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A Summary of Joint U.S.-Canadian Augmentor Wing Powered-Lift STOL Research Programs at the Ames Research Center, NASA, 1975-1980

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SUMMARY

Several different flight research programs carried out by NASA and the Canadian Government using the Augmentor Wing Jet STOL Research Aircraft to investigate the design, operational, and systems requirements for powered-lift STOL aircraft are summarized. Some of these programs have considered handling qualities and certification criteria for this class of aircraft, and have addressed pilot control techniques, control system design, and improved cockpit displays for the powered-lift STOL approach configuration. Other programs have involved exploiting the potential of STOL aircraft for constrained terminal-area approaches within the context of present or future air traffic control environments. Both manual and automatic flight control investigations are discussed, and an extensive bibliography of the flight programs is included.

INTRODUCTION

The current generation of STOL transport aircraft is characterized by turboprop engines and efficient mechanical flaps installed on a relatively large wing. Although these features permit the aircraft to operate at the low airspeeds necessary for good short-field takeoff and landing performance, they deny the capability to achieve the high cruise speeds typical of modern turbofan transports. Nevertheless, this generation of STOL transport aircraft can be competitive in terms of travel time with the smaller conventional turbofan transports over short ranges, partly because their lower airspeeds allow more direct approach and landing patterns in the terminal-area. In addition, they may enjoy exclusive use of otherwise inactive shorter runways at large congested airports, or instead, use much smaller airports located closer to the city centers. Under these conditions, not only can travel time be competitive, but net operating costs can also be favorable, as evidenced by the increasing use of aircraft such as the De Havilland Dash-7 for this kind of operation. Moreover, when the distributed costs of adding additional capacity to the total transport network are considered, STOL has the potential to provide benefits particularly in high-density, already congested areas.

In order to expand the useful role of STOL aircraft within the transportation network, it becomes necessary to extend the range for which these aircraft remain competitive with conventional turbofan transports. This implies obtaining an increase in cruising speed by equipping the aircraft with turbojet or turbofan engines, and reducing the wing area (increasing the wing loading) to values typical of modern short-range jet transports, at the same time maintaining the short-field performance of the STOL turboprop designs. As well, it is essential that this new generation of STOL aircraft remain efficient while operating at low speed in the terminal-area.

The case for a military tactical transport aircraft with the combined capabilities just described is based on somewhat different considerations. The requirement for fast STOL transports is becoming particularly attractive to military planners who are increasingly concerned with the vulnerability and geographic scarcity of large conventional air bases. At the same time, the military emphasis is typically on performance and operational flexibility, rather than operating economics and design efficiency, with the result that the design constraints (regarding fuel economy and noise for example) may be considerably relaxed for this particular application.

To retain the low takeoff and landing airspeeds in these new STOL transports, it becomes necessary to introduce some form of blown-flap or powered-lift system to furnish the additional lift that cannot be adequately provided at these higher wing loadings by a mechanical flap system. In some powered-lift designs, this additional lift may be provided simply by deflecting some or all of the engine thrust, thus allowing the engines to operate at moderately high-thrust settings during approach, while also allowing (by virtue of an adequate reduction in the longitudinal thrust component) the steep approach gradients which are typical of STOL operations. However, it is usually possible through clever aerodynamic design to generate "supercirculation," creating an amount of lift due to engine power which is substantially in excess of the amount of deflected engine thrust, as shown in figure 1. At the same time, operation at these unusually high-lift coefficients typically results in high levels of induced drag, and aircraft operating points located on the backside of the drag curve. These aerodynamic features create some new requirements that do not exist for conventional aircraft. For example, (1) the pilot's technique for controlling glidepath and aerodynamic safety margins during approach requires special consideration, (2) the criteria for ensuring adequate lift margin during approach must be modified to include the effects of changes in approach thrust, (3) design features must be incorporated to minimize the more serious effects of engine failure, and (4) the thrust-deflection feature implies the need for an additional control influencing the thrust-vector angle. Further details of these special features of powered-lift aircraft will be discussed in the following sections of this paper.

The major design challenge relating to the next generation of STOL aircraft concerns the ability of the designer to minimize the penalty associated with the powered-lift system and, if possible, make the STOL aircraft directly competitive with corresponding conventional types operating at various levels in the transportation network. At the same time, special design considerations such as those noted above must be addressed to result in levels of safety and operating simplicity that are comparable to conventional aircraft.

A major portion of the Canadian research in powered-lift has been carried out by De Havilland Aircraft of Canada working in close cooperation over many years with the NASA-Ames Research Center. The Canadian effort has concentrated on the development of jet augmentor technology for STOL aircraft, originating at De Havilland with small scale wind-tunnel and powered-model tests that were funded in Canada by De Havilland, the Defense Research Board and the Department of National Defense. Encouraging test results and early interest by NASA led to large-scale powered-model tests in the NASA-Ames

40- by 80-Foot Wind Tunnel, and subsequently, the modification in 1971 of a Buffalo aircraft intended to flight test the essential low-speed features of the augmentor wing concept.

The development of this test aircraft has been supported by joint U.S. and Canadian funding, and was carried out by the Boeing Company under contract to NASA for basic airframe and control system modifications, and by De Havilland and Rolls Royce of Canada under contract to the Canadian Department of Industry Trade and Commerce for the design and fabrication of the powered-lift system. Since its first flight in May 1972, the Augmentor Wing Jet STOL Research Aircraft (AWJSRA), shown in figure 2, has accumulated more than 650 flight hours in over 700 test flights, carrying out more than 2,500 landings in the powered-lift STOL approach configuration. The first two years of this flight program consisted of a proof-of-concept phase involving investigation and documentation of the aircraft's aerodynamic characteristics. The past six years of its operation at the NASA-Ames Research Center have been devoted to more general investigations of a wide variety of design and operational problems likely to be encountered by generic powered-lift aircraft. While the emphasis has been on civil applications of these aircraft, many areas of study also pertain to military missions. It is the purpose of this paper to provide a brief summary of these flight investigations, which together constitute the broadest base of powered-lift flight experience currently available.

Supporting these investigations, and in some cases the initial development of the aircraft, have been the NASA-Ames Flight Simulator for Advanced Aircraft (FSAA), an advanced digital avionics research system (STOLAND) provided by Sperry Flight Systems under contract to NASA, a separate fixed-base simulation facility, and the NASA flight test facilities at Ames and at Crows Landing, California. While most of these investigations (now nearing completion) have been initiated and carried out by NASA, several have been proposed and carried out by De Havilland and the National Research Council of Canada (NRC), still to meet mutual objectives. In the course of these flight tests, the aircraft has been flown and evaluated by pilots from a variety of government agencies and military services from the U.S. and Canada, and to a lesser degree, Britain and France.

Concurrent with these low-speed flight research efforts which have comprised the bulk of the more recent cooperative research efforts, some promising developments in the high-speed cruise regime resulting from theoretical design and model tests employing supercritical airfoil sections have been tested in both NASA and NRC wind tunnels. Some early results from this work, which was financially supported on the Canadian side by the Department of National Defense, are reported in reference 1. In addition, some encouraging results from recent large-scale powered-model tests at NASA-Ames indicate the potential benefits of applying augmentor technology to VTOL aircraft (ref. 2).

The success and significance of nearly fifteen years of cooperative development of augmentor technology stem from the continuity of effort which has been afforded, as well as the opportunity for the joint U.S./Canadian team of engineers and scientists from both industry and government to take advantage of these unique large-scale NASA aeronautical research facilities.

AIRCRAFT DESCRIPTION

The AWJSRA is a modified De Havilland of Canada DHC-5 Buffalo, as shown in figure 2. This airframe provided an effective means to investigate the basic low-speed features of the augmentor-wing powered-lift concept without incurring the considerably greater expense of a more comprehensive design. For example, it was possible to modify the basic Buffalo wing[a] to contain the powered-lift system, and except for the addition of a hydraulic control surface actuator, no changes were required to the empennage. In addition, the undercarriage is fixed, perhaps a desirable feature for an aircraft whose role is to perform primarily approach and landing investigations.

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 cross-ducted 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 provide 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. Provision exists for a modest amount of direct lift control through symmetric actuation of electrohydraulic choking surfaces designed as part of the inboard augmentor flap segments. The pilot has no direct control over these surfaces, which are available for incorporation in a stability augmentation system. Figure 4 illustrates the overhead cockpit control layout used for propulsion system management.

[a]To increase the wing loading to levels more representative of a proper design, the maximum gross weight was increased by 0.4 kN (9000 lb). In addition, the span was reduced by approximately 5 m (17 ft), although this results in a further compromise on the aspect ratio best suited to a twin-engine design.

This particular power-plant arrangement is one that is able to furnish the required blowing airflow to the augmentor flap while making effective use of the residual core thrust. Since the definition of this design, several developments have been made in power-plant and augmentor technology (refs. 3 and 4) that could result in significant improvements in key operating characteristics such as noise and fuel consumption. More details on the physical characteristics of the research aircraft are found in reference 5, while documentation of its basic aerodynamic characteristics from an earlier phase of flight testing not discussed in this paper is contained in reference 6.

RESEARCH AVIONICS SYSTEM

The AWJSRA is equipped with a comprehensive and flexible digital avionics research system referred to as STOLAND, providing the primary functions of navigation, guidance, control (via flight director and/or automatic servos), display generation, and system management. The system is shown schematically in figure 5, and is more extensively described in reference 7. The arrangement of the various controls and displays in the cockpit is shown in figure 6. A laboratory fixed-base simulation facility has provided the means for the development and verification of flight software, and has also been used for pilot familiarization and preliminary evaluation during the development of the various programs. The 32 K/18 bit word minicomputer shown in figure 5 serves navigational, guidance, and control requirements through interfaces with the programmable electronic cockpit displays, control system servos, and the pilot's mode selection panel. A rho-theta area navigation (RNAV) system is incorporated, providing a flexible capability for multisegment and curvilinear profiles, in a VOR, TACAN, or MLS navigation environment.

Control-system servos which provide the capability to implement a wide variety of flight control configurations consist of parallel electromechanical actuators on the pilot's column, wheel and rudder controls, the dual segment augmentor flaps, the throttles, and the nozzles. Electrohydraulic series actuators are located in the elevator, lateral control, and rudder control system linkages. The direct-lift-control chokes are also controlled through the computer providing a means to vary the lift characteristics of the aircraft. The pilot or copilot has the capability to effect programming changes in flight through a keyboard located on the lower center console, enabling a variety of system configurations to be evaluated during a single flight. The system employs an extensive set of on-line monitors to ensure proper operation of both hardware and software functions, a feature particularly important for automatic landing investigations and on advanced automatic flight-control programs where many controls may be moving at once.

The extensive capability of this system, particularly its programmable features, exploits the unusual control system flexibility of the research aircraft to allow investigation of a broad range of systems concepts potentially applicable to present and future powered-lift aircraft. However, it should be emphasized that the use of advanced avionics and control systems which may be implied in this presentation is not necessarily essential for the development and effective application of these aircraft. In addition, the systems and operational procedures needed to support effective application of these aircraft to meet military mission requirements may be substantially different.

FLIGHT-TEST ENVIRONMENT

The flight-test programs summarized in this presentation were carried out at the NASA-Ames test facility located at Crows Landing, California, shown in figure 7. A STOL runway defined in accordance with FAA Advisory Circular 150/5300-8 is established on one of the CTOL runways, and is served by a microwave landing system (MLS) equipped with DME. Radar tracking, air-to-ground telemetry, data monitoring and recording, and communication facilities are provided to support test operations. The terminal-area approach and landing investigations which have been carried out were conducted using the local navigation environment, consisting primarily of a TACAN facility located on the airport, interfacing to the precision MLS.

MANUAL CONTROL FLIGHT INVESTIGATIONS

Flightpath Control Considerations for Powered-Lift Aircraft. The operation of powered-lift aircraft at high-lift coefficients on the backside of the drag curve and using deflected thrust for glidepath control can present a number of control problems for the pilot. For example, the characteristics of the flightpath and airspeed responses to an incremental thrust change, when attitude is held constant, are shown in figure 8 for two different inclinations of the thrust vector angle. In the case of the forward-inclined thrust vector (fig. 8(a)), the pilot must contend with responses to his single control input in both speed and glidepath that typically develop with undesirably long time constants. The responses for a thrust vector inclined even slightly aft involve a speed reduction which, if allowed to persist, results in a depletion in the long-term flightpath angle from its maximum value. As a prelude to flight experiments in the AWJSRA, these characteristics had been investigated in detail analytically and during piloted simulations, as reported in reference 8. The flight evaluation of a range of these characteristics in the AWJSRA, which were implemented using the programmable features of the STOLAND flight control system, validated the previous findings and provided new design criteria for this class of aircraft.

This research effort also considered various aircraft design parameters which influence the short-term flightpath response characteristics in the context of the landing flare. Flare techniques using both pitch attitude and throttle, separately or together, were evaluated. For the case of flaring with pitch, the single most important parameter was found to be heave damping, a quantity strongly affected by lift-curve slope, approach airspeed, and wing loading. Preliminary results defining boundaries of acceptability are reported in reference 9: a more detailed analysis will be reported in a NASA technical publication.[b] In addition, selected configurations representing different flare characteristics were evaluated at night in conjunction with various runway lighting arrangements that were based on the lighting system developed for the Canadian STOL Demonstration Program (reference 10). The results of this evaluation, which will be reported separately,[c] indicated that the night environment characterized by a variety of lighting arrangements did not materially affect the conclusions (regarding the minimum acceptable flare characteristics for powered-lift STOL aircraft) that were drawn from the more comprehensive daylight tests.

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[b] Franklin, J. A.; Innis, R. C.; and Hardy, G. H.: Flight Evaluation of Flightpath and Airspeed Control Requirements for the Approach and Landing of STOL Aircraft.

[c] Franklin, J. A.; Innis, R. C.; and Hardy, G. H.: Flight Evaluation of the STOL Flare and Landing During Night Operations.

While this research applies to a broad range of powered-lift concepts, some configurations which were evaluated were particularly relevant to the augmentor wing. Some of these configurations which could significantly improve the handling characteristics of an augmentor wing aircraft are separately reported in reference 11, where the design details of several supporting systems such as a rate-command attitude-hold SAS used in the course of the general research are also described. Finally, a summary of some operational experience with the AWJSRA, which had been accumulated during the first four years of flight testing when much of the work reviewed in this section was in progress, is reported in reference 12.

Development of Proposed Airworthiness Criteria for Powered-Lift Transport Aircraft. A joint NASA-FAA research program was undertaken in 1972 in recognition of the requirement for special consideration in the certification of powered-lift aircraft. Its objectives were to develop tentative airworthiness criteria (concentrating on the approach and landing flight phases), to define demonstration test techniques, and to explore design implications of the criteria. Representatives of the U.S., British, Canadian, and French airworthiness authorities participated in this study, which proposed criteria based on (1) simulation results obtained using the Ames Flight Simulator for Advanced Aircraft, (2) previous Ames Research Center flight experience with a variety of experimental powered-lift aircraft (for example, ref. 13), and (3) recommendations from other sources. This effort resulted in publication in 1976 of "Progress Toward Development of Civil Airworthiness Criteria for Powered-Lift Aircraft" (ref. 14).

These proposed criteria were then subjected to a limited flight evaluation by U.S. and Canadian pilots using the AWJSRA. The categories which were considered during the simulation and review effort of reference 14 and those which were also evaluated in flight are summarized below:

- Flight envelope limits*
- Safety margins*
- Approach path control*
- Flare and landing*
- Go-around
- Propulsion system failure
- Landing field length

*criteria evaluated in flight

As an example of this flight-test application of the AWJSRA, the Safety Margins category will be discussed briefly, since it usefully demonstrates some important characteristics of powered-lift aircraft.

