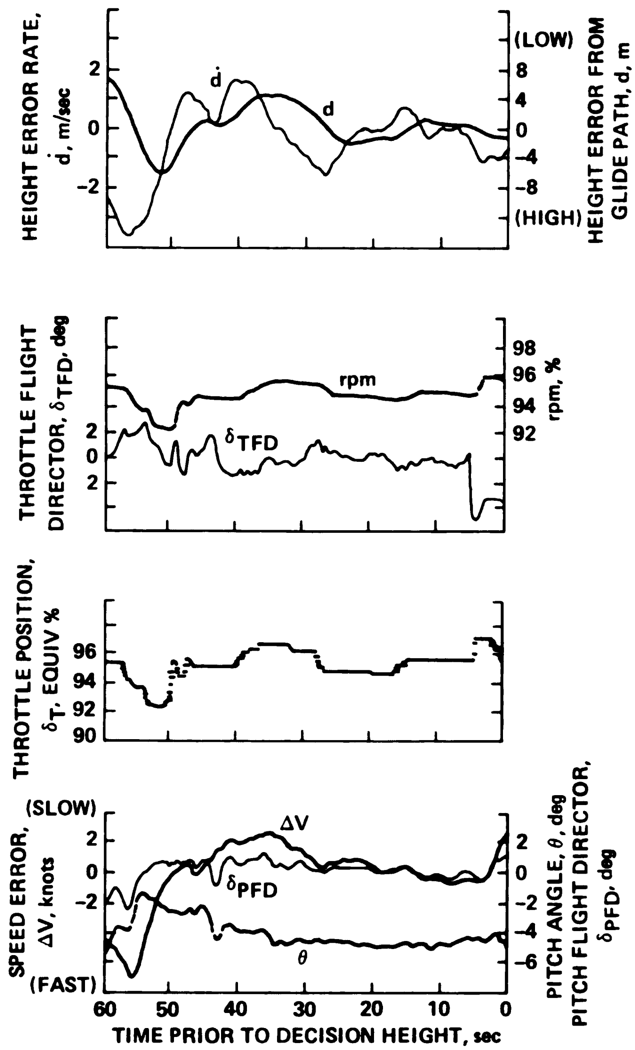
The throttle and pitch-flight director control laws just described were implemented and evaluated in the fixed-base simulator and briefly in flight. Some limited flight-test data for the case of the throttle director supporting the backside glidepath control technique are presented here, along with pilot comments regarding the characteristics and suitability of both the throttle and pitch flight director based on simulator and flight evaluations in smooth and moderately turbulent atmospheric conditions.

The results of a limited flight evaluation of the alternative throttle flight director control laws of equation (A4) are presented in figures 63-66. Twenty-two straight-in approaches were carried out using the basic aircraft configuration, but unfortunately in uniformly smooth atmospheric conditions. The time history data of figure 63 show none of the



(a) Pilot A.

Figure 63. – Sample approach time histories for three pilots using improved throttle director control laws.

