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FLIGHT EXPERIENCE WITH ADVANCED CONTROLS AND DISPLAYS DURING PILOTED CURVED DECELERATING APPROACHES IN A POWERED-LIFT STOL AIRCRAFT

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SUMMARY

A program to assess the feasibility of piloted STOL approaches along predefined, steep, curved, and decelerating approach profiles was carried out with a powered-lift STOL aircraft. To reduce the pilot workload associated with the basic control requirements of a powered-lift aircraft equipped with redundant controls and operating on the backside of the power curve, separate stability augmentation systems for attitude and speed were provided, as well as a supporting flight director and special electronic cockpit displays.

It was found to be particularly important to assist the pilot through use of the flight director computing capability with the lower frequency control-related tasks, such as those associated with (1) monitoring and adjusting configuration trim as influenced by atmospheric effects, and (2) preventing the system from exceeding powerplant and SAS authority limitations.

This paper briefly describes the control, display, and procedural features of the flight experiment that have led to the conclusion that, given an adequate navigation environment, such constrained approaches may be feasible from a pilot acceptance point of view. Many of the technical and pilot related issues identified in the course of this flight investigation are representative of similarly demanding operational tasks that are thought to be possible only through the use of sophisticated control and display systems.

INTRODUCTION

A capability to perform steep, turning, and decelerating approaches under manual control and in instrument meteorological conditions has been developed and flight tested in the Augmentor Wing Jet STOL Research Aircraft. This powered-lift STOL aircraft is operated by the NASA-Ames Research Center as part of a comprehensive investigative program in terminal-area STOL operating systems, and is partially supported by funding and personnel from the Canadian Government. The general objective of this program is to assess the potential for enhancing the operational efficiency of STOL aircraft by reducing terminal-area arrival times, selectively locating the final approach route for reasons of noise curtailment, obstruction clearance, conflicting CTOL operations, or military tactical constraints. The emphasis of this experiment was on the manual control and flight director considerations for powered-lift STOL terminal-area operations, with the objective of evaluating the extent to which significant operational utility can be achieved without requiring the extensive use of automatic systems, with their attendant reliability and cost considerations.

That powered-lift aircraft require special attention arises from the peculiar lift, drag, and pitching aerodynamics and perhaps their undesirable couplings that are associated with thrust turning. Accompanying this thrust turning feature is the requirement for use of an additional longitudinal control to adjust lift-drag trim states during steep approach operations. In addition, low aerodynamic dampings associated with low speed flight, and the details associated with lift sharing between the more conventional wing aerodynamics and the propulsive lift forces generally result in dynamics with a more sluggish and less stable response relative to CTOL aircraft. The result of these factors is an increase in complexity of the pilot's control task, or alternatively, the need to incorporate an appropriately designed automatic control or stability augmentation system.

Recognizing the comprehensive nature of the STOL instrument approach task, the major objective of this work was to integrate the navigation, guidance, control and handling qualities, cockpit display, and procedural factors into a potentially feasible operational framework. The curved approach task was carried out in a real navigation environment and furnishes new operationally oriented data for this class of aircraft. Features contributing to the feasibility of the task were a multi-function, three-cue flight director along with integrated electronic cockpit displays. A variety of STOL control concepts were also evaluated for their effect on the task. This paper discusses the essential elements of the approach task, briefly describes the test aircraft and associated avionics, and presents representative data from the flight experiments. A more detailed description of the flight test effort is to be found in a prospective NASA report,[1] which also substantiates the general conclusions summarized in this paper.

APPROACH TASK

Approach profiles similar to that shown in figure 1 were used for the evaluation. Included were some minor variations in turn radius and final approach roll-out altitude optional to the pilot. Choice of the 180° descending turn ensured that methods be developed to deal with (1) the discontinuity in the terminal-

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[1] W. S. Hindson and D. W. Smith: Flight Evaluation of Several STOL Control and Flight Director Concepts for a Powered-Lift Aircraft Flying Steep Curved and Decelerating Approaches. Prospective NASA Technical Publication.

area navigation environment (during transition from VORTAC to precision Microwave Landing System (MLS) coverage), and (2) the effects of the changing relative direction of significant ambient winds on lateral and longitudinal control requirements. Conversion from the conventional terminal area arrival configuration to an intermediate powered-lift flap setting (50°) was accomplished during the level downwind leg before capturing the 7° descent path. The major deceleration from the terminal area arrival speed was also carried out in this segment. The final deceleration to landing speed was generally accomplished immediately prior to roll-out at 150 m (500 ft) from the descending turn. A simulated decision height of 30.54 m (100 ft) was used for the hooded approach, where the glidepath performance objectives were chosen for purposes of initial evaluation to be those currently used for CTOL Category II operations. Landing transitions were carried out to a 30.5-m-wide STOL runway, where touchdown dispersions were measured. Provision was also made for adapting the landing configuration and associated approach airspeed to the wind conditions of the day and the runway length available for landing, hence recognizing an additional variable believed necessary for economical operation of powered-lift STOL or V/STOL aircraft. The configuration-speed schedule used for the test aircraft is shown in figure 1.

THE RESEARCH AIRCRAFT

The research aircraft used for these tests was a modified DeHavilland of Canada DHC-5 Buffalo shown in figure 2. The aircraft is equipped with an augmentor flap arrangement, shown in figure 3, which is blown internally by the cold bypass flow from two Rolls Royce Spey 801-SF engines. This cold flow is crossducted to minimize lateral and directional transients in the event of an engine failure. The residual hot thrust from each engine is exhausted through rotatable nozzles, which when vectored to a downward position, conveniently provides ample reduction in longitudinal force for steep approaches. These nozzles are capable of high rotation rates, and when also modulated about their deployed position, furnish significant control of longitudinal force without any major disruption in lift.

The aircraft is equipped with a rate-command, attitude-hold Stability Augmentation System (SAS) for pitch and roll, and has turn coordination and rate-damping augmentation in yaw.

A flexible digital avionics system known as STOLAND, pictured in figure 4, is installed in the aircraft. A 32K/18bit word minicomputer serves navigational, guidance and control requirements through interfaces with the cockpit displays, electronic servos, and the pilot's mode selection panel. A rho-theta area navigation system is incorporated, providing a flexible capability for multi-segment and curvilinear profiles in a VOR, TACAN, or MLS navigation environment.