Figure 9 shows the trim (unaccelerated) flight envelope for a powered-lift transport in the landing configuration in terms of airspeed and flight-path angle. The central clear area constitutes the ultimate limits of the flight envelope. In the shaded region at the top of the chart, the thrust required for steady flight is greater than the maximum available; in the lower right-hand corner it is less than flight-idle thrust. Beyond the right edge of the chart, the airspeed exceeds the placard (structural) limit, and in the lower left-hand corner, the aircraft is either stalled or otherwise uncontrollable. The broken minimum-speed contour V_{MIN} corresponds to the maximum-lift coefficient, $C_{L_{MAX}}$. The region of the flight envelope between the α_{MAX} and V_{MIN} contours is not useful for controlled operation, but can provide additional protection against vertical gusts. (In general for powered-lift aircraft, it is necessary to consider the maximum angle of attack, α_{MAX}, separately from V_{MIN} or $C_{L_{MAX}}$.)

Safety margins must then be applied to this ultimate flight envelope to define the normal or operating envelope. Figure 10 summarizes the safety margins recommended in the proposed criteria. Two speed-margin boundaries were defined; one based on a speed margin of 30% (minimum 20 knots) from the minimum speed at maximum thrust, and one based on a 15% (minimum 10 knots) margin from the minimum speed corresponding to the thrust setting for each flightpath angle. An angle-of-attack margin providing protection against an abrupt 20-knot vertical gust without exceeding α_{MAX} was also recommended. The clear area remaining in the ultimate flight envelope after these boundaries have been applied is termed the normal or operating flight envelope. All expected flight operations should be carried out within this normal envelope while maintaining safe margins from the ultimate envelope limits. The figure also shows the penalty on the operating envelope that certification under the current regulations (FAR Part 25) would impose.

The next question considered is where within this normal envelope the nominal operating point (A in fig. 10) should be located. An important requirement — also considered in detail in reference 14 — is that it be located sufficiently remote from the upper and lower flight envelope boundaries to ensure adequate glidepath control authority when making sustained corrections to glidepath. However, it is also necessary to consider how the actual instantaneous operating point may change as the pilot makes flightpath corrections during the approach. In a conventional aircraft, the pilot attempts to maintain the approach airspeed nominally constant. On the other hand, most of the powered-lift research aircraft have been flown to a reference angle-of-attack. It can be seen from figure 10 that maximum use of the powered-lift envelope for the purpose of making flightpath angle changes would result from using the speed-margin boundary for maximum thrust when making shallow glidepath corrections (from below the nominal path), and using the angle-of-attack margin boundary when making steep glidepath corrections (from above the nominal path). However, there is some question whether the pilot can follow such contours successfully in that separate flight reference parameters are involved. The purpose of the safety margin phase of the flight evaluation was to examine problems associated with using a flight reference that utilizes as much of the normal operating envelope as possible. Questions were investigated such as, "Can the pilot utilize a flight reference that is near the corner formed by the intersection of the two margin boundaries?" and, "How steeply inclined (in the airspeed-flightpath angle plane) can the angle-of-attack boundary be?".

Several successful flight reference mechanizations were developed, but two appeared most promising. The first was a straightforward combination of the speed-margin boundary, and the angle-of-attack margin boundary shown in figure 10, hence addressing, for the particular case of the AWJSRA, the issues questioned above. These were combined on a single-needle instrument which displayed deviation from the critical boundary, normalized by the required safety margin. If the aircraft was on reference, the indication was 100%; if it was at α_{MAX} (or minimum airspeed), the indication was 0%. For deviations into the normal envelope, the instrument indications were greater than 100%. The operating point A was located close to the intersection of the speed and angle-of-attack boundaries in figure 10. Because of the piloting problems associated with changing from controlling airspeed during upward corrections and angle-of-attack for downward corrections, as well as the effects of atmospheric disturbances, this implementation was somewhat difficult to fly, but nevertheless was rated as acceptable.

In order to alleviate higher than desired workload, an additional directive element was added to the display which, when nulled with an appropriate change in pitch attitude, resulted in a recovery of desired margins. This eliminated the differing response of the "raw" flight-reference display when changing between speed and angle-of-attack boundaries and suppressed short-term effects of atmospheric disturbances. This directed pitch attitude was now considered as a new single consistent flight reference, while the "raw" display was used to confirm its proper effect. This significantly reduced the workload associated with maintaining safety margins during both visual and instrument approaches (to a level below that for maintaining reference speed in a CTOL aircraft) without sacrificing any of the normal operating envelope.

The definition and implementation of a flight-reference parameter, which, like speed in a conventional aircraft, serves to preserve aerodynamic safety margins, is somewhat more complicated in a powered-lift aircraft. This research demonstrated that the safety margin criteria developed in reference 14 appeared to be suitable for the AWJSRA, and that a single flight reference which did not sacrifice any of the resulting normal operating envelope could be implemented and flown easily by the pilot.

Vectored Thrust and Automatic Speed Control Concepts for Powered-Lift Aircraft. Characteristic of powered-lift aircraft is the deflection (usually by some aerodynamic means) of a significant percentage of the available thrust to a direction approximately normal to the flightpath. For designs where virtually all of the available thrust is deflected through aerodynamic means associated with the wing or flap design, glidepath control is then usually effected by modulating the magnitude of this powered-lift thrust that is used during the course of an approach. If speed is kept approximately constant, this action in the long term influences the aerodynamic angle-of-attack resulting in a change in induced drag, thereby causing a change in flightpath angle. The issues associated with this mode of control, usually termed the "Backside Control Technique," have been widely investigated over recent years, as evidenced by the research programs just discussed. However, some powered-lift concepts may have available a significant amount of undeflected thrust which can be independently modulated without significantly affecting lift, thus raising the question of whether use can be made of this residual longitudinal force to permit a more conventional flightpath control technique. Even if all of the engine thrust is deflected, it may be that the direction of a significant amount of this thrust can be sufficiently vectored to provide the same effect.[d] The particular control technique of interest involves controlling glidepath with pitch attitude, maintaining airspeed by modulating the longitudinal thrust component, and leaving the components of thrust contributing to powered-lift at essentially constant values which are aerodynamically or economically optimum for the particular approach configuration. This basically conventional flightpath control technique is usually referred to as the "Frontside Control Technique," although strictly speaking,

[d]To enable an alternative control technique to be considered, there must be available a significant range of longitudinal force control which can be obtained at moderately high rates, similar to simple throttle usage in a conventional aircraft. Consequently, slow-moving flaps, although strongly influencing the thrust vector angle, cannot be considered a candidate for longitudinal force control and instead are treated as conventional configuration devices.

the aircraft is still being operated at a point on the backside of the drag curve.

In the AWJSRA, longitudinal thrust control is available by modulating the nozzles about their downward position at rates as high as 80 deg per sec. In the range 80 ±25 deg, for example, a signifi^ant amount of longitudinal control power (±0.08 g) is available, while also providing a nearly fixed addition to the powered-lift produced by the augmentor flap system, as shown in figure 11. A future augmentor wing transport might employ a "three stream" engine embodying a geared variable pitch fan (ref. 3). This design (fig. 12) could allow the longitudinal thrust to be modulated by the variable pitch fan, while the offtake air needed to power the augmentor flap remains essentially fixed. One advantage of this type of design is to allow installed thrust requirements to be determined by trim performance specifications, without the need for additional installed thrust to also provide flightpath control.

The long-term effectiveness of the alternative control techniques just discussed is evident in the speed vs flightpath angle trim maps shown in figure 13. The figure on the left indicates the range of control over flightpath angle which can be achieved with throttle changes for the fixed vectored-thrust nozzle position shown, without considering the safety margin boundaries discussed in the previous section. Alternatively, about the same range of flightpath angle control can be obtained, in the long term, by varying the vectored-thrust nozzle angle while leaving the throttle fixed. In addition, it should be apparent that the "fixed" control can be adjusted in a trim sense in order to bias the available envelope upwards or downwards, a consideration addressed in a following section.

The details associated with accomplishing glidepath control in the STOL configuration using a "Backside," or alternatively, a "Frontside" control technique, require consideration of many factors, especially the short-term control characteristics. Complementary to the work described in the previous sections which emphasized Backside control, research has been carried out towards determining the stability augmentation, cockpit display, and pilot control-system requirements that may be necessary to support the use of the Frontside control technique.[e] Although the availability of a significant amount of longitudinal thrust does present the possibility of some of the glidepath control features of a conventional aircraft, the high levels of induced drag characteristic of powered-lift operations results in other objectionable features that may present control difficulties for the pilot. For example, angle-of-attack changes due to maneuvering or turbulence are quickly translated into speed changes, which require immediate correction to avoid undesired changes in flightpath angle. In addition, the low airspeeds and steep approach angles characteristic of STOL aircraft result in the need for significantly higher levels of control activity if using pitch attitude to control glidepath.

The solution to some of these problems has been found to be the use of a stability augmentation system that automatically modulates the longitudinal thrust component to maintain a constant approach airspeed during the glidepath control task. The essential features of an automatic speed-control system for the AWJSRA were investigated during the research of reference 11 and had earlier been proposed by De Havilland. The system was considerably refined

[e]Hindson, W. S.; Hardy, G. H.; and Innis, R. C.: Flight Evaluation of Systems to Support the Use of the Frontside Control Technique During Steep Approach in a Powered-Lift Aircraft. Proposed NASA technical report.

during the research of reference 15 for use during a complex instrument approach task, where, as shown in figure 14, the speed reference employed by the system was made a function of flap configuration and weight. The crossfeed from nozzles to chokes shown in the figure serves to increase the range of useful control authority by offsetting the lift loss that occurs if the nozzles are excessively retracted (below 60 deg) in the course, for example, of moving to hold speed during a large upwards correction to glidepath. Use is also made of any residual direct-lift authority from the chokes to augment heave damping, hence improving the initial glidepath response to pitch attitude changes.

In addition to evaluations of automatic speed-control systems, the investigations of this control technique included the development of systems to better assist the pilot in safely executing the STOL approach task should this stability augmentation system fail. A speed-control flight director and a sidearm arrangement that integrated throttle and nozzle control into a single propulsion system control lever were evaluated in flight. They were found to be effective aids in reducing the workload involved in coordinating pitch attitude and nozzle position (or simulated variable-pitch fan blade angle) in the nearly simultaneous manner that is required by this control concept.

Development of a Curved Decelerating Instrument Approach Capability. A capability to perform steep, turning, and decelerating approaches under manual control and in instrument meteorological conditions which was developed and flight-tested in the AWJSRA is summarized in reference 16 and reported in detail in reference 15. The general objective of this investigation was to assess the potential for enhancing the operational efficiency of STOL aircraft by reducing terminal-area arrival times, and selectively locating the final approach route for reasons of noise curtailment, obstruction clearance, conflicting CTOL operations, or military tactical constraints. The emphasis of this investigation 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.

A typical approach profile flown during the investigation is shown in figure 15. In recognition of the comprehensive nature of the STOL instrument approach task, an underlying aim of this work was to integrate the navigation, guidance, control and handling qualities, cockpit display, and procedural factors into a potentially feasible operational framework. Features contributing to the feasibility of the task were a multifunction, three-cue flight director for pitch, roll, and throttle control, along with the integrated electronic cockpit displays illustrated in figures 5 and 6. Procedures were developed to accomplish the deceleration from terminal-area entry speed to the final approach speed and to deal with strong winds during the descending turn and the final approach.

Three STOL control concepts summarized in figure 16 were also evaluated for their effect on the task, including the automatic speed-control system described in the previous section. The designations of control functions which are shown in figure 16 indicate another unique aspect of powered-lift aircraft operations that is related to the thrust-vectoring feature described earlier. Use must typically be made of some third longitudinal control (other than the controls used for glidepath and speed control) to adjust lift-drag trim states during approach, with the objective of maintaining control authorities, safety margins, and operating economics in the prevailing wind conditions. This requirement can be deduced from study of figure 13 which implies that a change in the position of the fixed control has the effect of biasing the available flight envelope upwards or downwards about the desired operating point. The procedure is analogous to employing a reduced flap setting for approaches in strong winds in a CTOL aircraft in order to preclude excessive approach thrust settings. In the system which was developed, the proper position for the trim control, which typically required adjustment only once or twice during the turning descent, was displayed to the pilot as a flight-director cue, and was found to be an instrumental factor in reducing the workload to more acceptable levels. For the case of the basic AWJSRA flown using a Backside control technique and without any speed-control augmentation, the nozzle was the trim control, and its proper position was computed and displayed as a fourth cue on the flight director.

A comprehensive set of flight-test data describing navigation and guidance system performance, flight-director tracking performance, pilot control inputs, and aircraft response parameters are presented in reference 15. 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. The results of this investigation indicated that instrument operations on significantly constrained terminal-area approach profiles are potentially feasible from a pilot acceptance point of view.

Engine Failure Studies for Powered-Lift Aircraft. The problem of engine failure during low-speed approach and landing is particularly critical for powered-lift aircraft which are equipped with only two engines. The most critical region appears to be in the vicinity of flare and landing, since the time necessary for the pilot to (1) recognize that a failure has occurred, (2) achieve maximum thrust on the remaining engine, and (3) modify the flare and landing technique appropriately, may result in excessively hard and perhaps short touchdowns. Although the probability of a failure occurring at this particular time may be very low, systems and procedures to ensure a satisfactory level of safety must still be developed.

A program of analysis, simulation, and flight test was carried out cooperatively with De Havilland Aircraft, NRC, and NASA that employed the Augmentor Wing Jet STOL Research Aircraft to investigate these issues. The objective of these investigations was to identify aircraft design requirements that may be necessary in order to satisfactorily handle these failures. Various levels of restored thrust settings were evaluated following a simulated engine failure occurring at various stages of an approach and during a simulated landing. In addition to assessing the sink-rate and height-loss performance that resulted from the pilot's manual response to engine failure, the capability of a fully automatic thrust-compensation system, which immediately applied maximum thrust on the remaining engine following the sensed failure, was also evaluated. For this investigation, a simulated flare to a simulated "ground" level was employed. The programmable features of the electronic cockpit displays were used to improve repeatability of the simulated flare, since flight safety considerations precluded failures during actual landings.

A typical series of time histories for the automatic thrust-compensation system is shown in figure 18. The lower set of curves shows the programmed throttle and choke control inputs which were injected using the STOLAND servos to simulate the symmetric lift loss that would occur during an actual engine failure. (Asymmetric effects were also considered.) In order to adequately simulate the initial very rapid lift loss that would occur in the event of an actual sudden engine failure, it was necessary to retard both of the throttles and to dump additional lift with the chokes at the time of "failure" as shown. In this example, the automatic compensation system which was simulated restored the thrust to just over 100% of the original trim approach value starting 0.5 sec after "failure." A thrust-restoration rate corresponding to maximum single engine spool-up capability was simulated. The upper set of curves in figure 18 shows the flightpath angle and angle-of-attack responses which result from the "failure" and the rapid pitch rotation which the pilot initiated upon its recognition. In the example shown, "failure" was caused to occur at a point 30 m (100 ft) above the simulated "ground" level. The pilot's success in arresting the sudden increase in sink rate prior to "touchdown" to a level comparable to a normal (no failure) landing is indicated in figure 19, where the sink-rate and pitch-attitude profiles with height are plotted.

Although the scope of this investigation was limited, the experience of this program will contribute to the development of certification procedures for this important aspect of twin-engine powered-lift operations. The results of these tests appear to indicate that heavy reliance can be placed on analytical and simulation techniques to certify these critical failure cases.