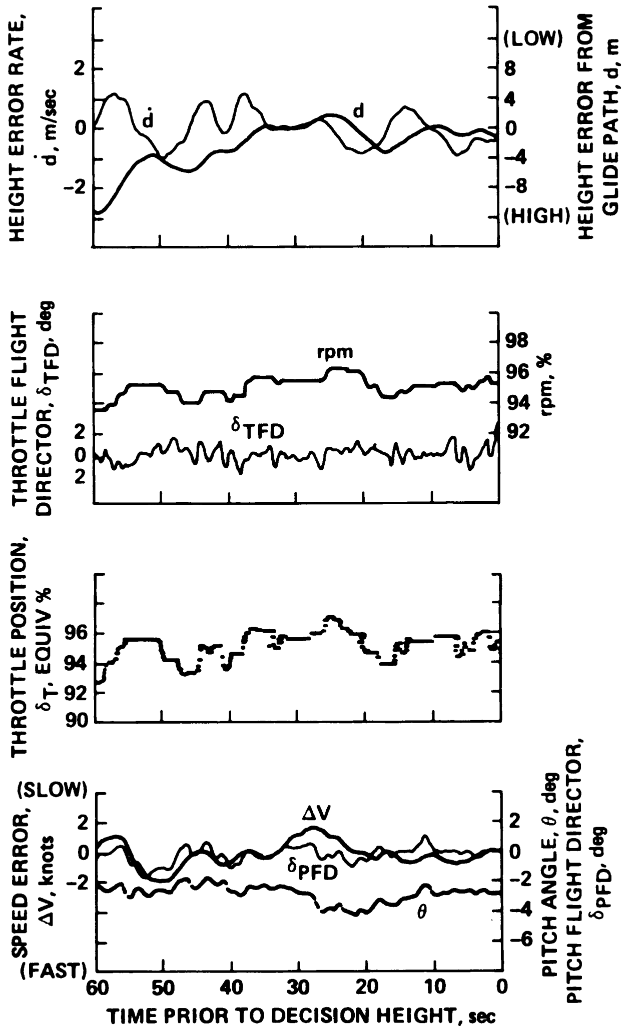


(b) Pilot B.

Figure 63.– Continued.

oscillatory character seen in figures 38 or 56, and the histograms of performance and control measures (figs. 64 and 65) show noticeably tighter control than the equivalent data presented earlier. The conditions existing at decision height, measured in terms of combinations of vertical position (guidance) errors and longitudinal velocity vector are shown in figure 66 and are to be compared with the data previously presented in figure 50. The flight-test data are insufficient to demonstrate the effectiveness of the scheduled control law gain K_{Δ_γ} which was employed in order to rationally constrain the corrective flightpath angle approaching breakout, since atmospheric disturbances were minimal and the pilots were briefed to accomplish the best tracking possible during the latter stages of the approach. To obtain data under a wider variety of conditions, 50 approaches were carried out in a fixed-base simulator employing both moderate turbulence and intentional glidepath abuses; these data are also presented in figure 66. Although the simulator data clearly tend to confirm the theoretical objective, the real effectiveness of the design feature requires more extensive flight evaluation.

During the limited flight evaluation of these alternative throttle flight director control laws, and during the course of gathering the simulator data, pilot commentary indicated very little tendency



(c) Pilot C.

Figure 63.– Concluded.

toward oscillatory glidepath tracking characteristics. The pilots were not aware of providing any compensation while tracking the throttle-director bar, and were able to easily null the flight-director command bar without overshoot, using what were frequently step-like throttle inputs, as can be seen in figure 63. Once a correction was made, attention could temporarily be diverted to other display-scanning tasks without large errors developing in the throttle-director bar. However, the increased higher-frequency activity in the display was noted, and this was typically ignored. During one evaluation flight conducted in moderate turbulence, and in the course of the many simulated approaches with moderate turbulence, the slightly greater activity of the throttle-director bar did not present any difficulty.

To better understand this apparently clear preference for constant-gain flight-director dynamics, the K/s control laws of reference 16, shown in figure 60, were implemented and evaluated in the fixed-base simulator. It was found that these dynamics exhibited the same oscillatory tendencies that characterized the main effort, but on a reduced scale. Nevertheless, the pilots commented that it was difficult to set and leave the throttle while other display-scanning tasks were carried out (an important consideration for multichannel control tasks), and that some lead appeared necessary in order to null the display. The most probable cause of the difficulty with these dynamics is considered to be the characteristics of the control manipulator, a throttle lever that had no physical centering characteristics and because of