The variable stability capability of this system was also used to incorporate an autospeed control augmentation system for use in the powered-lift descent configuration. This system, shown in figure 5 modulates the vectored thrust nozzles to maintain a specified speed reference while maneuvering with other longitudinal controls, or in the presence of atmospheric disturbances such as shears. This system is conceptually similar to one evaluated during the previous research reported in reference 1, where it had yielded encouraging pilot ratings. However, in this work, considerably more attention was given to some of the many factors involved in the design of such a system for operational use, such as engagement procedures, trim control, and authority limits. Use was also made of electrohydraulically actuated surfaces located within the augmentor flaps. These "chokes" can be modulated symmetrically about an intermediate deployed position to provide direct lift control, and are used for heave damping augmentation and to offset small lift losses that occur as the hot thrust nozzles are rotated aft when controlling to the reference speed. The speed reference in the system is indirectly controlled by flap angle as shown in figure 6, so that as the pilot progressively configures the aircraft towards the final landing flap setting, the speed reference automatically reduces to programmed values appropriate to configuration and weight. This provides a convenient way to control a decelerating approach without any additional cockpit actions.

Finally, the authority of the autospeed control system is sufficient to deal with the secondary control coupling generated when throttle is used for path control, commonly referred to as the Backside Control Technique, as well as the primary control coupling associated with using pitch attitude to control glidepath, as in the conventional Frontside Control Technique. With the Backside Control Technique, pitch attitude is maintained constant at an appropriate trim position, while with the Frontside Technique throttle is maintained at an appropriate trim position, effectively determining the optimum proportion of powered-lift needed for the approach. Consequently, three differing STOL control concepts, summarized in Table I, were available for evaluation during the flight tests reported here, since the Basic Aircraft, without speed control augmentation, was also tested.

COCKPIT DISPLAYS AND FLIGHT DIRECTOR

Two electronically generated cockpit displays provide an integrated display format, which contributed greatly to the reduced workload necessary to permit the curved approach. As shown in figure 7, the electronic attitude director indicator (EADI) embodies a three-cue director format for pitch, throttle, and roll angle. Other symbology includes an inertially referenced flight path angle bar, a speed error thermometer scale, a raw-data tracking box of increasing sensitivity towards decision height, and three digital display windows as shown in figure 7. Also included is a perspective runway presentation, calculated from MLS position data for use with the flight path angle bar.

The multifunction display (MFD), shown in figure 8, fills a requirement conventionally met by a horizontal situation indicator (HSI), furnishing a pictorial plan position presentation particularly suitable for constrained multisegment, curvilinear, terminal-area navigation. Also shown in figure 8 are main symbology elements, and the several options for map orientation, scale sensitivity, map content, and route selection available to the pilot. The location of these displays in the cockpit is illustrated in figure 9.

The functional design of the flight director that evolved to support the curved decelerating approach task is shown in figure 10. Four distinct requirements are involved in contrast to the usual situation for

CTOL aircraft where, in addition to mode switching, the flight director consists simply of guidance laws combining path error and path error rate in suitable proportions. The basic guidance laws used here remain basically conventional, except that they include control-feedback limiting, such as maximum and minimum power settings, to ensure that control parameters remain within prescribed bounds, thus reducing the need for additional pilot monitoring. Also incorporated are control configuration blending constants, which meet the requirement to smoothly blend the pilot's control technique from frontside to backside as the aircraft's configuration is changed toward powered-lift settings. The configuration-dependent form of these parameters is shown in figure 11; they begin to come into play during the initial level deceleration on the downwind leg, typically to a flap setting of 50°. The trim management function of the flight director assists the pilot in establishing appropriate lift-drag trim settings during the turning approach through trim data stored over a range of aerodynamic flight path angles. This trim management requirement is an important consideration for all powered-lift aircraft, including V/STOL aircraft, which are especially sensitive in terms of operating economics and safety margins to the larger variations in aerodynamic flight path angle encountered during steep approach operations in moderate wind fields. The computed trim setting is displayed to the pilot on the EADI either through the throttle director bar for the Frontside autospeed mode, the pitch bar for the Backside autospeed mode, or through the center window as a fourth director cue for the manual nozzle positioning necessary for the Basic Aircraft mode. Finally, the decelerating approach reference speed, mentioned earlier in connection with the autospeed control system, is incorporated in the flight director. Errors from this reference are either input to the autospeed control system (if engaged) or drive the pitch director bar for the Basic Aircraft mode.

SELECTED FLIGHT TEST RESULTS

Data from approximately 60 approaches were analyzed from the viewpoint of achieved outer loop navigation and guidance performance, inner loop flight director tracking performance, pilot control inputs, and aircraft control utilization measures. These results constitute an initial body of data that can contribute to the development of navigation and airspace requirements, pilot workload factors, control authority design requirements, and pilot and passenger acceptance factors for this class of aircraft. Among others, these factors, will determine the mission capability of powered-lift STOL aircraft. Representative flight test data selected from the experiment are provided here.

The net profile performance achieved during thirteen approaches flown on one of the experimental approach profiles is shown in figure 12. The width of the lateral performance envelope in the earlier stages of the approach represents profile capture peculiarities, as well as day-to-day variations in the enroute VORTAC navigation signal accuracies, particularly bias errors in range measurement. These data were analyzed in greater detail for all approaches during the sequential approach segments defined by the downwind leg, the descending turn, and the final approach, and are summarized in the prospective report[2] in the form of tabulated dispersions of lateral and vertical navigation and guidance errors.

Although the emphasis of this work was on longitudinal performance and control, some lateral parameters of significance were also studied. Lateral control data during the descending turn are illustrated in figure 13 for approximately 50 approaches. These probability density functions represent the relative amount of time during all turn segments that the parameters shown fall within the intervals defined along the abscissa. Despite the moderately strong winds which prevailed during some of the evaluation flights, the nominal bank angle during the turn was maintained near the desired 15° by appropriate choice of turn radius and initial approach airspeed. Recognizing the importance of winds during the approach on both lateral and longitudinal kinematics and hence control requirements, the wind profile to be anticipated on descent was available to the pilot from a wind estimate calculated on board and displayed, and from a wind forecast briefing derived from balloon and surface wind data. Figure 13 also shows the statistics for roll flight director tracking during the descending turn, along with the amplitude characteristics of the pilot's roll control input.