Power-plant Control Integration Investigations. The typical requirement in powered-lift aircraft for an additional longitudinal control to govern the orientation of the thrust vector may complicate the pilot's control manipulation and control management functions in the cockpit. In some powered-lift designs, this additional control may be an aerodynamic surface, such as the Coanda flaps for an upper-surface blowing concept. For the AWJSRA, thrust vectoring is accomplished mostly by deployment of the slow-moving augmentor flaps, and partly through nozzle vectoring (or, in a three-stream engine design, blade angle adjustment of the variable-pitch fan). In either case, there is usually a control available to the pilot (which is part of the propulsive-lift system and which is closely associated with the throttle) that has the capability to exercise a significant amount of authority over the thrust vector angle at control rates which are substantially higher than might be typical of a configuration control (such as conventional flaps). The requirement for such a control is based on the need for a rapid devectoring capability to provide more immediate missed-approach capability in the event of engine failure, and also to provide a method for rapid and effective speed control particularly in wind shear conditions.

As described in a previous section, this additional control can be managed by a stability augmentation system, usually incorporated in an automatic speed-control system. For completely manual operation, however, it has been of interest to evaluate in the AWJSRA different cockpit propulsion-system control configurations, other than the separate overhead throttle and nozzle levers shown in figure 4. To provide some flexibility in this regard, the power-lever installation shown in figure 20 was designed to allow the throttles and nozzles to be controlled via the STOLAND servos in a variety of ways from a single control handle. One designation of control functions which was evaluated is labelled in figure 20. In addition, the friction and centering characteristics of the power-lever could be varied to assess their utility for improving the pilot's management of the propulsive-lift system during Backside operations, using either a Backside or a Frontside control technique.

AUTOMATIC FLIGHT CONTROL INVESTIGATIONS

Automatic Landing System Development. A major effort has been devoted by NASA to the development of an automatic landing capability for the AWJSRA. A primary objective of this work has been to assess the applicability to powered-lift STOL aircraft of systems development and certification techniques which are in current use for CTOL transport aircraft. Briefly, these procedures place heavy reliance on simulation, initially as a development tool and subsequently as the primary source of a broad base of system performance data in the presence of specified atmospheric disturbances (and system failure cases). A limited amount of flight testing is then carried out in order to validate the simulation results. In particular, the reliability of the low-probability data obtained from the simulation tests is deduced from how well the flight-test data validated the near-nominal cases.

Sample data from simulation and flight test of the AWJSRA is presented in this manner in figure 21 for one of the automatic control configurations which was tested. Fast-time simulation techniques were used to obtain a large population, exceeding 10,000 samples, of landing performance data (touchdown distances and sink rates) in three different atmospheric conditions. The number of observations which fall within specified successive performance intervals is accumulated and normalized by the total sample size, resulting in a probability density function. This function is then integrated and the results plotted in figure 21. (A straight line implies the observations are from a Normal or Gaussian distribution.) In figure 21(a), the ordinate indicates the probability associated with achieving a touchdown sink rate which is in excess of any value specified on the abscissa. The probabilities associated with touchdown distance (figure 21(b)) are interpreted similarly, with additional interest shown in the likelihood of short touchdowns, for example, at distances less than the mean. These probabilities are indicated by the lower left leg of the curves, which are to be associated with touchdown distances less than the values specified on the abscissa. The fact that the touchdown dispersions appear normally distributed about the mean is fortuitous and a reflection of the particular automatic control system and simulation model employed. To complete the presentation of figure 21, flight-test data from 31 landings in a variety of atmospheric conditions using this same control system are similarly reduced and plotted for comparison.

For this powered-lift automatic landing investigation, the philosophy which was established for the landing flare control law was similar to the one typically used for conventional jet transports. That is, closed-loop control following flare entry was based on a programmed sink rate vs height above runway. For this investigation, appropriate compensation was also made for winds, and a Backside control technique was used in following the landing flare profile. An open-loop pitch rotation, linear with decreasing height towards a target touchdown attitude, accompanied the throttle's closed-loop control of the flare profile. The availability of the augmentor chokes for direct lift control and the vectoring nozzles for speed control allowed evaluation of a variety of powered-lift STOL automatic control configurations in an effort to determine the tradeoffs between system complexity and performance. Although interest was focused on the landing maneuver (including decrab techniques for runway alignment in crosswinds), precision glideslope and localizer tracking also received major emphasis, since off-nominal conditions at flare entry can strongly affect the landing performance. More than

300 automatic landings culminating in three distinct longitudinal control configurations and two runway alignment techniques were carried out in a variety of atmospheric conditions. Preliminary flight data from this investigation have been previously reported in reference 17, while reference 18 is representative of the large effort which has been made in control law development and in establishing the simulation data base. A more comprehensive report[f] of the simulation and flight test results is in preparation, outlining factors for consideration in the development and certification of an automatic landing capability for powered-lift STOL transport aircraft.

Advanced Autopilot Design Concepts. Similar to several new aircraft concepts which are currently being developed, an augmentor wing jet STOL transport would be characterized by an unusually large flight envelope, complex nonlinear aerodynamics, and control system redundancies. These features, particularly for V/STOL aircraft, present a challenge to the designer of an automatic flight control system since classical techniques based on a large number of single-point linear perturbation models, adaptive designs, or gain scheduling become impractical to employ. Indeed, there is a requirement for even more capable automatic or semiautomatic flight control for these aircraft since rapidly accelerating or decelerating transitions from or to the powered-lift configuration are desirable to minimize operating costs and enhance operational effectiveness. These maneuvers typically involve the most intractable aerodynamics and the use of several controls at once.

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[f]Watson, D. M.; Hardy, G. H.; and Warner, D. N., Jr.: Analysis, Simulation and Flight Test Determination of the Runway Length Required for the Augmentor Wing Jet STOL Airplane Automatic Landing System. Paper to be presented at the NASA Aircraft Safety and Operating Problems Conference, Langley Research Center, Nov. 1980.

A structure for an advanced automatic control concept which has the potential for dealing with these problems is proposed in reference 19. Motion or trajectory commands are generated based on a predefined reference trajectory or alternatively, by the pilot controlling in some manner the components of an appropriate motion vector (such as velocity). As illustrated in figure 22, the motion commands are conditioned to ensure acceptability of the associated accelerations to the pilot (and compatibility with the capability of the aircraft) and are compared in a feedback sense with the actual motion produced by the system. Any differences are processed linearly (except for authority limiting) and summed with the trajectory command for input to the central feature of the system, a mathematical model of the aircraft which is based on a priori knowledge of its force and moment characteristics. This model is solved inversely to obtain the control positions needed to produce the required motion, while the essentially linear feedback loop makes up for any inadequacies in the model and compensates for atmospheric disturbances.

The advantages of this design concept stem from the large amount of a priori knowledge employed in the feedforward control function which, if correct, significantly reduces the feedback control requirements. The modeled aircraft reflects in a rational way the known effects of nonlinear aerodynamics and changes in aircraft mass and inertia parameters. Similarily, flight envelope limiting and a hierarchy for the use of redundant controls can be easily established. In addition, the basic structure of the autopilot is essentially identical for all flight vehicles, whose details are reflected in the aerodynamic and control system elements of the aircraft model. Finally, the computational implementation of this concept is made possible by the rapid development of digital computer capacity, which when combined with improved reliability from control system actuators and motion transducers, presents the possibility for major savings in structural complexity and the eventual design of future complex aircraft using active controls technology.

Although this autopilot design concept allows for inaccuracies in the aerodynamic model, the importance of adequate precision in the modeling of the force and moment characteristics of the aircraft may be crucial in the effort to maintain linearity and simplicity in the feedback loops. Although wind tunnel and parameter estimation techniques have improved the modeling accuracy over recent years, there remain many difficulties in fully understanding the complex aerodynamic interactions that may be associated with powered-lift aircraft, particularly V/STOL aircraft. In an effort to assess the potential for this flight control concept in the light of these and other difficulties, its application to various research aircraft operated by the NASA-Ames Research Center is being undertaken. Reference 20 describes the development of the inverse aircraft model with its imposed operational constraints for the AWJSRA, including algorithms for its computational implementation. Using the fixed-base simulation facility, the system was developed for evaluation on specified terminal-area trajectories which exercised the aircraft throughout a large part of its flight envelope. Flight tests have demonstrated considerable success and will be reported in a forthcoming technical publication.[g]

Advanced Techniques for Terminal-Area Trajectory Management and Optimization. The requirement for improved efficiency in the terminal area is

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[g]Meyer, G.; Cicolani, L. S.: Application of Non Linear Systems Inverses to Automatic Flight Control Design — System Concepts and Flight Evaluations. In AGARDOGRAPH on Theory and Applications of Optimal Control in Aerospace Systems. To be published in 1980.

driven by a need for increased capacity of existing airports as well as the ever-increasing requirement for improving the fuel and noise efficiencies of arriving and departing aircraft. The application of these requirements to powered-lift STOL aircraft assumes particular significance because of the far greater range of possible approach profiles for these aircraft, as well as their high fuel consumption and noise penalties during the landing approach in the powered-lift configuration. To realize these improved efficiencies will likely require advanced computational procedures to be shared between the air traffic control system and the individual aircraft. For example, runway threshold times at a congested CTOL airport may be assigned to a mix of aircraft types equipped with the capability to meet these arrival times, while maintaining the necessary separation along fixed or variable arrival profiles. Alternatively, approaches to less-congested outlying STOLports could be made more efficient if the aircraft could synthesize its own optimal profile (within reasonable routing constraints associated with noise footprint and obstruction clearances) from whatever point approach clearance is authorized.

Programs of analysis, simulation, and flight test have been carried out at the Ames Research Center to develop these systems and evaluate their potential to both CTOL and STOL aircraft. For example, a fully integrated air traffic control and piloted simulation investigation of a time-of-arrival control concept showed significant increase in airport capacity and reduced pilot and controller workload (ref. 21). In order to investigate time-of-arrival control for STOL aircraft in the flight environment, a 4-D RNAV system was incorporated in the STOLAND avionics system. The results of the flight tests are reported in reference 22. A fully automatic flight control system was employed for the AWJSRA investigations in order to relieve the pilot workload in the management of the multiplicity of controls that are involved in longitudinal path and speed control (throttle, flap, nozzle, and pitch). The performance characteristics of several algorithms to control velocity along the profile were investigated, along with consideration of the net effect of changing winds on time-of-arrival control precision. Complementary to the results of the simulation trials noted above, the pilot felt that the aircraft system concepts and performance characteristics which were demonstrated on the AWJSRA showed potential for operational applications.

The research reported in reference 23 describes an approach profile energy-management system which was developed to minimize fuel consumption and/or noise on descending, decelerating, and curved approaches in the AWJSRA. Iteration algorithms involving backward integration (from the desired final aircraft position and state) are carried out in fast time in order to synthesize an approach profile from the current aircraft position. Constraints reflecting acceptable usage of controls are placed on achievable energy rates, which in turn define deceleration and descent capability. Based on a computer-stored model of the thrust and drag characteristics of the aircraft over its entire flight envelope (lift = weight assumed throughout), the autopilot positions the longitudinal controls to the "trim" position necessary to generate the required energy rate, while a sufficient amount of control authority is reserved to accomplish control-loop perturbation control in a hierarchically designated manner. In order to exploit this control concept, all four longitudinal controls may be at least slowly moving at one time, making the pilot's monitoring task significantly more difficult than for a conventional autopilot. Figure 23, from reference 23, presents an example of longitudinal control activity and profile performance from flight test on a straight-in decelerating steep approach.

An important feature of this concept is the presentation on the electronic multifunction display, shown in figure 5, of continuously updated optimal trajectories as the aircraft approaches the terminal-area under its own navigation, or alternatively, under the management of air traffic control vectors prior to receiving approach clearance. An example is shown in figure 24, where updated trajectories to the final approach waypoint 2 (or any other preselected fixed point) are synthesized at intervals of approximately 5 sec as the aircraft progresses along some initial course. When the pilot selects the approach track mode, the currently synthesized trajectory is frozen and tracked with the optimal energy management configurations appropriate to the initial and final aircraft states. Associated with each synthesized trajectory is the predicted arrival time at the final position, suggesting the potential for combining the 4-D time of arrival control system described earlier with this more flexible system which is not necessarily constrained by any single fixed trajectory.

The requirement for methods to improve the efficiency of terminal-area procedures will persist and will eventually be realized in one form or another as cost-benefit factors improve. The rapidly developing capabilities of digital microprocessor-based avionics systems and electronic displays will be instrumental in achieving capabilities such as those described in this section and throughout this paper.

CONCLUDING REMARKS

The programs which have been reviewed here represent a very significant contribution to the powered-lift STOL technology base that has been developed by NASA in the past twelve or more years. The scope of these programs is a reflection of the flexibility and capability of the STOLAND digital avionics system, and the unusual capability of the research aircraft that together allowed a wide variety of control system concepts to be investigated. In addition to contributing in a general sense to the design of systems for new powered-lift aircraft, the specific experience and data accumulated during these programs will strongly benefit any future development of the augmentor wing concept. In consequence, and taking into account the many wind tunnel investigations, considerable confidence has been established towards design definition of a production augmentor wing transport aircraft for military use, an intermediate step which for mission requirement and economic reasons frequently has preceded civil application of new-technology aircraft.

ACKNOWLEDGMENT

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course, due mainly to those listed in the bibliography, but the contributions of many other individuals at all levels were also instrumental in their successful completion.

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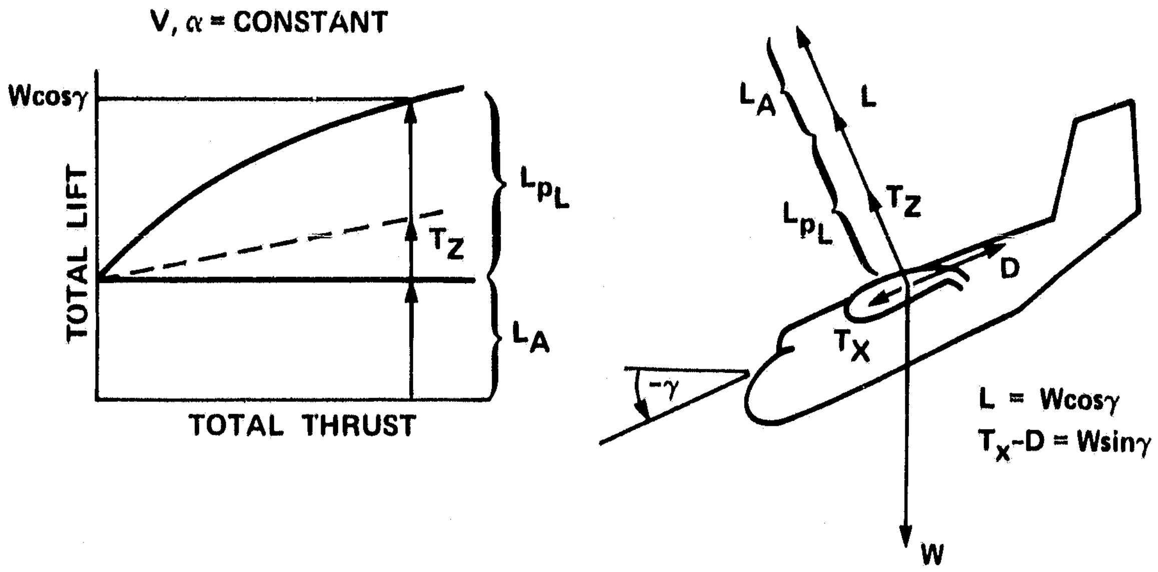


Figure 1.- Aerodynamic and powered-lift components.