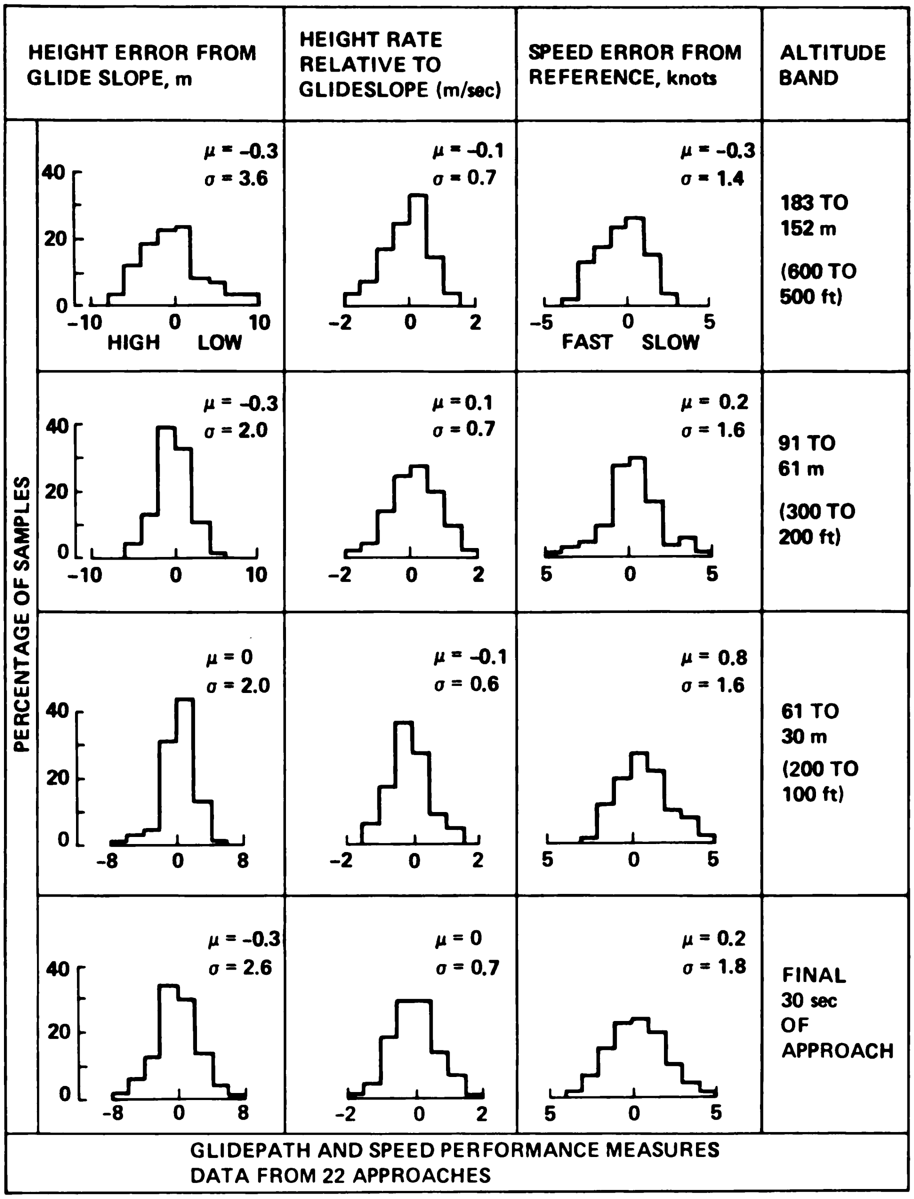


Figure 64. – Glidepath and speed performance measures using the improved throttle flight director control laws.