Differences in the three STOL concepts evaluated are most evident in terms of the speed control achieved. Figure 14 illustrates how speed errors from the reference are substantially reduced for either version of the autospeed control system described previously, relative to the Basic Aircraft mode where larger speed dispersions and a mean velocity error on the slow side are evident. This speed bias for the Basic Aircraft arises from the high degree of thrust turning that is characteristic of the Augmentor Wing concept. This feature results in a reduction in forward speed when power is added, unless pitch attitude is decreased. The data suggest that the pilot, although continuously reminded by the flight director to use this abnormal control technique, remains reluctant to pitch down when adding power to make an up correction to path. The glidepath performance statistics, shown in figure 14, are similar for all three STOL concepts. However, somewhat poorer performance is shown for the Basic Aircraft mode, where the bias toward persisting errors below path correlates with the slow speed bias just discussed. Despite the improved performance and safety margin that inherently accrue from good speed control, these tests did not encounter the atmospheric conditions of turbulence and shear in which these benefits of automatic speed control are likely to be important.

The utilization of the longitudinal controls during the final straight approach segment is illustrated in figure 15 for the Basic Aircraft mode and the Frontside autospeed control mode. In the Basic Aircraft mode, power is used to control glidepath, while pitch attitude is used for speed control. Nozzle angle is used for trim with the objective of maintaining power and pitch close to their optimum settings for the wind conditions of the day. The range of power settings encountered during the final 30 sec of 24 approaches is shown in figure 15, together with the range of pitch excursions and an associated typical use of nozzle trim as adjusted by the pilot. A separation of the data according to mean wind condition illustrates the effect of wind on the operation of powered-lift aircraft equipped with both thrust and thrust vector controls. For the Frontside autospeed control mode, power is used for lift-drag trim, while pitch attitude is used for glidepath control. The nozzle is driven by the autospeed control system to maintain

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[2] See footnote 1

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speed at the predetermined value. The data demonstrate that one disadvantage of this type of STOL control concept is a noticeably greater activity in pitch control. However, the advantages of (1) maintaining a nearly constant power setting on the approach, (2) preserving a fixed reserve of propulsive lift for go-around or engine failure, and (3) reducing the pilot's longitudinal control task to manipulation of a single control may present significant considerations for aircraft operation and design. Some of these considerations may be in the form of (1) requirements for preserving aerodynamic safety margins, (2) ensuring consistency of pilot control technique over the entire flight envelope, (3) specifying installed thrust-to-weight, (4) defining control authority and bandwidth of the speed control device, or (5) limiting the effects of power modulation transients on engine life.

Vertical and lateral performance achieved at the 30.54 m decision height for the three control modes combined is shown in figure 16. There were no discernible differences in glidepath performance with control mode in the atmospheric conditions of these tests. The vertical guidance errors are shown in relation to the ± 3.7 m performance criterion currently established for CTOL operations. It was not an objective of these tests to relate the lateral performance objectives to currently established CTOL criteria. Rather, moderate lateral offsets were intentionally induced to provide the pilot with a more demanding landing task. The width of the shaded area in figure 16 encompasses the lateral guidance errors that were experienced. Despite the dispersions recorded at decision height, satisfactory landings were accomplished from all approaches. Nevertheless, some reservations were expressed about acceptable combinations of vertical position error and instantaneous flight path angle occurring at breakout.

Shown in figure 17 is the range of pilot opinion ratings assigned to the three STOL control concepts during the descending turn, final approach, and landing task segments. Three pilots provided the data from 14 evaluation flights. Atmospheric conditions consisted of both light and moderately strong winds; however, turbulence conditions were generally negligible to light. Under these conditions, little preference among the three STOL control concepts is evident, the assigned ratings reflecting a relatively uniform level of pilot effort involved in executing this moderately complex precision approach task. This level was considered comparable to that encountered in a conventional ILS approach task performed without the aid of a flight director in a CTOL jet aircraft.

Of greater significance was the totally new capability, provided chiefly by the area navigation system and the flight director, to perform tight, turning, and decelerating approaches to the STOLport with repeatable precision. Despite extensive flight experience with this aircraft, represented by more than 1600 landing approaches, the pilots felt that this capability substantially exceeded that formerly possible, even during visual approaches, hence providing a measure of the improvement in mission capability that can be achieved. The single control feature contributing most to this capability is the trim management function of the flight director, relieving the pilot of the otherwise burdensome task of determining lift-drag trim strategy.

CONCLUSIONS

A flight test program was carried out using electronic cockpit displays and a specially designed flight director concept, which permitted curved decelerating STOL approaches to be flown in simulated instrument conditions. Also evaluated were three STOL control concepts representative of those applicable to powered-lift STOL and V/STOL aircraft. Two of these control concepts used a speed control augmentation system modulating lift and drag forces, which was additional to a three-axis rotational stability augmentation system normally used in the aircraft. Although complete supporting data has not been included in this paper, based on a more detailed study to be published, the following general conclusions have been drawn.

- Curved decelerating approaches in instrument meteorological conditions do appear feasible in powered-lift STOL aircraft from a pilot acceptance point of view.
- By providing suitable guidance and display information, a notable improvement in approach profile efficiency appears possible for visual approaches.
- Differences in pilot acceptance, workload, and performance are not widely separated for the various STOL control concepts evaluated, at least in atmospheric conditions of light turbulence and gentle shears.
- It was found important to provide the pilot with a computed position for the longitudinal control used for trim, primarily to relieve the mental workload associated with evaluating and determining satisfactory longitudinal lift-drag trim states.
- Changing the pilot's control technique from frontside on the initial approach to backside on the turn and final approach, which was accomplished by blending in a multiloop flight director, was well received by the pilots and resulted in no control difficulties.
- The equivalent of Category II decision heights and performance criteria for manual powered-lift STOL operations may differ from those now used for CTOL aircraft. In addition, they are likely to be strongly influenced by both the nominal descent rate on approach and excursions about this nominal rate that may exist at decision height, created in the course of attempting to follow the flight director control laws.

The control and flight director features developed for the aircraft of this study may differ in detail when applied to other powered-lift configurations, but nevertheless represent general design considerations. Assuming the existence of an adequate navigation environment, most of these considerations for powered-lift aircraft are control related, and if dealt with satisfactorily, offer potential for operational acceptance. On the other hand, it is considered that operations on these approach profiles with low wing loading STOL aircraft, or RTOL aircraft, present substantially fewer control considerations, and principally require an adequate navigation, profile computation, control authority, and cockpit display environment for their implementation.