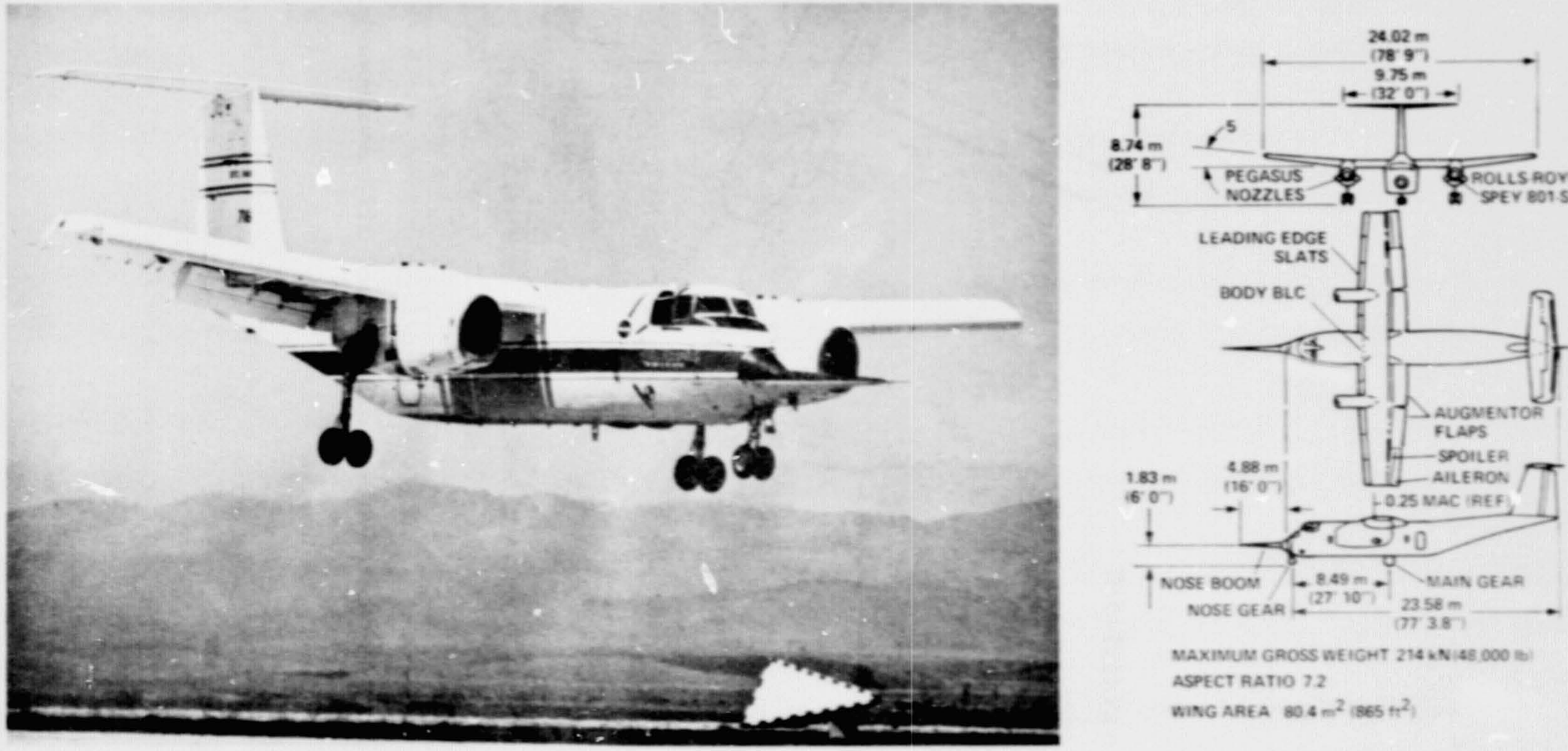
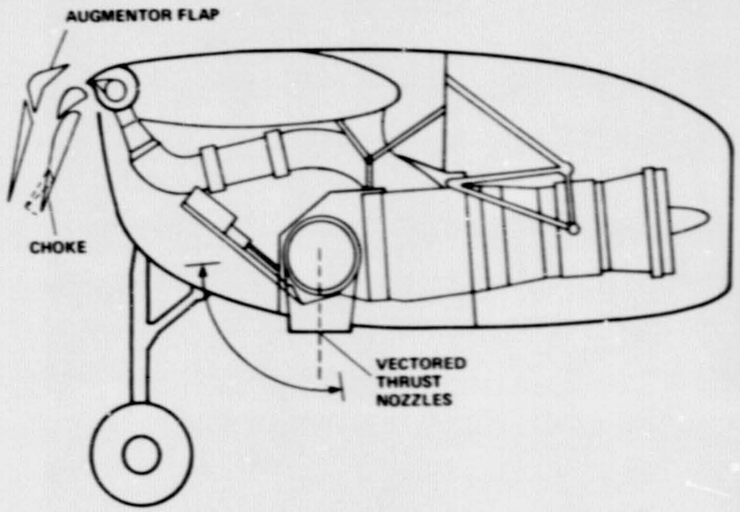


Figure 2.- Augmentor Wing Jet STOL Research Aircraft.



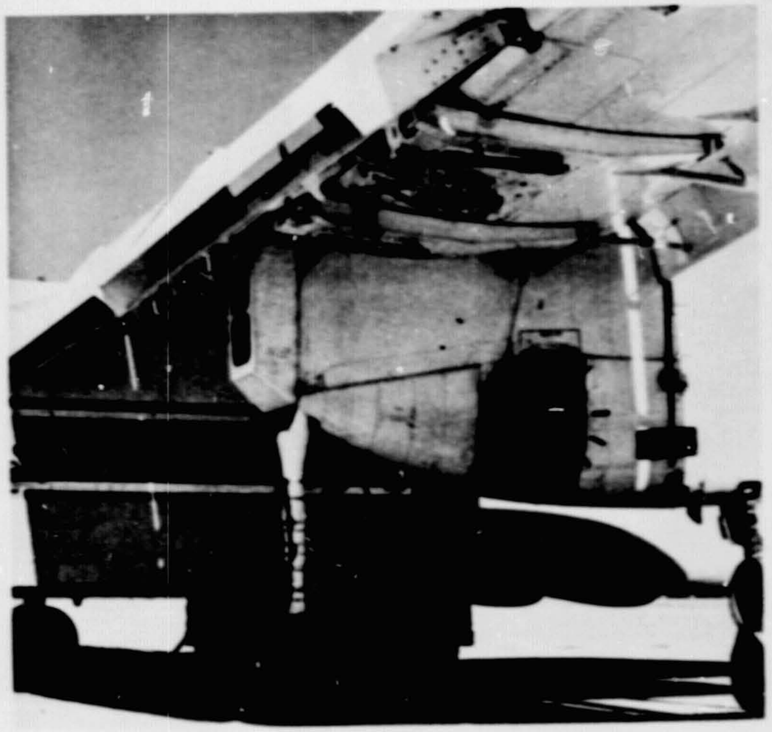


Figure 3.- AWJSRA propulsive lift system.

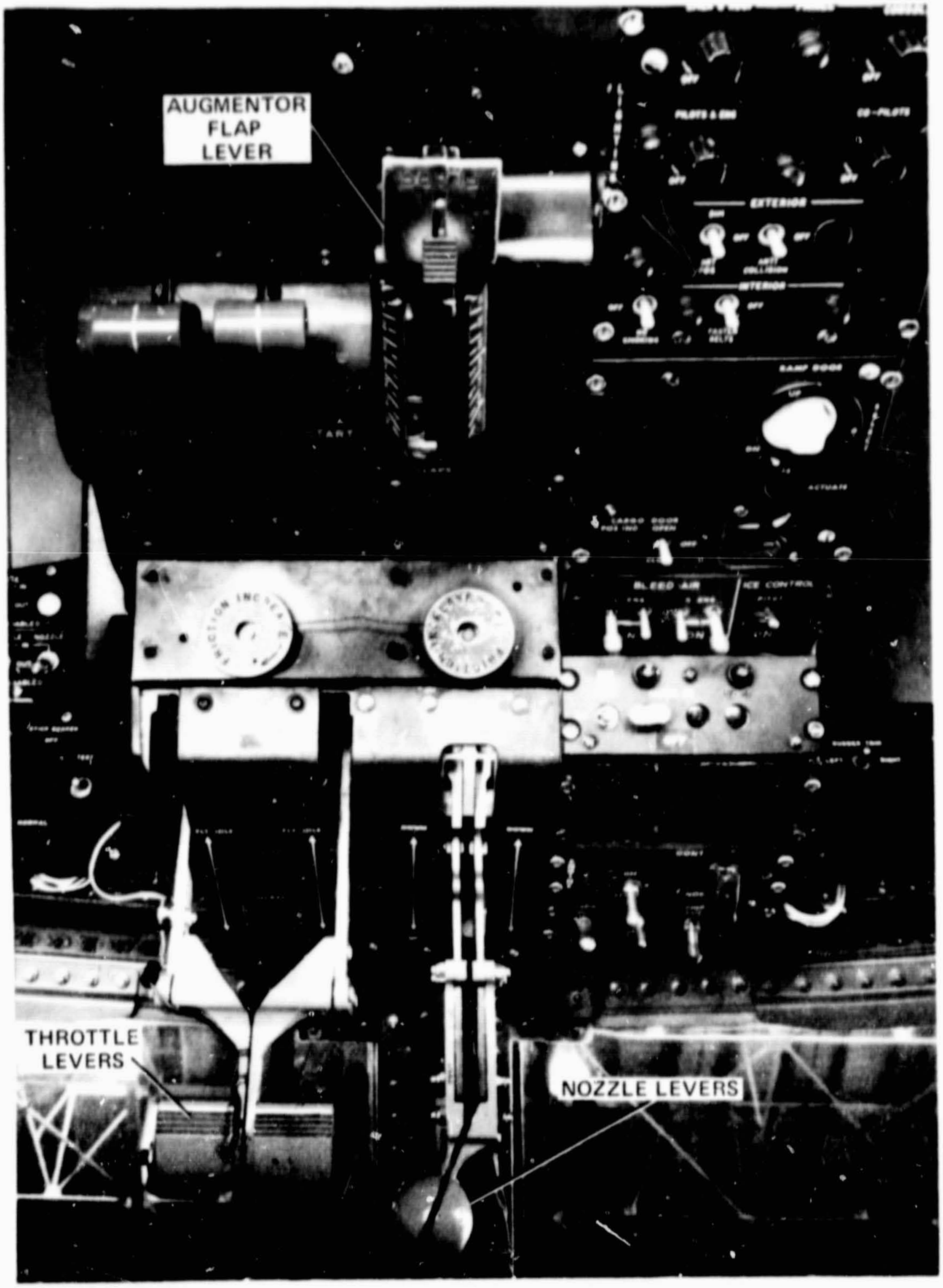


Figure 4.- Overhead propulsion system controls.

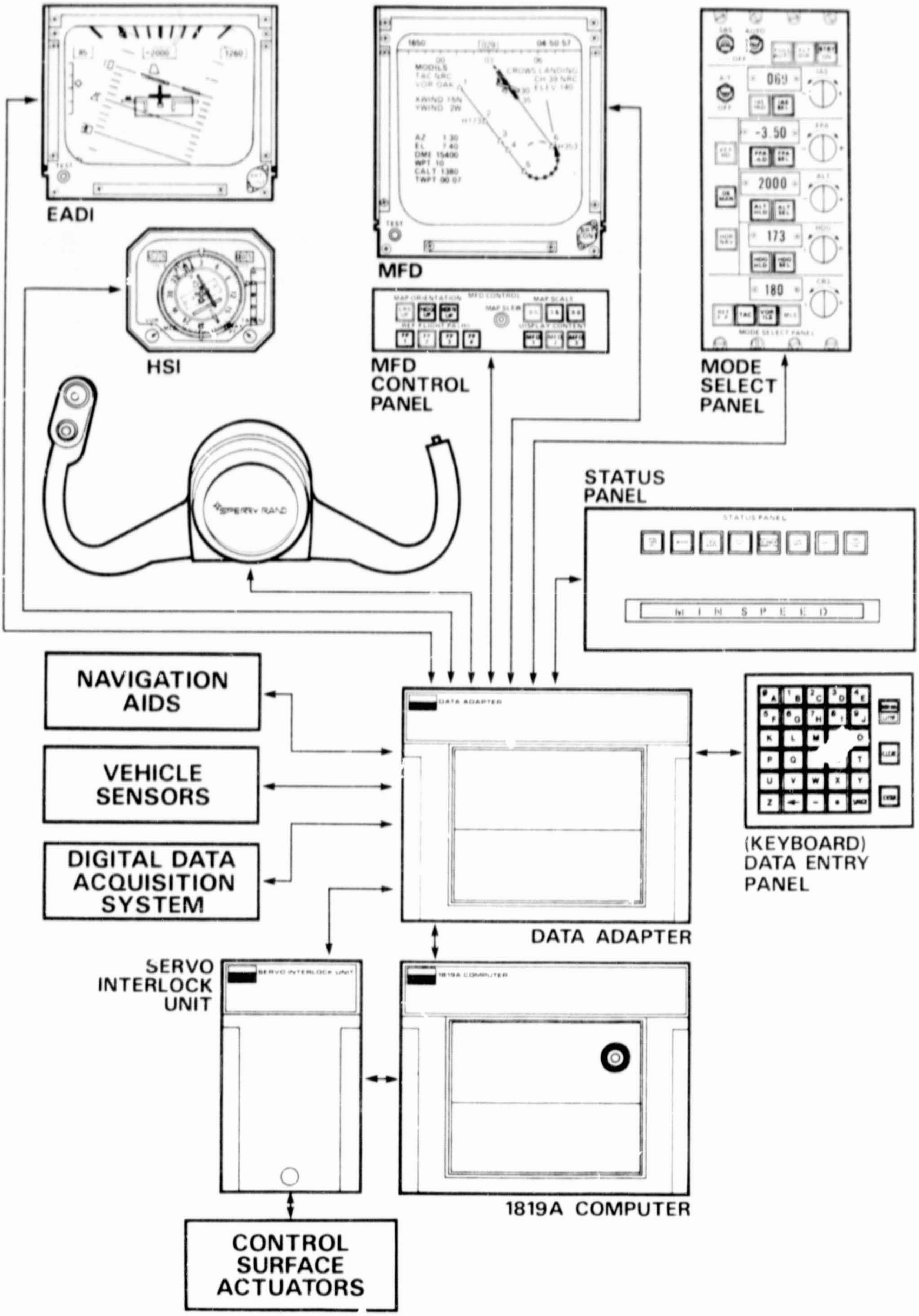


Figure 5.- STOLAND research avionics system.