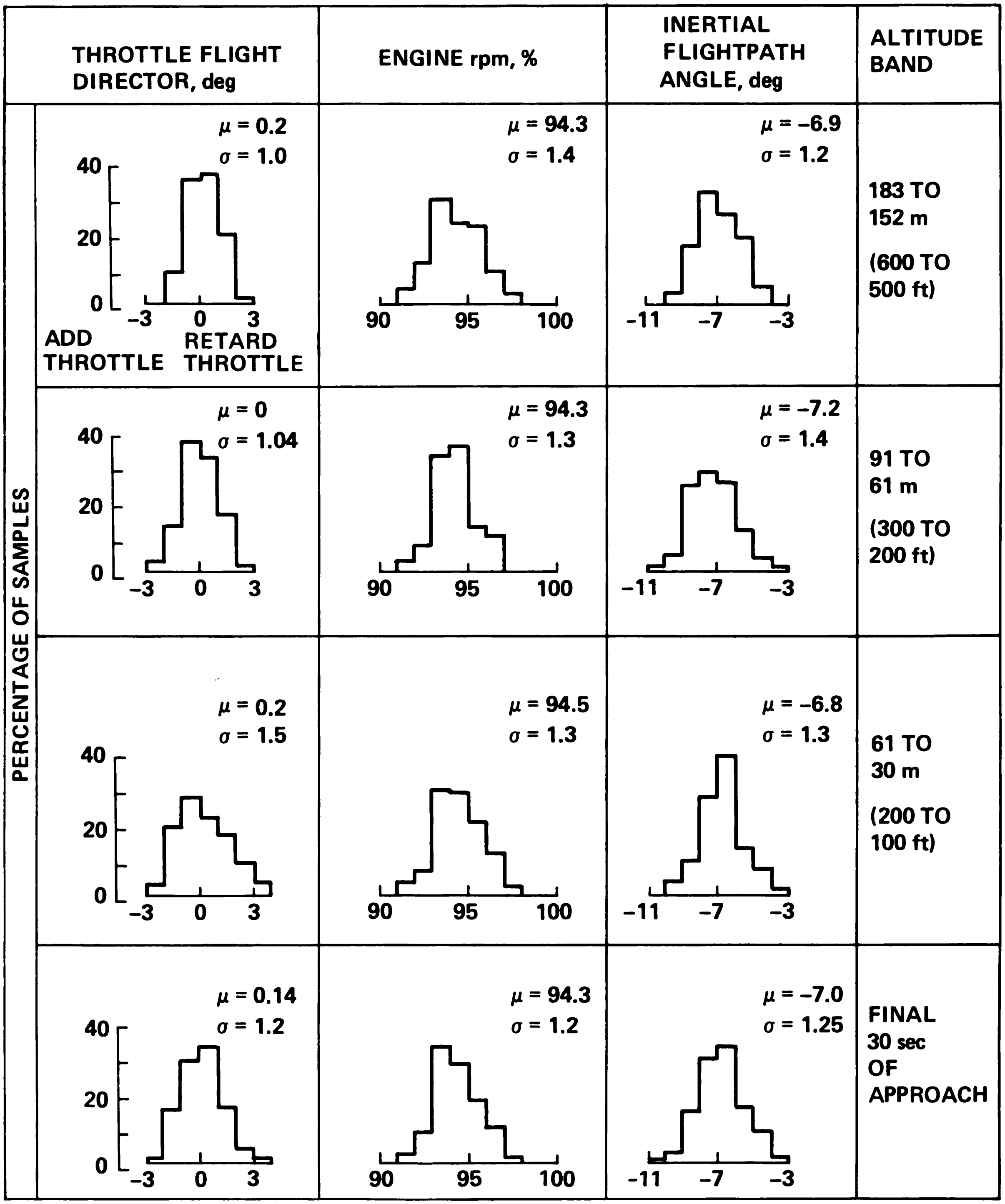


Figure 65.– Control utilization associated with the improved throttle flight director control laws.

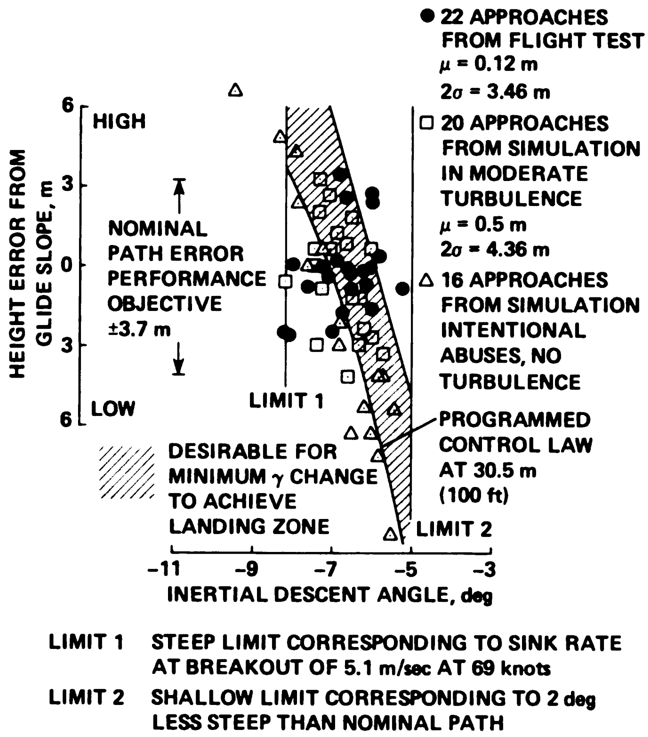


Figure 66.– Combinations of glidepath error and flightpath angle at decision height; flight test and simulation data.

its overhead location provided only limited proprioceptive cues of its position relative to trim. In addition, a significant hysteresis between the throttle lever and the engine fuel control unit, amounting to an equivalent of 1% rpm, probably contributed to the steplike nature of throttle control inputs that seemed to generally characterize the pilot technique.