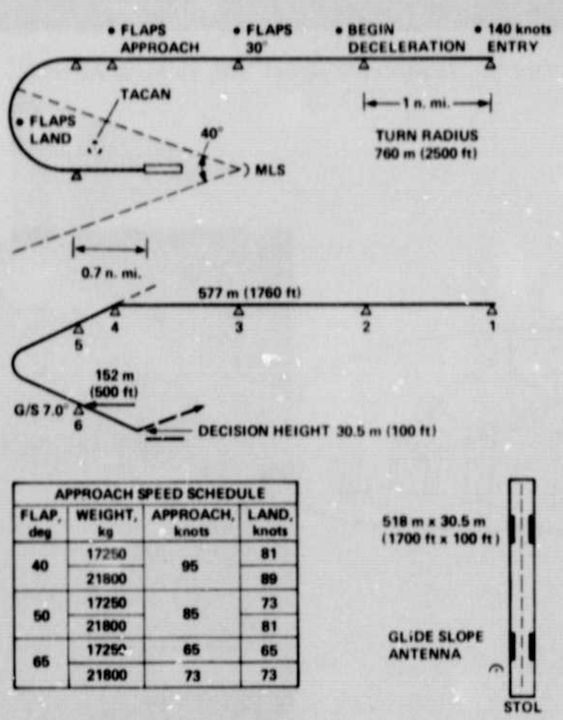
REFERENCE

1. Franklin, J.A. et al. "Flight Evaluation of Advanced Flight Control Systems and Cockpit Displays for Powered-Lift STOL Aircraft." NASA SP-416, Oct. 1976, pp. 43-62.

Table 1. Summary of STOL control concepts.

CONTROL CONCEPT	BASIC AIRCRAFT	BACKSIDE SAS	FRONTSIDE SAS
PRIMARY CONTROL (PATH)	THROTTLE	THROTTLE	PITCH ATTITUDE
SEC'Y CONTROL (SPEED)	PITCH ATTITUDE	NOZZLE*	NOZZLE*
TRIM CONTROL	NOZZLE	PITCH ATTITUDE	THROTTLE

*SAS MANAGED



APPROACH SPEED SCHEDULE			
FLAP, deg	WEIGHT, kg	APPROACH, knots	LAND, knots
40	17250	95	81
	21800		89
50	17250	85	73
	21800		81
65	17250	65	65
	21800	73	73

Fig. 1. Approach profile.

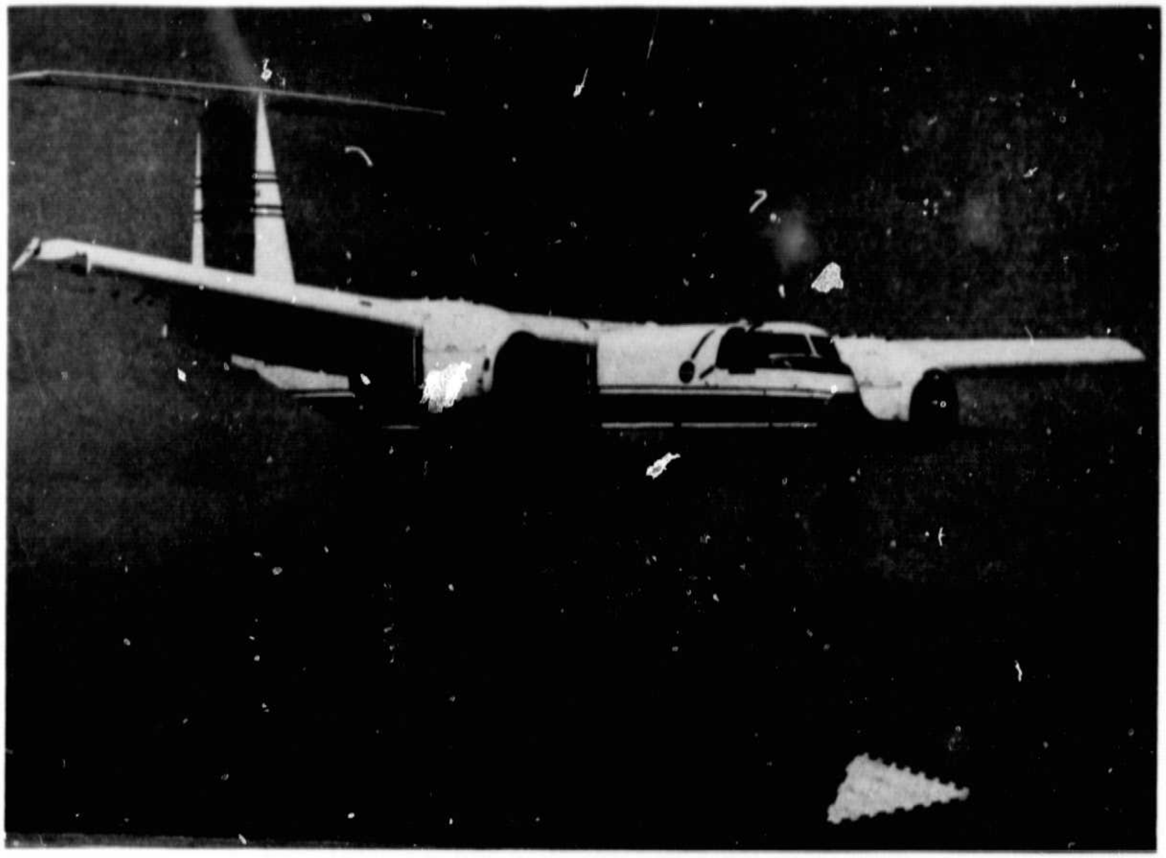


Fig. 2. Augmentor Wing Jet STOL Research Aircraft.