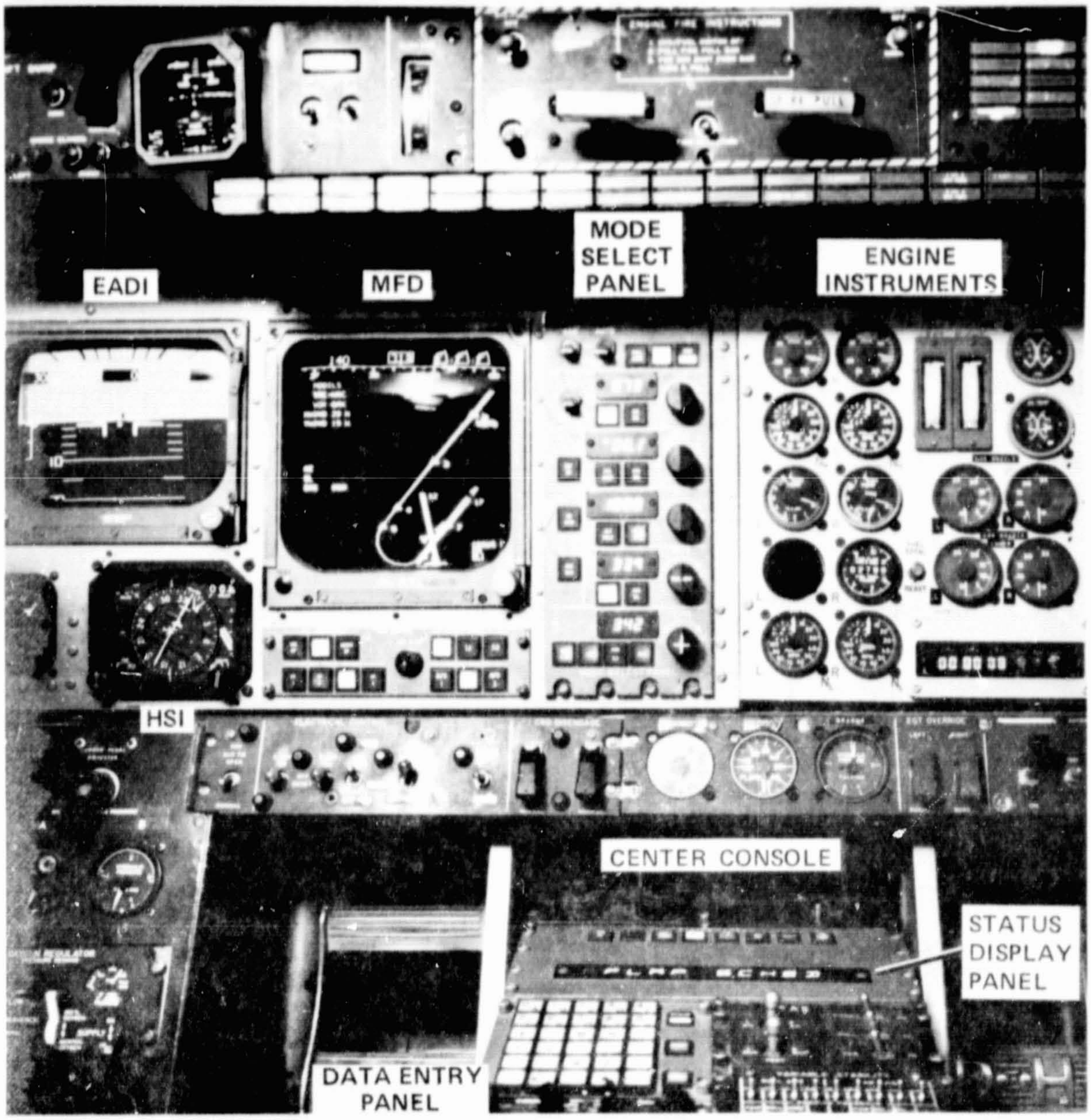


Figure 6.- Cockpit arrangement.

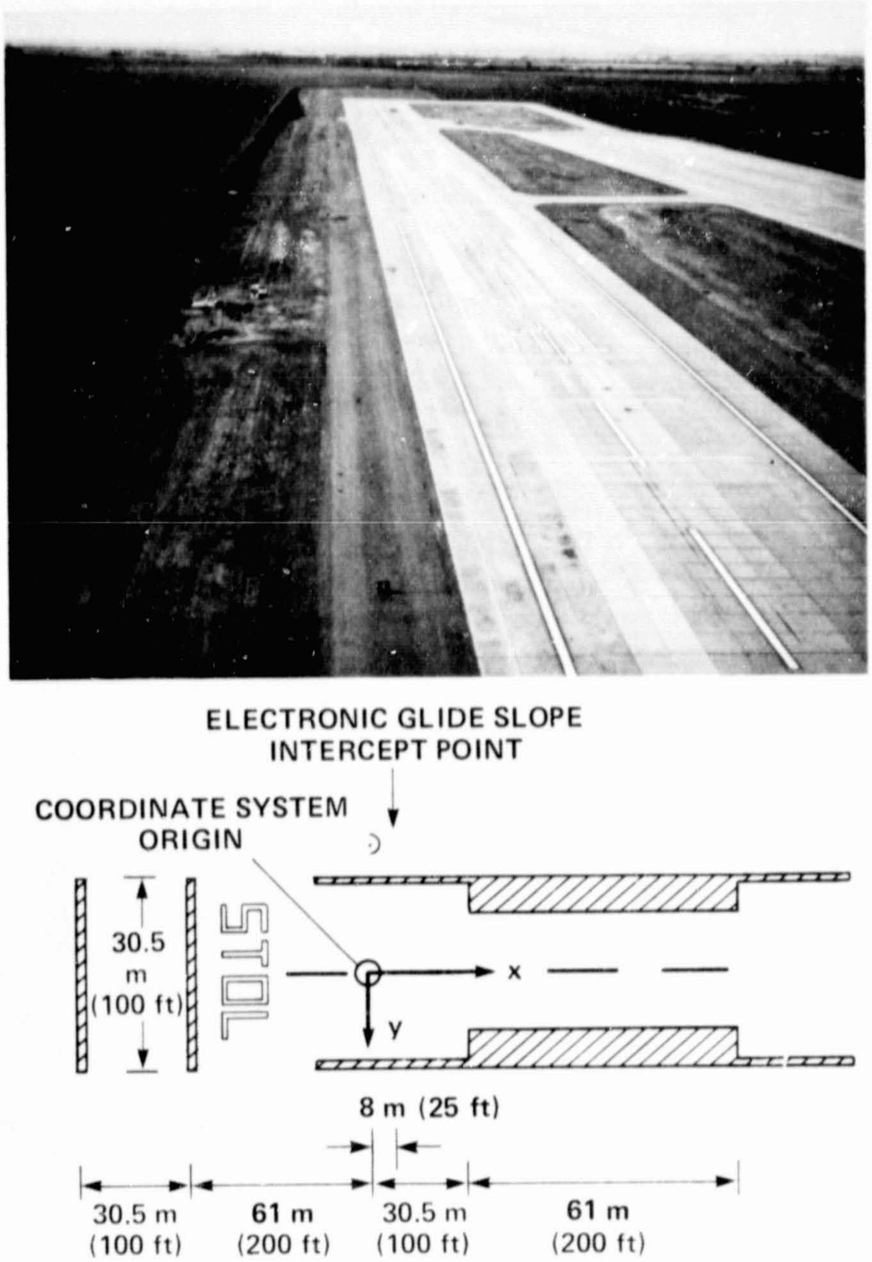


Figure 7. Test site and STOL runway.

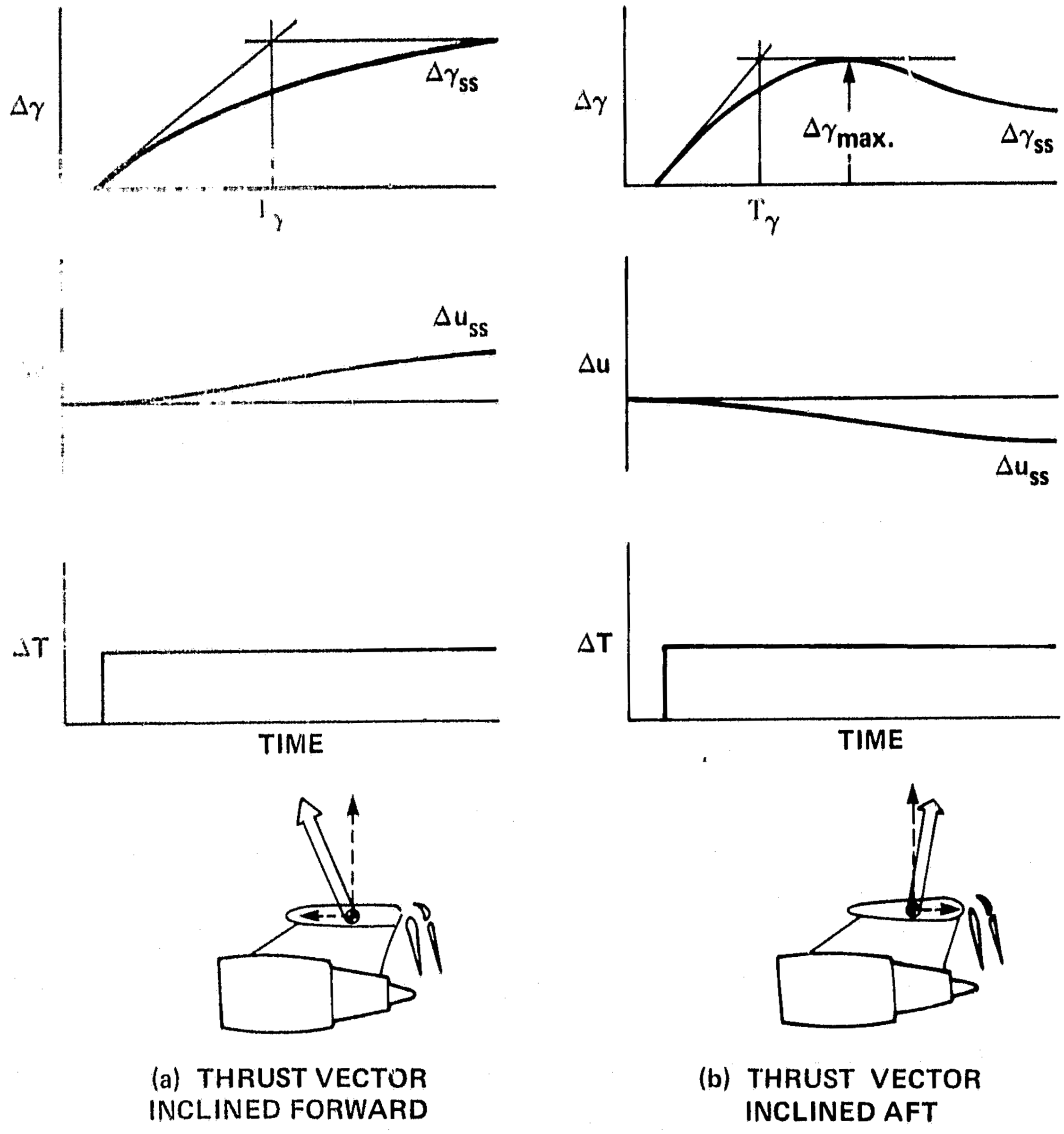


Figure 8.- Characteristics of flightpath and airspeed response to a step increase in thrust.

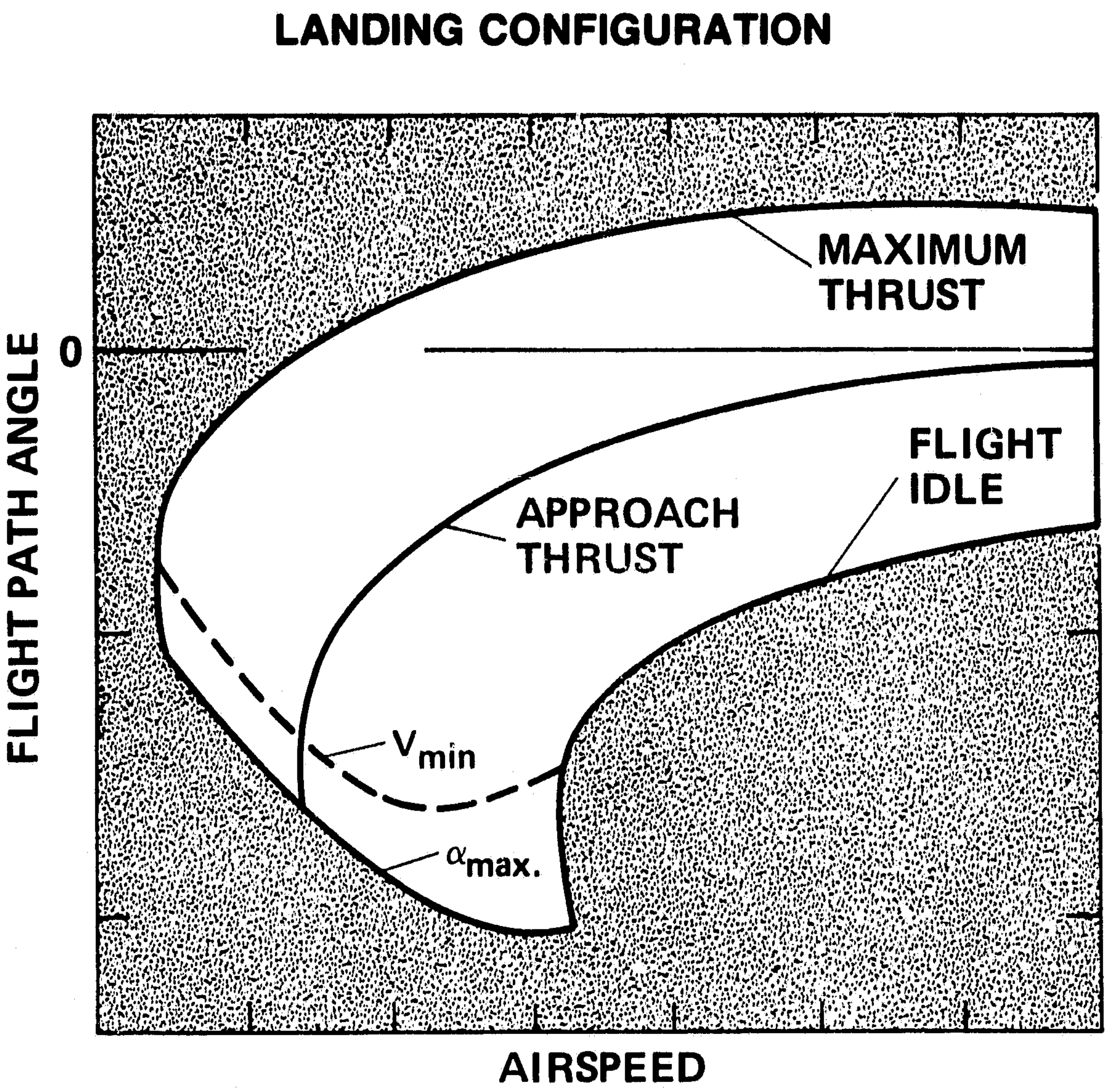


Figure 9.- Flight envelope for a powered-lift transport.