There is some theoretical basis for these empirical results in a pilot model discussed in reference 22, which asserts that in tracking tasks, such as nulling flight-director errors, the pilot's equalization capabilities are obtained as the result of a proprioceptive feedback loop in which the rate, the displacement, or the integral of displacement of the manipulator is the primary sensed or derived quantity. The latter two quantities imply that the pilot has knowledge of the manipulator null or trim position at all times. In particular, it has been shown in reference 22 that the required pilot equalization for K dynamics (roughly, a first-order lag) can be obtained by utilizing the proprioceptively sensed rate of change of manipulator position. For K/s dynamics, sensed manipulator displacement itself is utilized to obtain the pure gain equalization. For K/s^2 dynamics, the integral of sensed manipulator displacement is used to yield the required first-order lead equalization. Thus, any controlled element that has the form K/s^n in the region of crossover will, in terms of the model, require proprioceptive "knowledge" of the equilibrium manipulator position when $n > 0$. For $n = 0$ (pure gain dynamics), however, only manipulator rate information is necessary. The overhead throttle used in the simulator and flight experiments described here possessed characteristics that made the proprioceptive acquisition of an equilibrium position (corresponding to trim approach power) somewhat difficult. However, rate information is more easily obtainable, and this may explain the pilot preferences for the K as opposed to the K/s "effective vehicle" dynamics for the throttle director.

These observations and tentative conclusions require additional measurement and more rigorous interpretation that are beyond the scope of this report. Nevertheless, various considerations in the design of throttle-lever characteristics, vehicle dynamics, and flight-director control laws have been highlighted in this limited consideration of improved throttle-director characteristics.

The improved pitch flight director for frontside glidepath control was also evaluated in flight and in the simulator in calm and moderately turbulent conditions; it too received similarly favorable comments. The conformity with existing manual control theory regarding the suitability of K/s dynamics apparently stems from the excellent centering and linear force-gradient characteristics of the pilot's control column. It was felt that the dynamic characteristics of the improved control laws represented a significant improvement over the pitch-director laws that were employed in the main body of this investigation. Pilot A, who was most inclined to develop oscillatory tendencies during the main investigation, had no difficulties with the improved laws. He was generally able to quickly null moderate errors without appreciable overshoot, even in turbulence. Consequently, it would seem that these control laws show good potential for minimizing the pitch-control activity, as measured by pitch rate, that has been identified in the main body of this report and elsewhere as being a possibly limiting factor in the use of this glidepath control technique by powered-lift STOL aircraft.

The alternative flight-director control laws described in this appendix showed significant improvement over the control laws that were used in the main body of this report. As was demonstrated, these control laws conformed to the basic principles of modern manual control theory, with the significant variation that the pilots strongly preferred throttle-director dynamics that were very nearly a constant gain over the frequency range of control, a finding thought to result from the particular characteristics of the throttle-control lever, as well as the shared multichannel aspects of the control task. Although the flight evaluations were limited and were not carried out in the framework of the decelerating-curved approach task, it was felt that these improved control laws could result in a reduction of one-half point from the least favorable pilot ratings shown in figure 55 for the final approach case.

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16. Abstract

Flight tests were carried out to assess the feasibility of piloted steep, curved, and decelerating-approach profiles in powered-lift STOL aircraft. Several STOL control concepts representative of a variety of aircraft were evaluated in conjunction with suitably designed flight directors. The tests were carried out in a real navigation environment, employed special electronic cockpit displays, and included the development of operational procedures considered appropriate to this class of aircraft. Data are presented describing the performance achieved and the control utilization involved in flying 180° turning, descending, and decelerating-approach profiles to landing. The results suggest that such moderately complex piloted instrument approaches may indeed be feasible from a pilot acceptance point of view, given an acceptable navigation environment. Systems with the capability of those used in this experiment can provide the potential of achieving instrument operations on curved, descending, and decelerating landing approaches to weather minima corresponding to CTOL Category II criteria, while also providing a means of realizing more efficient operations during visual flight conditions.

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