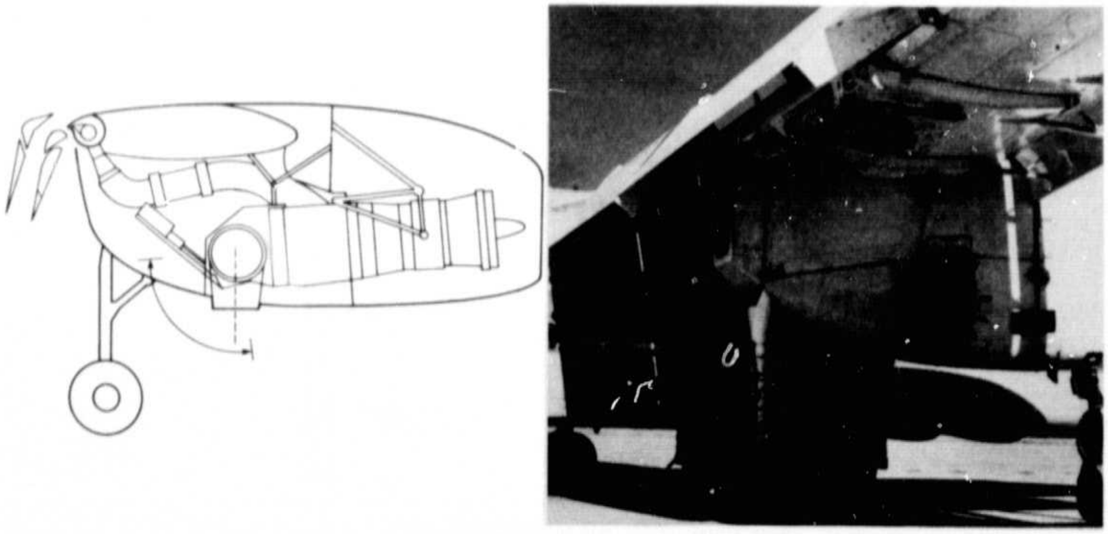


Fig. 3. Augmentor wing propulsive lift system.

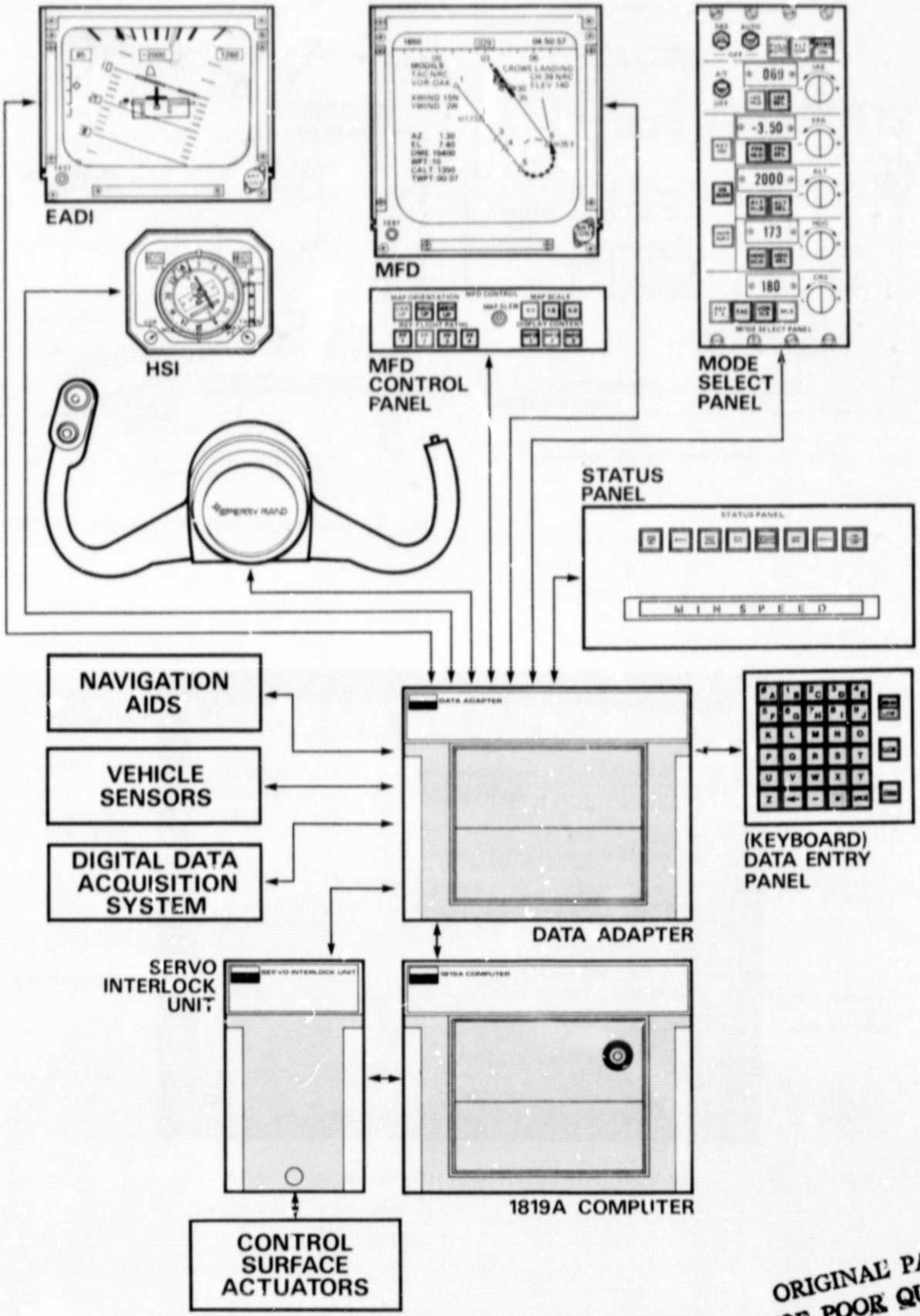


Fig. 4. STOLAND Research AVIONICS System.

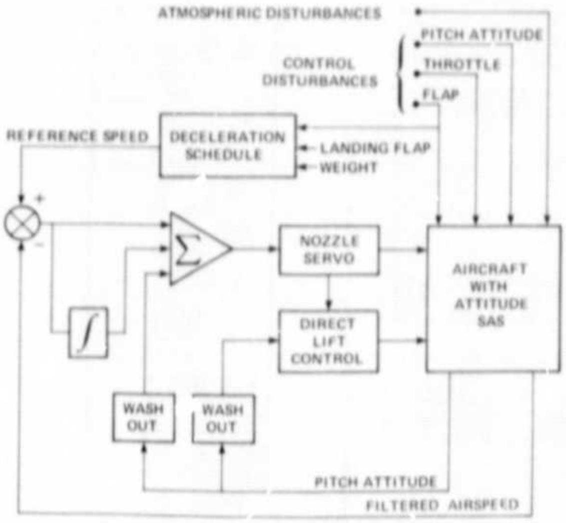


Fig. 5. Autospeed control system.