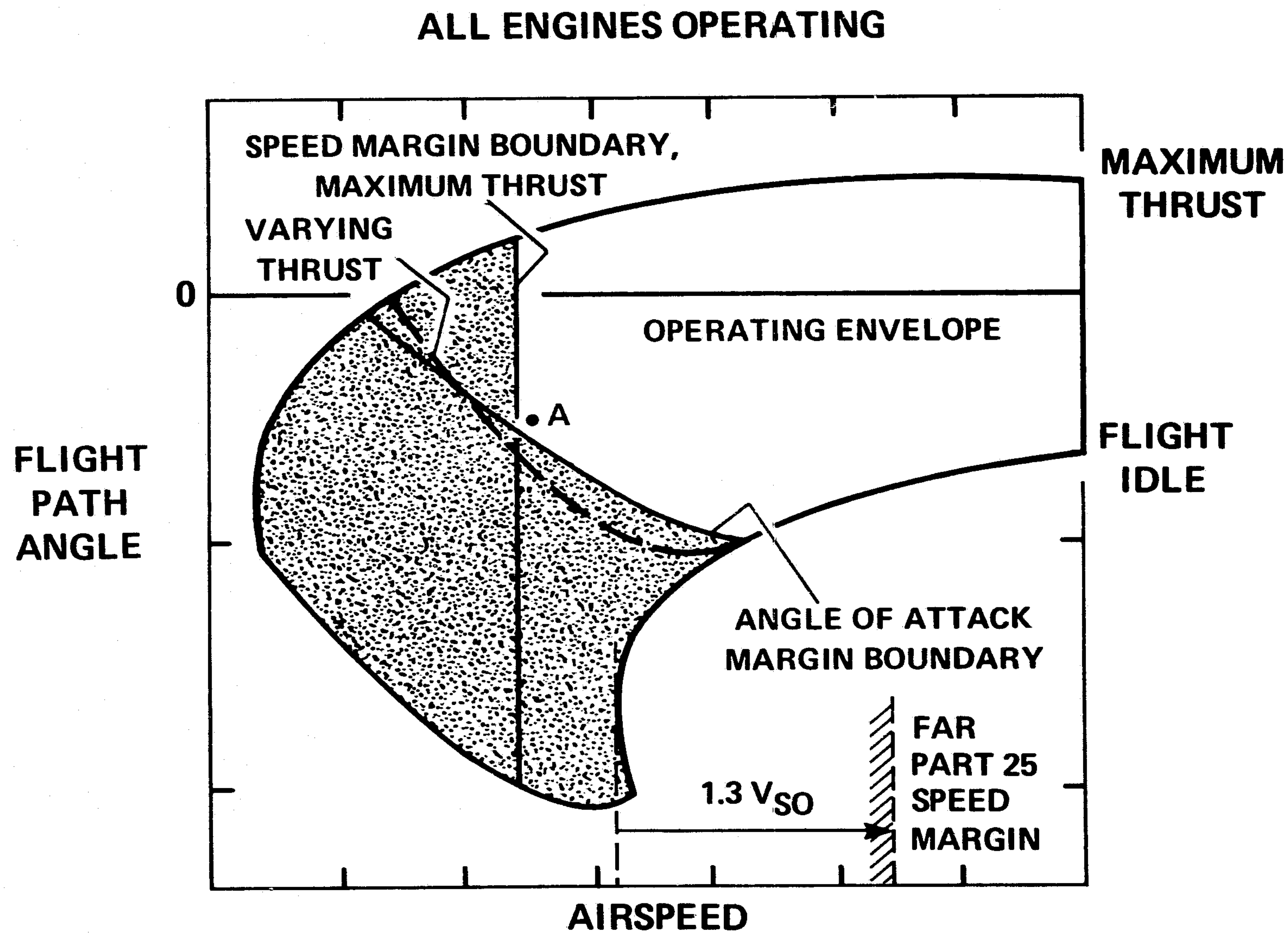


Figure 10.- Operating envelope as limited by proposed margin criteria.

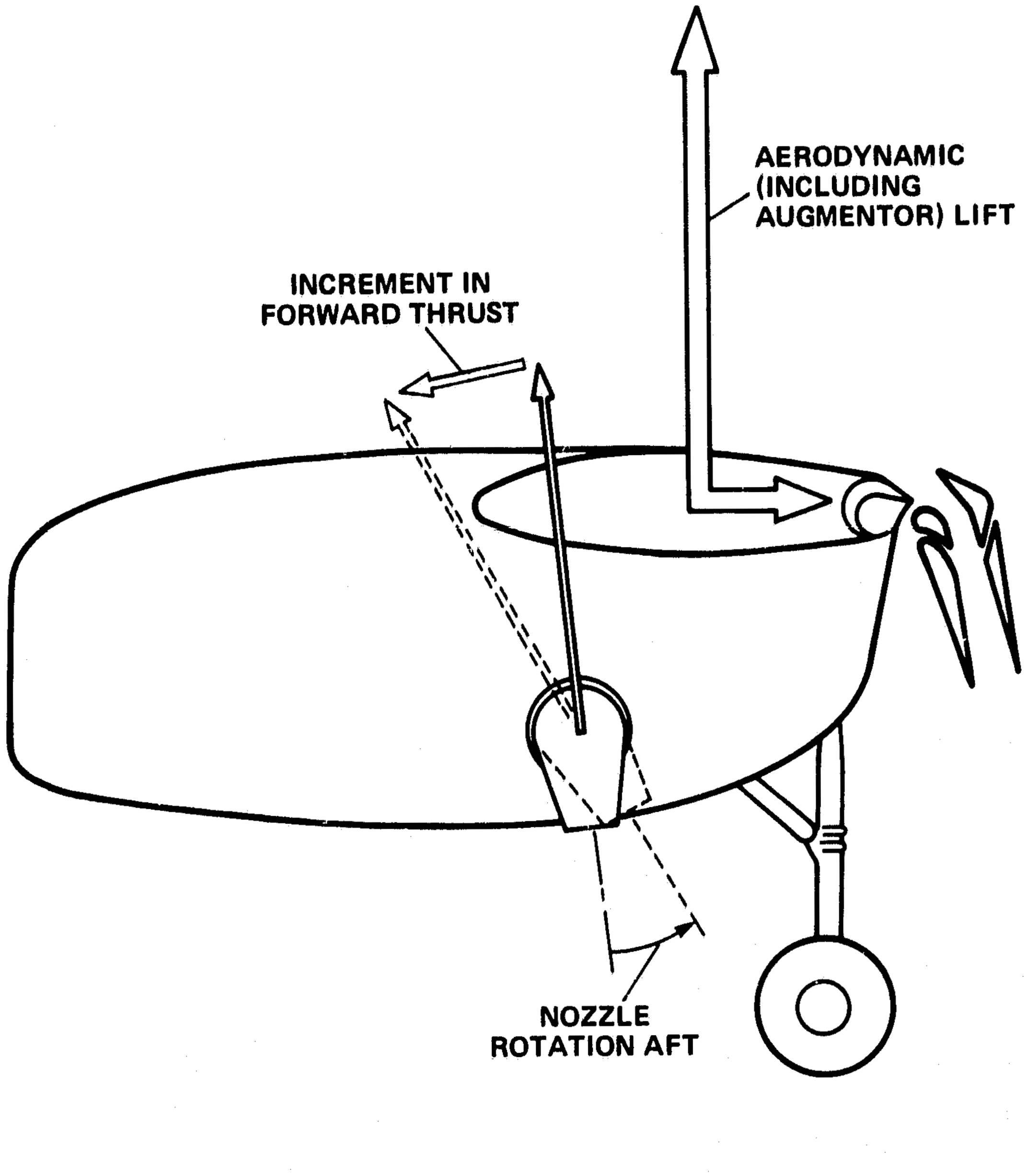


Figure 11.- AWJSRA thrust-vectoring through nozzle rotation.

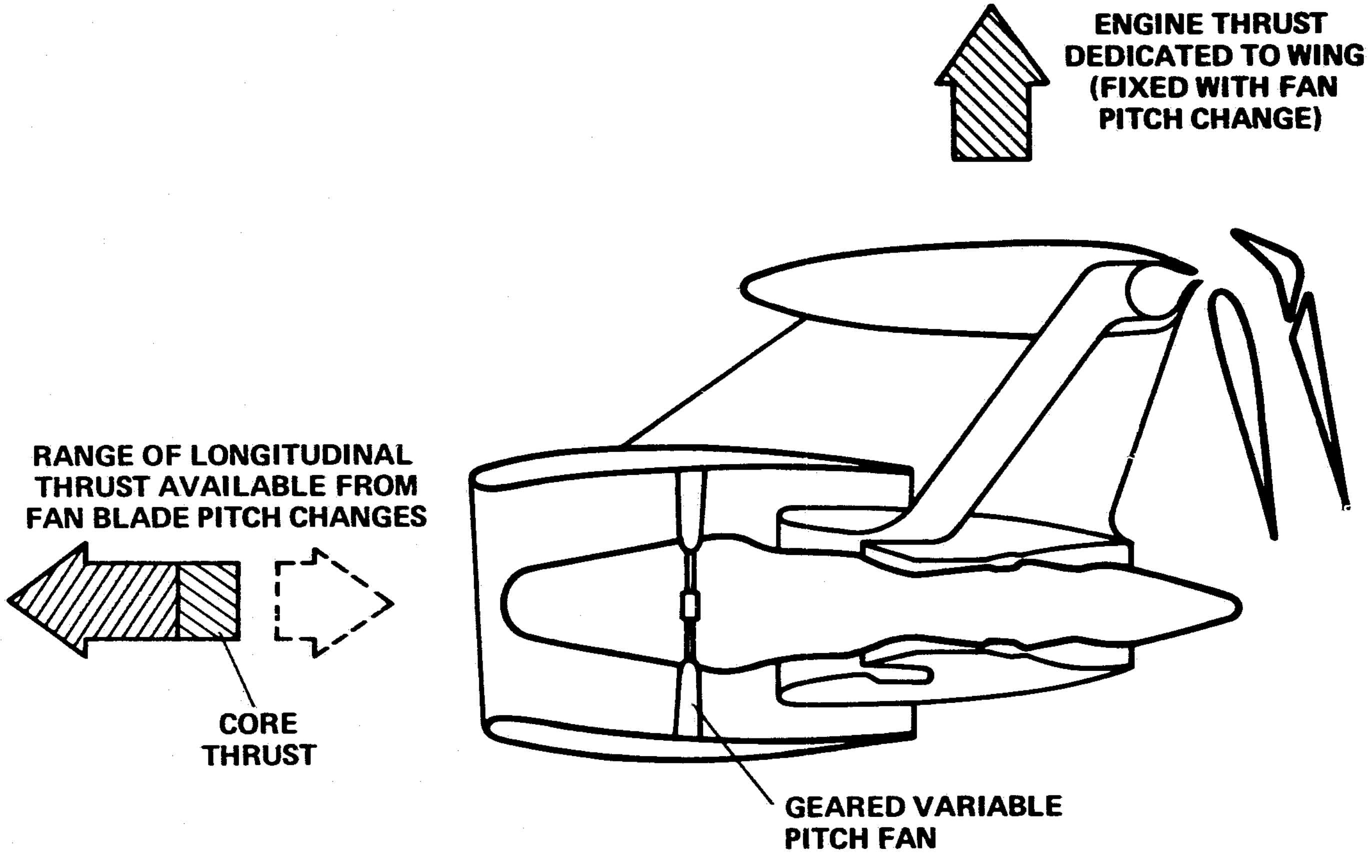


Figure 12.— Independent longitudinal thrust control with a three-stream engine.

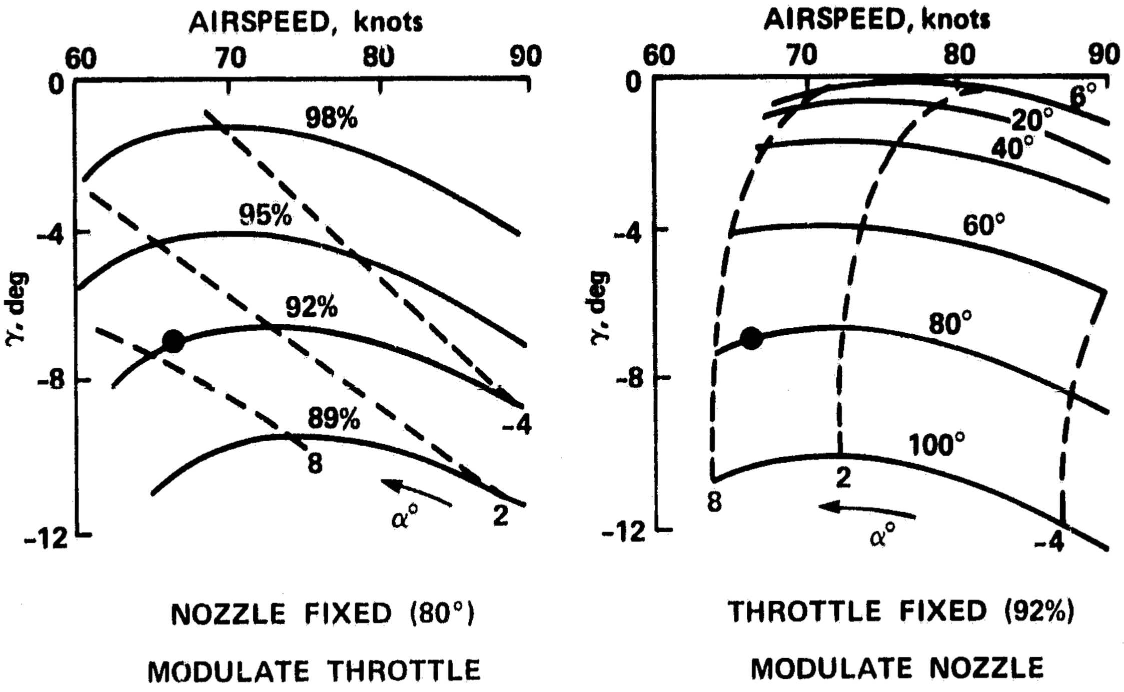


Figure 13.- Glidepath control using throttle or nozzle.