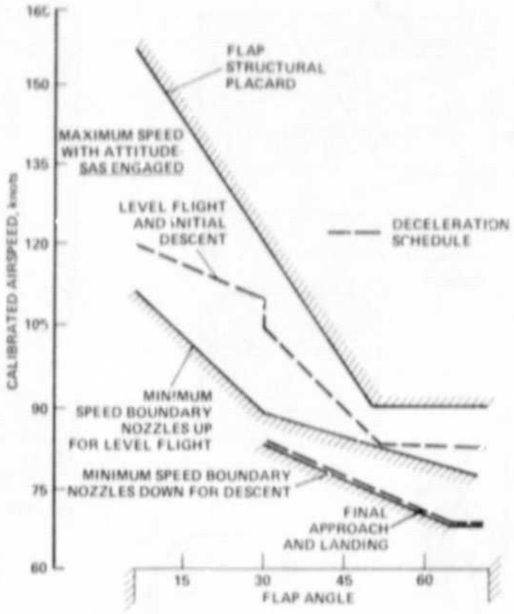


Fig. 6. Decelerating Reference Speed Scheduling.

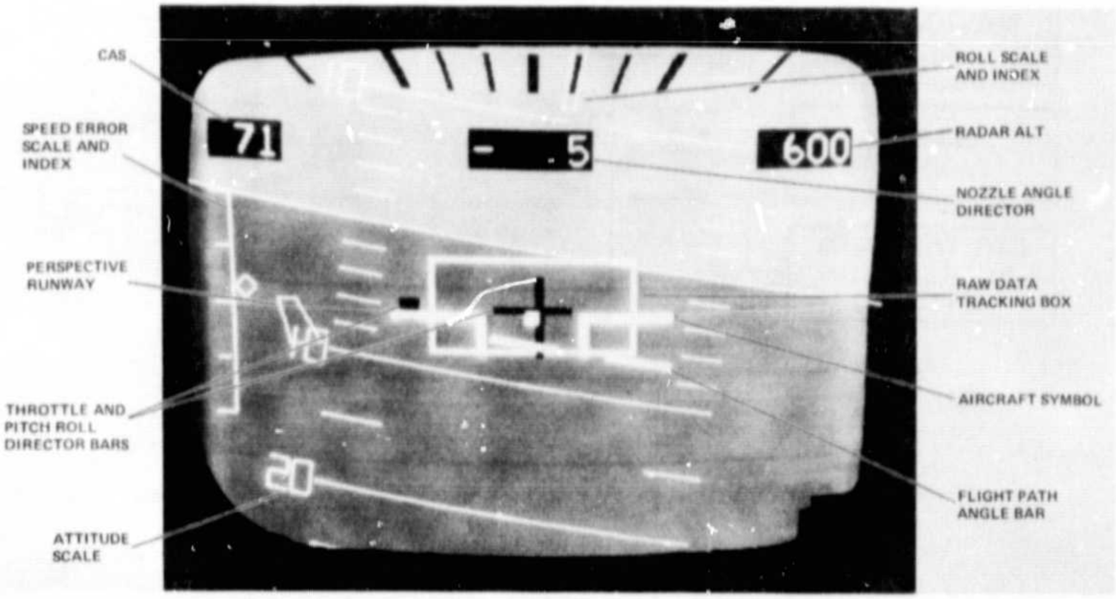


Fig. 7. Electronic altitude director indicator (EADI).

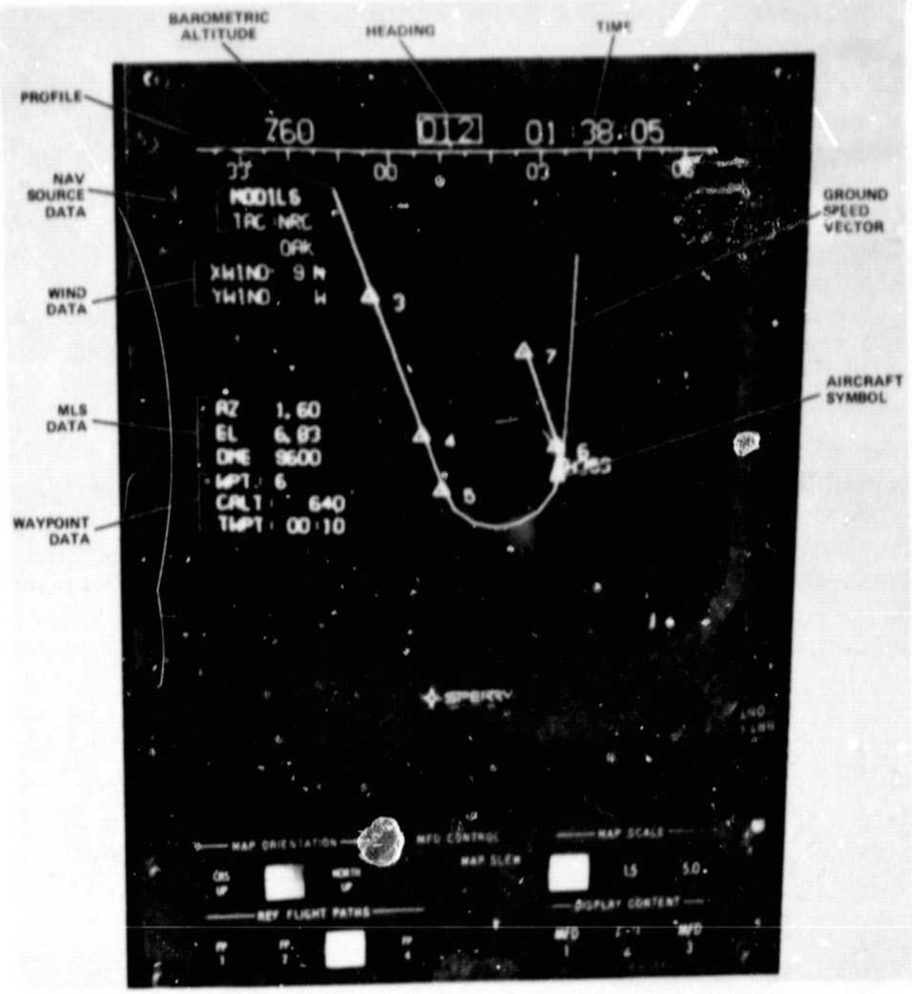


Fig. 8. Multifunction display (MFD).

Fig. 9. Cockpit display installation.

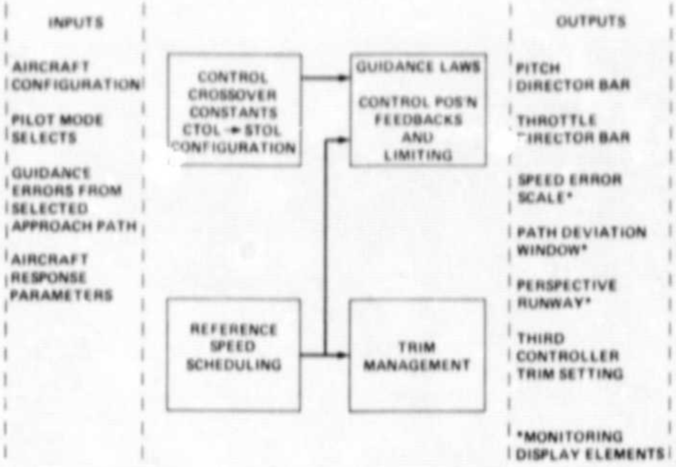


Fig. 10. Flight director functioned design.

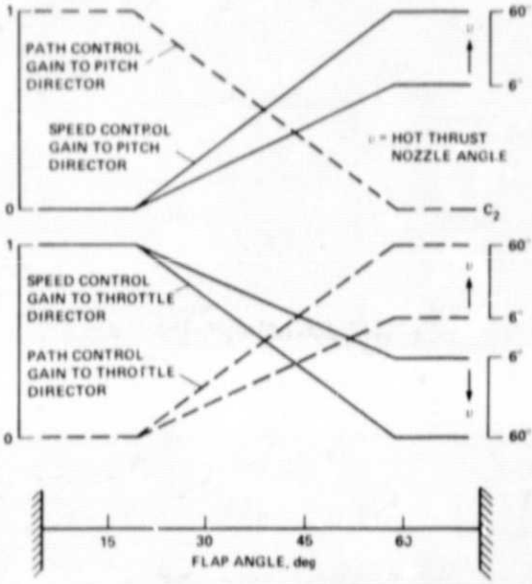


Fig. 11. Normalized control blending gains.

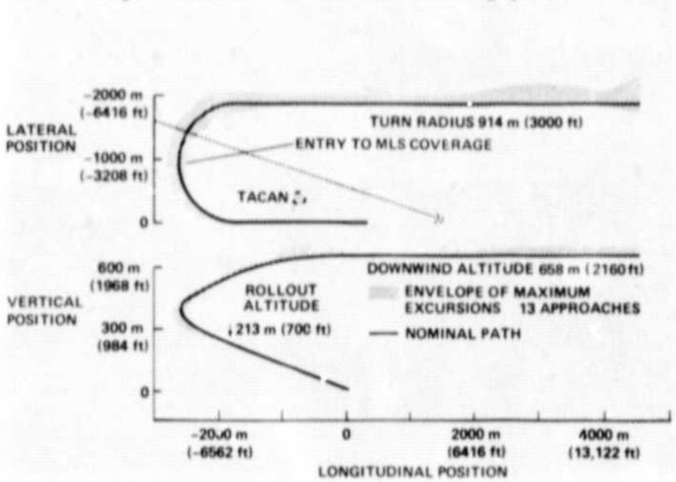


Fig. 12. Gross profile performance.

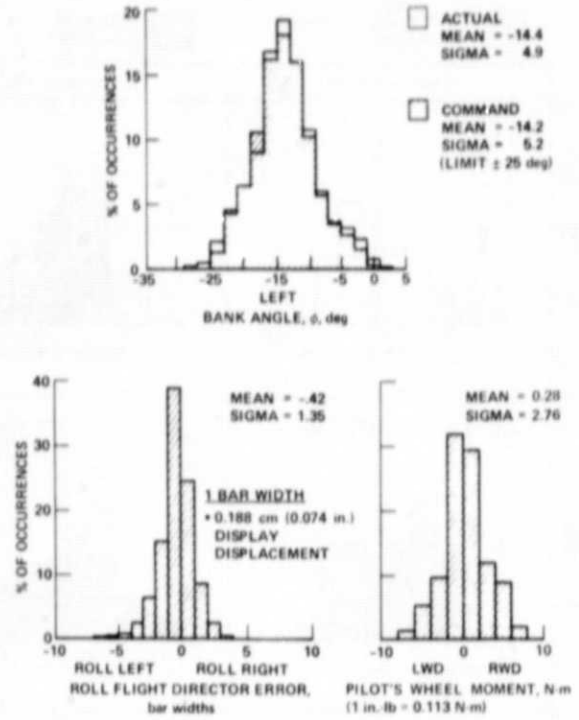


Fig. 13. Lateral control parameters during descending turn.