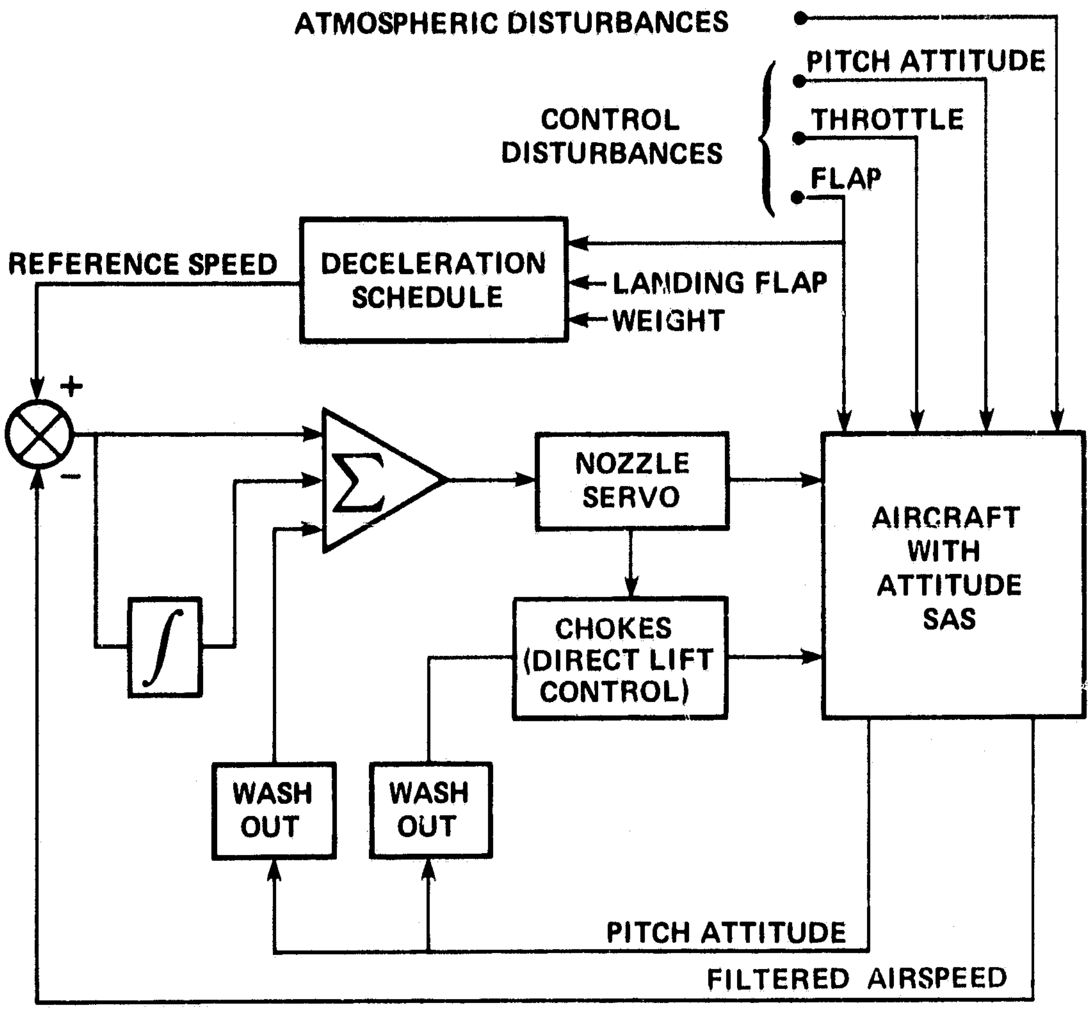
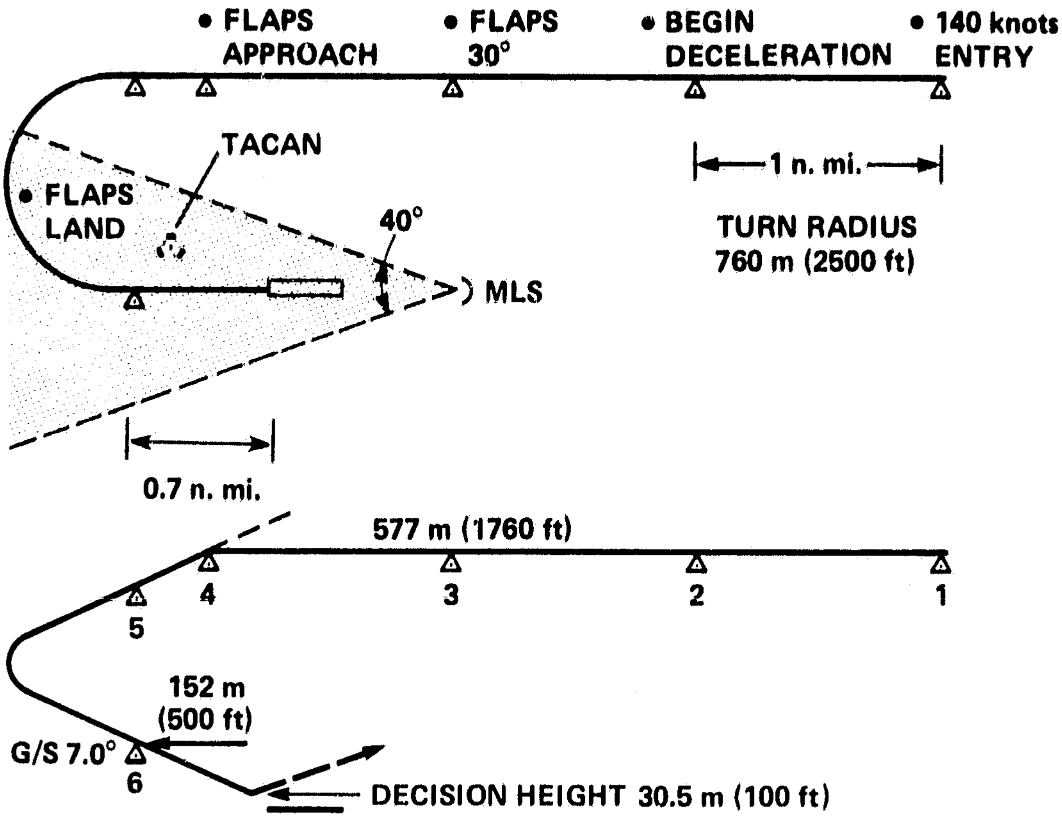


Figure 14.- AWJSRA automatic speed control system.



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

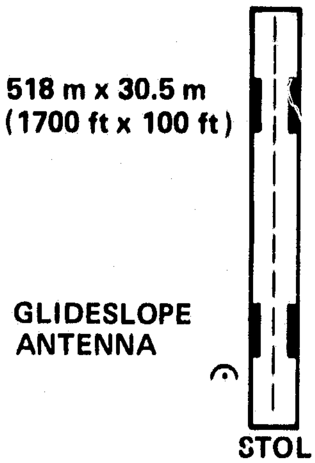


Figure 15.- Curved decelerating steep approach profile.

STOL CONTROL CONCEPTS EVALUATED DURING MANUAL CURVED DECELERATING APPROACHES

CONTROL CONCEPT	NO SPEED SAS BASIC AIRCRAFT	SPEED SAS BACKSIDE TECHNIQUE	SPEED SAS FRONTSIDE TECHNIQUE
PRIMARY CONTROL (GLIDEPATH)	THROTTLE	THROTTLE	PITCH ATTITUDE
SECONDARY CONTROL (SPEED)	PITCH ATTITUDE	NOZZLE*	NOZZLE*
TRIM CONTROL	NOZZLE	PITCH ATTITUDE	THROTTLE

*SAS MANAGED

Figure 16.- STOL control concepts evaluated during manual curved decelerating approaches.

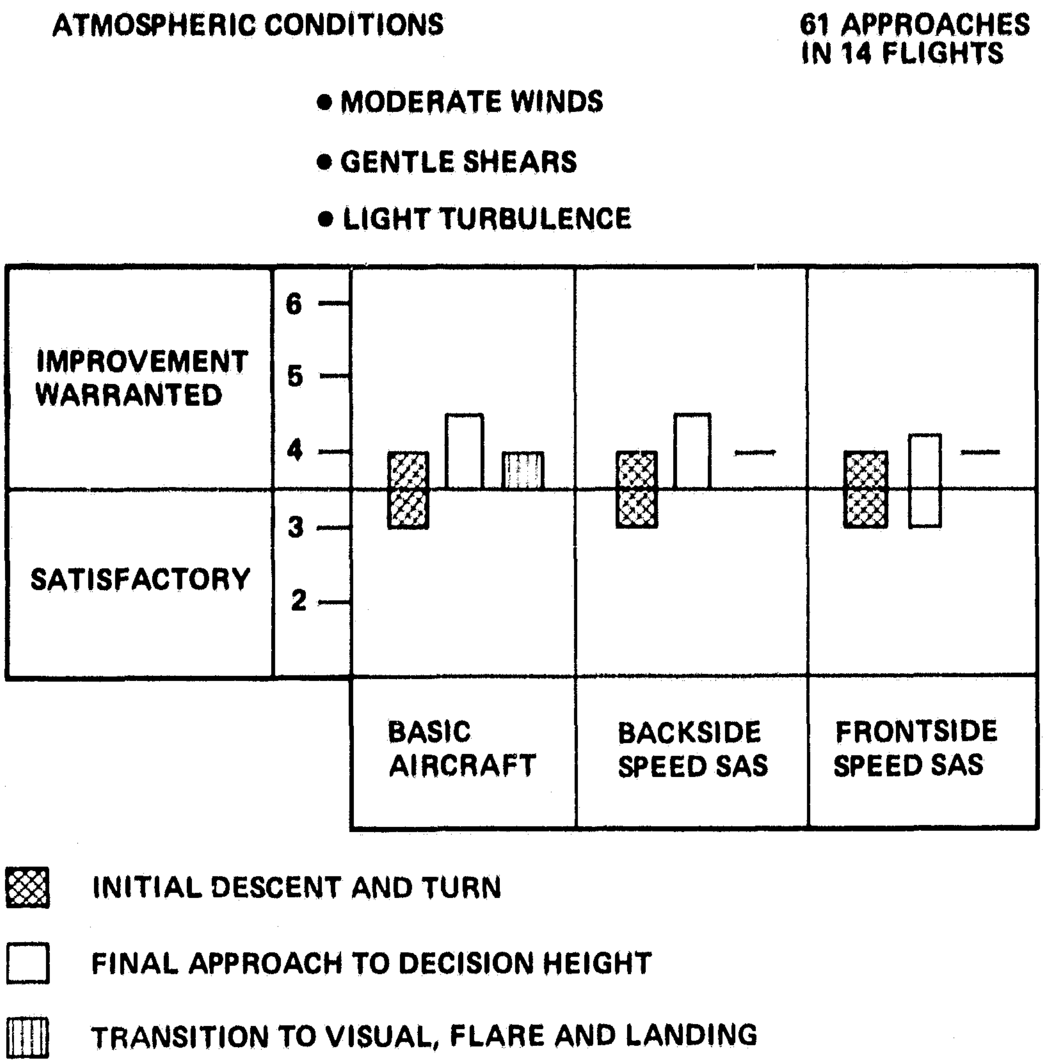


Figure 17.— Range of pilot ratings assigned — decelerating curved approach task.

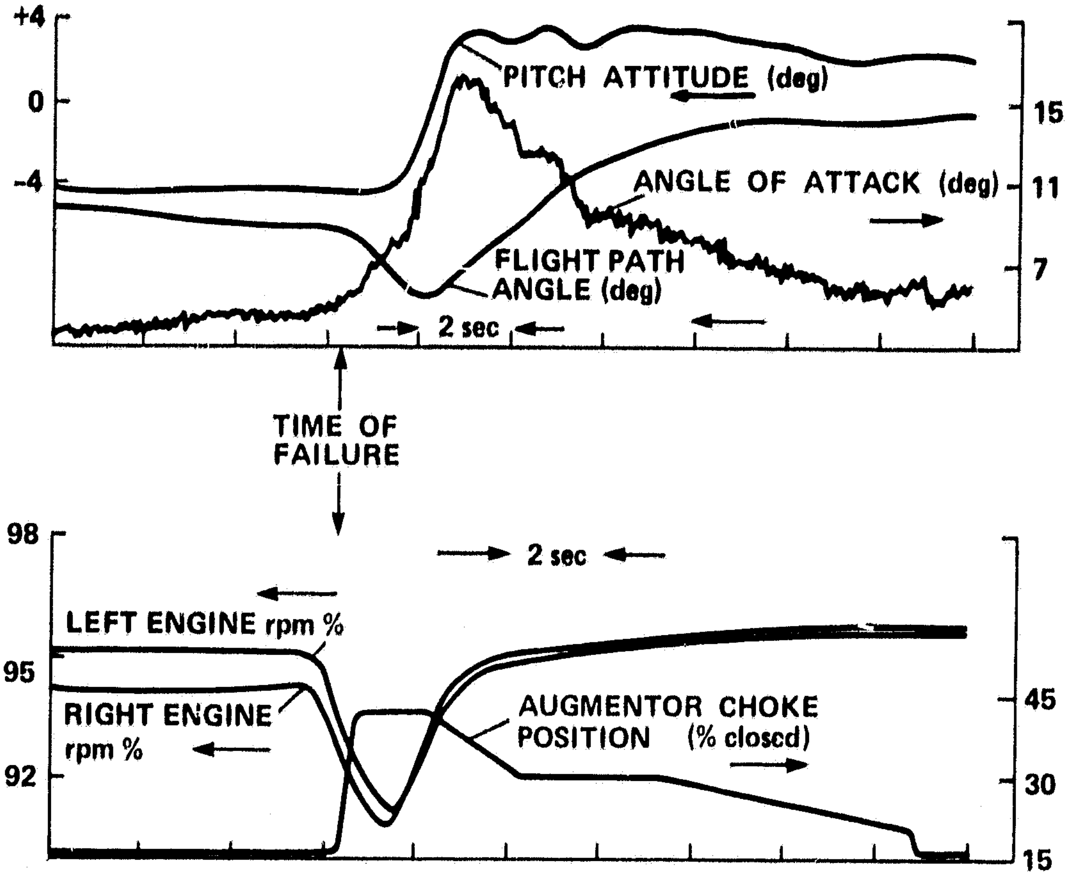


Figure 18.— Control input and response time histories during simulated engine failure and recovery.

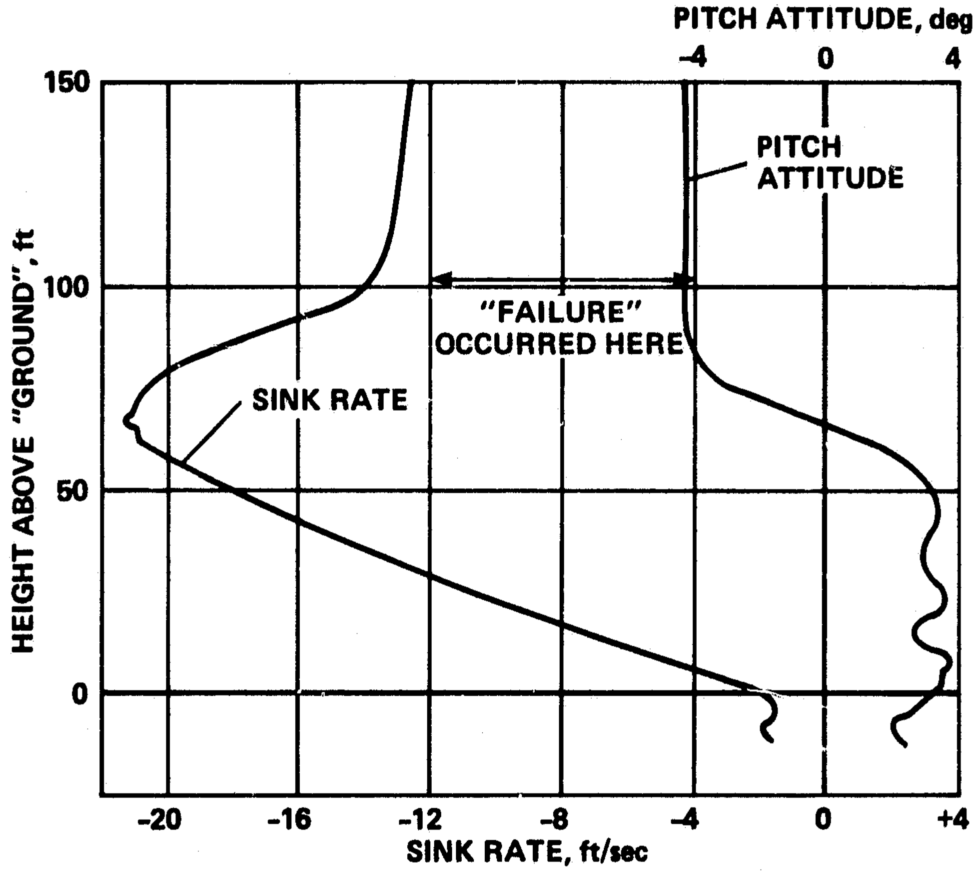
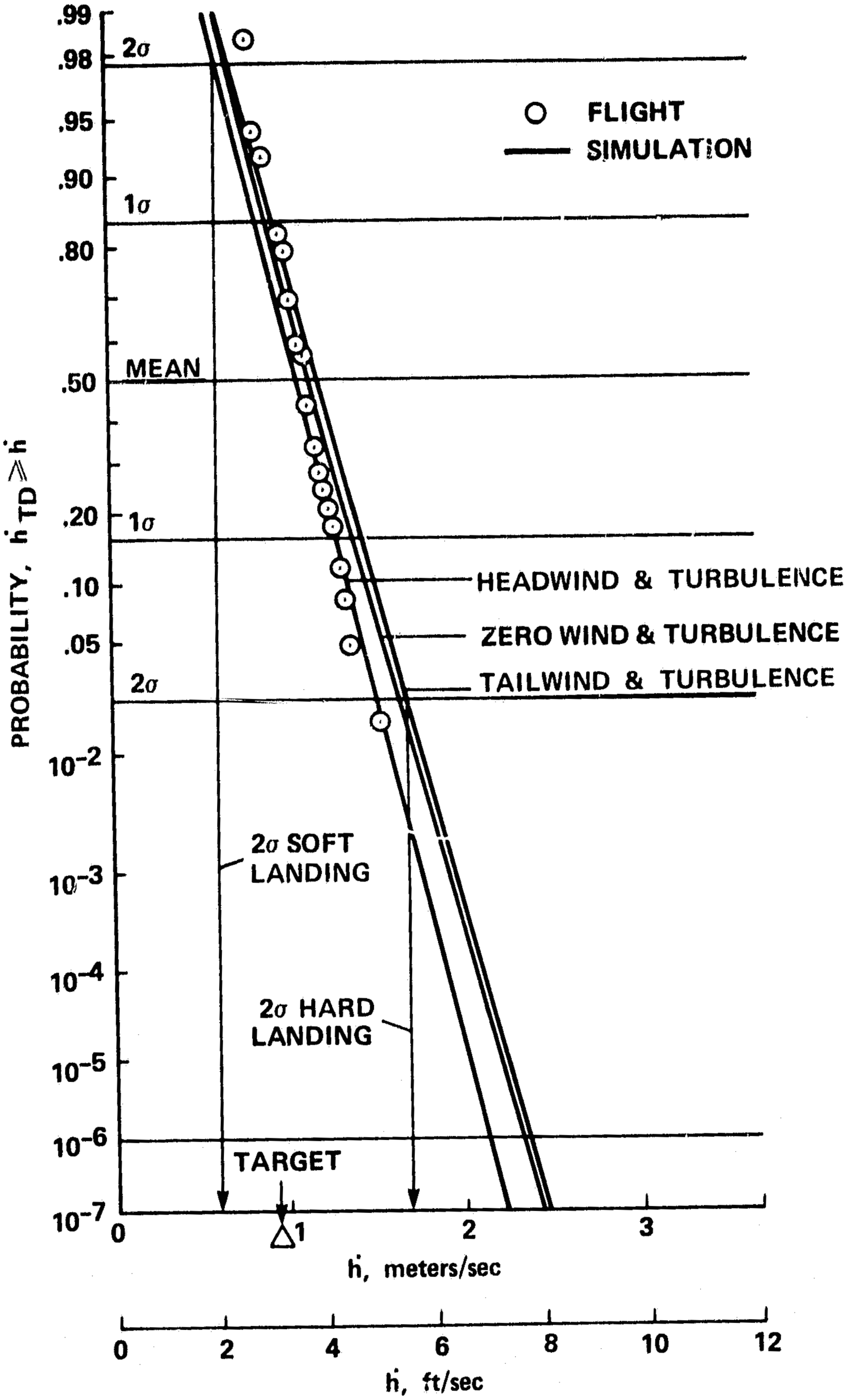