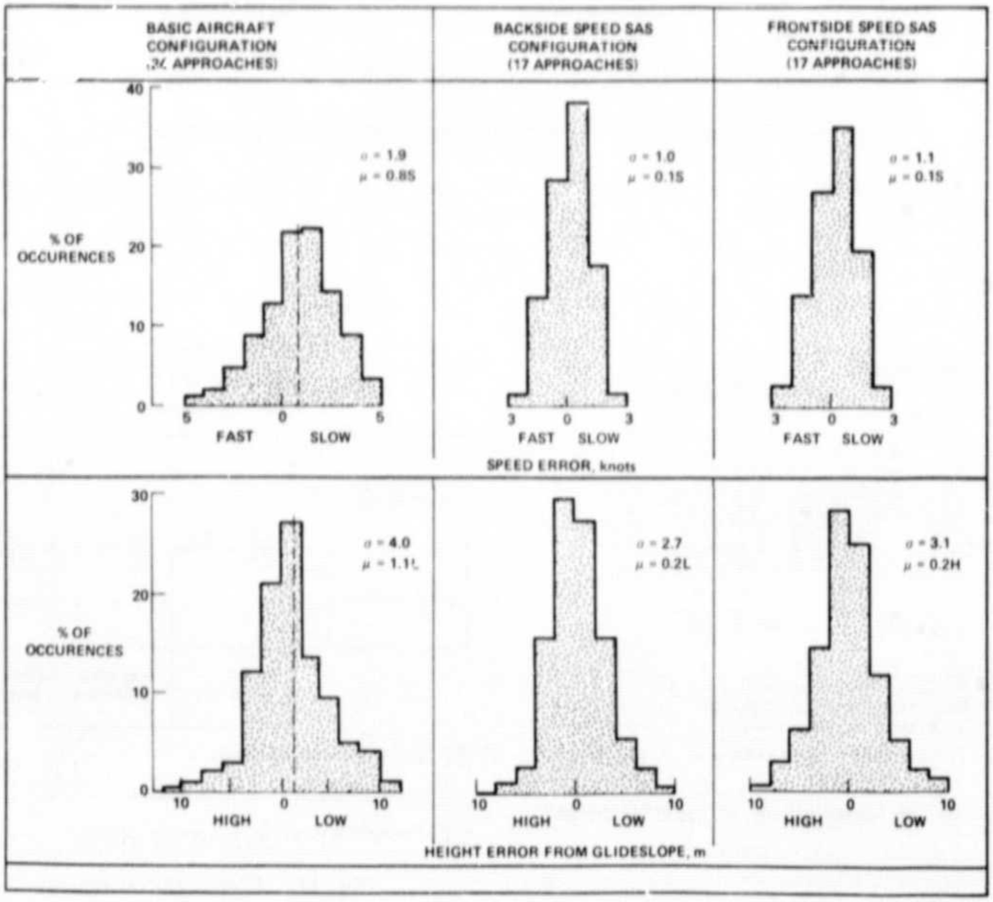


Fig. 14. Longitudinal performance measures during final straight segment.

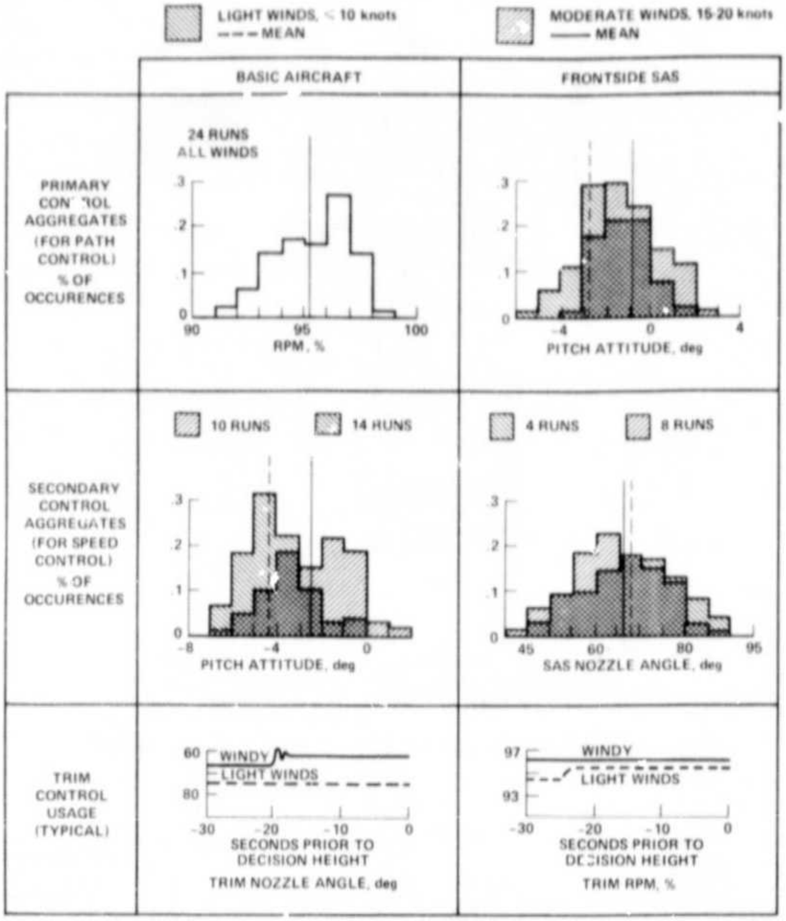


Fig. 15. Control utilization data during final straight segment.

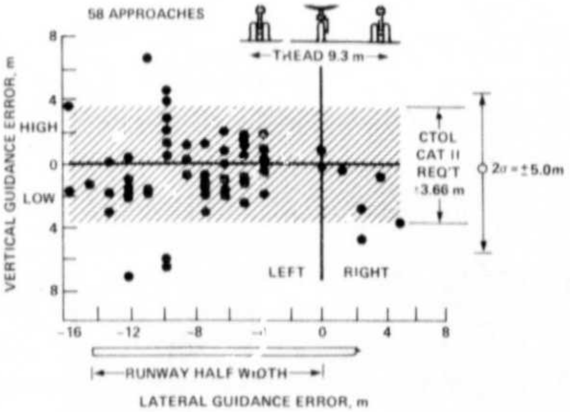


Fig. 16. Guidance errors at decision height.

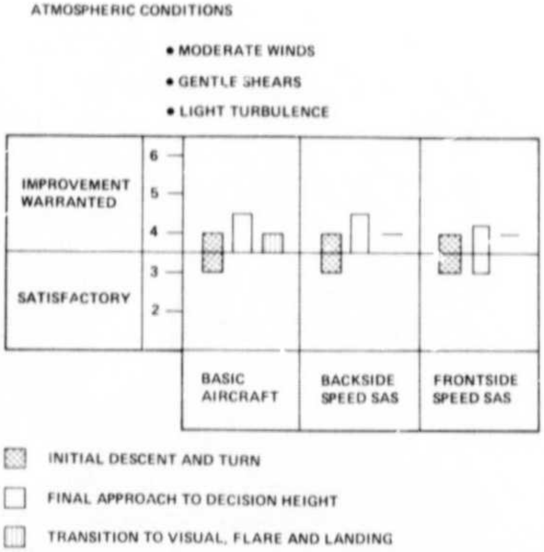


Fig. 17. Pilot opinion ratings.