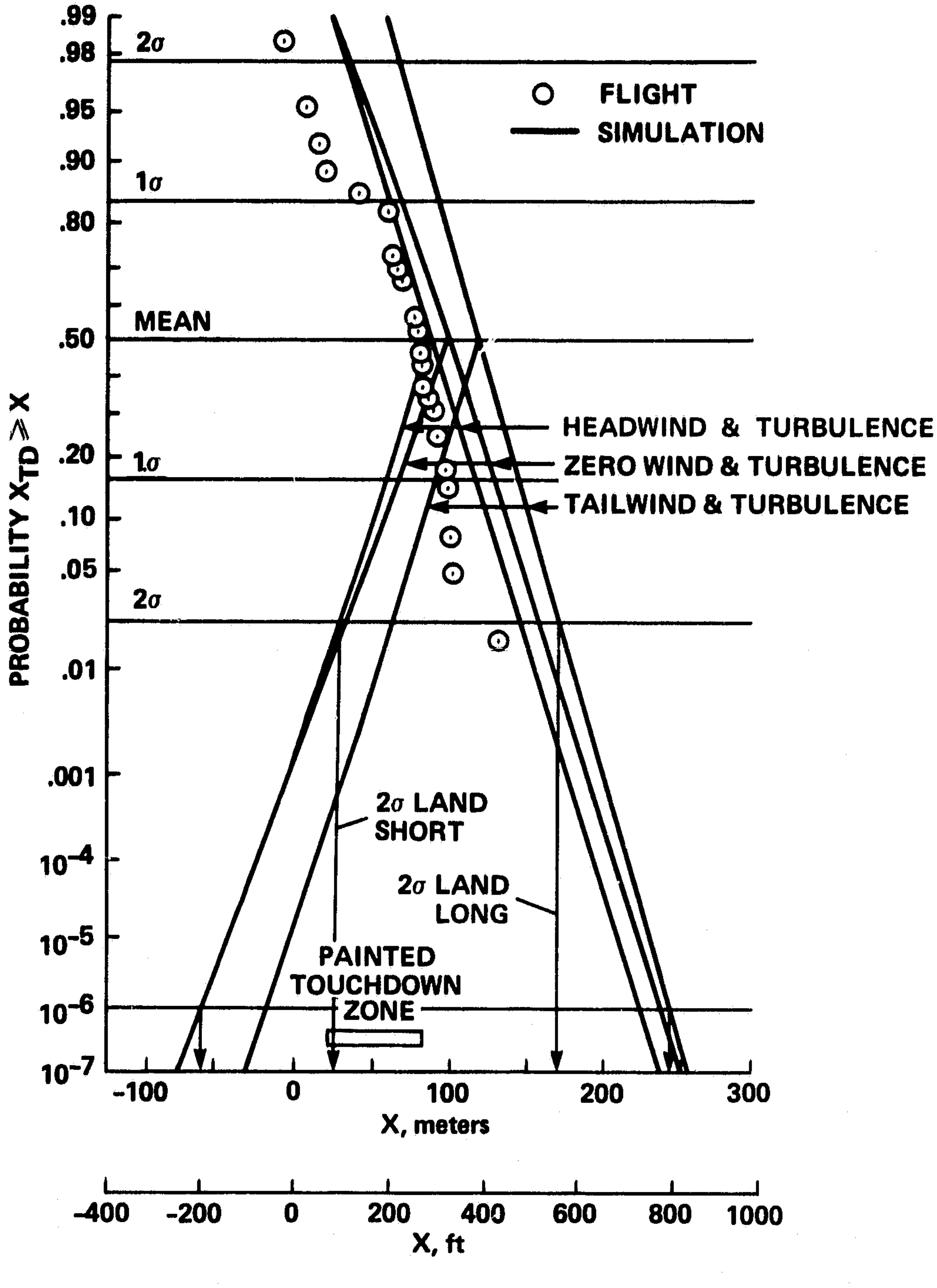
Figure 19.— Sink rate reduction relative to "ground" level.

Figure 20.— Power lever installation.



(a) Touchdown distance

Figure 21.— Comparison of autoland performance from flight test with simulation data.



(b) Touchdown sink rate.

Figure 21.— Concluded.

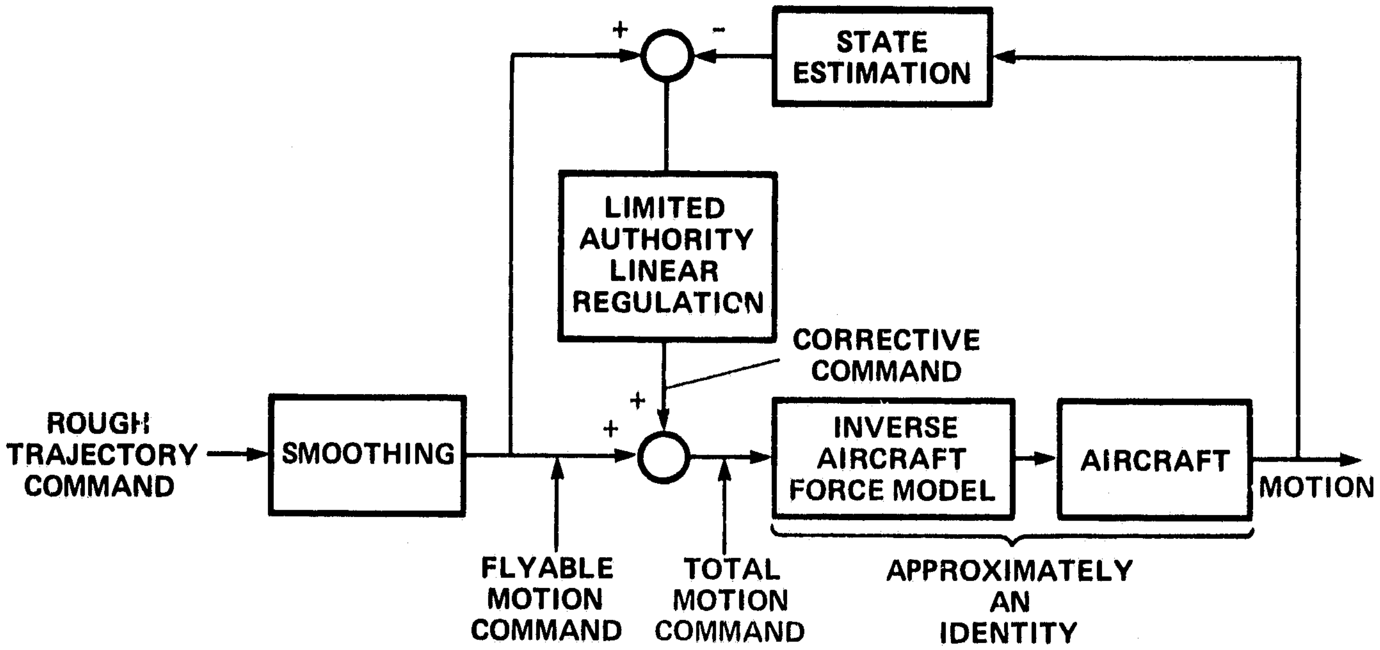


Figure 22.— Advanced autopilot control loop structure.

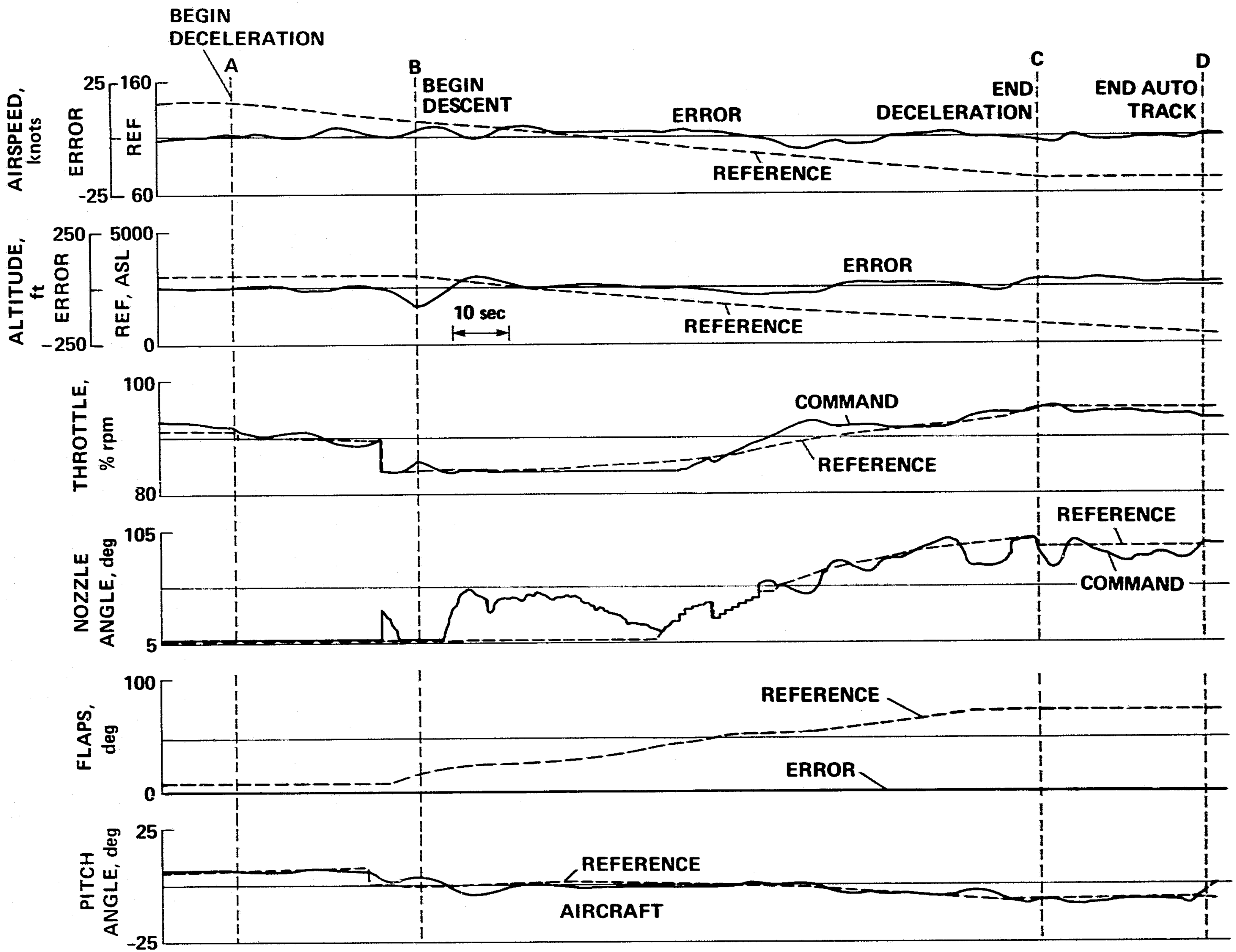


Figure 23.— Control utilization and performance during minimum fuel automatic approach.

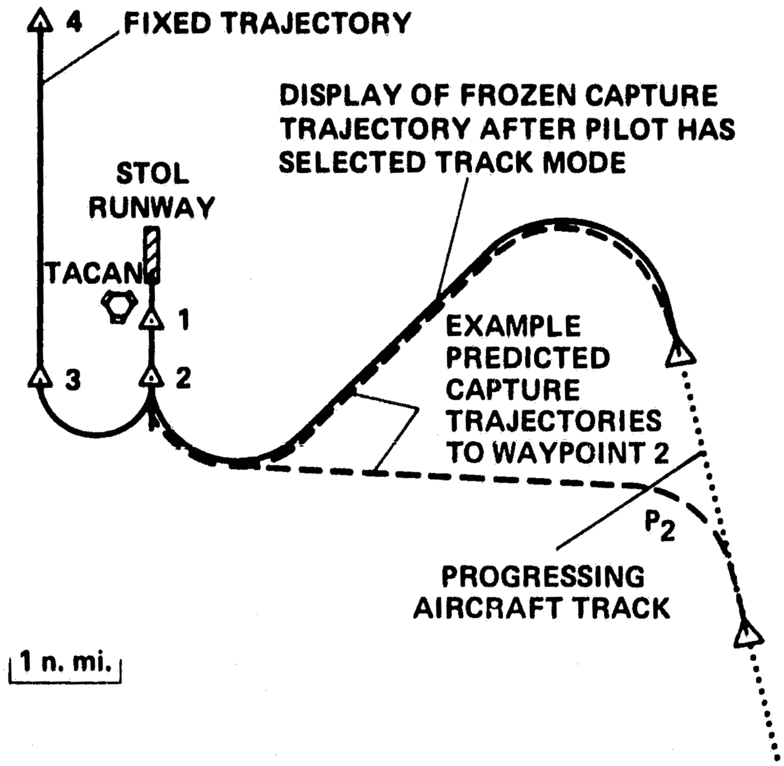


Figure 24.— Horizontal flightpaths displayed on cockpit electronic map display.

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16. Abstract

Several different flight research programs carried out by NASA and the Canadian Government using the Augmentor Wing Jet STOL Research Aircraft to investigate the design, operational, and systems requirements for powered-lift STOL aircraft are summarized. Some of these programs have considered handling qualities and certification criteria for this class of aircraft, and have addressed pilot control techniques, control system design, and improved cockpit displays for the powered-lift STOL approach configuration. Other programs have involved exploiting the potential of STOL aircraft for constrained terminal-area approaches within the context of present or future air traffic control environments. Both manual and automatic flight control investigations are discussed, and an extensive bibliography of the flight programs is included.

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