DESIGN CRITERIA FOR INTEGRATED FLIGHT/PROPULSION CONTROL SYSTEMS FOR STOVL FIGHTER AIRCRAFT

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ABSTRACT

As part of NASA's program to develop technology for short takeoff and vertical landing (STOVL) fighter aircraft, control system designs have been developed for a conceptual STOVL aircraft. This aircraft is representative of the class of mixed-flow remote-lift concepts that was identified as the preferred design approach by the US/UK STOVL Joint Assessment and Ranking Team. The control system designs have been evaluated throughout the powered-lift flight envelope on Ames Research Center's Vertical Motion Simulator. Items assessed in the control system evaluation were: maximum control power used in transition and vertical flight, control system dynamic response associated with thrust transfer for attitude control, thrust margin in the presence of ground effect and hot gas ingestion, and dynamic thrust response for the engine core. Effects of wind, turbulence, and ship airwake disturbances are incorporated in the evaluation. Results provide the basis for a reassessment of existing flying qualities design criteria applied to STOVL aircraft.

NOMENCLATURE

AC	attitude command
F_G	gross thrust, lb
g	acceleration due to gravity, ft/sec^2
h	landing gear wheel height above ground, ft
HGI	hot gas ingestion
HUD	head-up display
IGE	in-ground effect
IMC	instrument meteorological conditions
LIDS	lift improvement devices
OGE	out-of-ground effect
PIO	pilot-induced oscillation
SCAS	stabilization and command augmentation system
T	propulsion system vertical thrust, lb
VC	velocity command
W	gross weight, lb
WOD	wind over deck
ΔL	lift increment referenced to out-of-ground effect conditions, lb
$\Delta L/T$	normalized jet-induced aerodynamic ground effect
$(\Delta L/T)'$	normalized lift increment due to ground effect and hot gas ingestion
θ	temperature ratio as a function of wheel height
σ	standard deviation

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INTRODUCTION

NASA has been involved in a collaborative program with other government agencies in the United States and with the Ministry of Defence of the United Kingdom to develop technology for supersonic short takeoff and vertical landing (STOVL) aircraft. As a result of this effort, a wide variety of airframe and propulsion system concepts have been assessed through analytical studies, and critical technical issues have been identified for investigation (Ref. 1). The preferred design approach identified by the US/UK STOVL Joint Assessment and Ranking Team for the airframe and propulsion system is known as mixed-flow remote-lift, an example of which is illustrated in Figure 1. This configuration features mixed fan and core flows that can be directed forward or aft to generate the lift and thrust forces and to provide (partially or exclusively) control moments. The propulsion system will have forward thrust-producing device(s) that may deflect as well as modulate that thrust component, a variable area cruise nozzle that may provide thrust deflection for pitch and yaw control, and rear lift nozzle(s) that provide a thrust component for pitch control and which may also deflect about the vertical. Combined with these propulsion components are the aerodynamic surfaces that function during both wing-borne and jet-borne flight. These may include leading and trailing edge flaps on the wings, canards, ailerons, stabilators and rudders for lift and moment control.

Integration of these flight and propulsion controls has been identified as one of the critical technologies to be developed for these aircraft. A program has been conducted to define control concepts that combine the various aerodynamic and propulsion control effectors with control laws designed to achieve fully satisfactory (Level 1) flying qualities throughout the powered-lift flight envelope. Furthermore, criteria for the control authority and dynamic response of the individual effectors have been explored. The control system designs have been evaluated throughout the powered-lift flight envelope on Ames Research Center's Vertical Motion Simulator. Included in the control system evaluation were assessments of maximum control power used in transition and vertical flight, control system dynamic response associated with thrust transfer rates for attitude control, thrust margin in the presence of ground effect and hot gas ingestion, and dynamic thrust response for the engine core. Effects of wind and turbulence and airwake disturbances from a ship are incorporated in the assessment. The purpose of this paper is to review these assessments as a basis for possible revisions or extensions of flying qualities design criteria for this class of aircraft.

This paper includes a description of the aircraft, the simulation facility and the experiments which were conducted. A summary of the results of these experiments follows, including suggestions for revision or modification of existing criteria.

MIXED-FLOW REMOTE-LIFT AIRCRAFT

The design criteria presented in this paper are based on simulation experiments involving a mixed-flow remote-lift STOVL aircraft concept (Fig. 1). This concept is specifically referred to as mixed flow vectored thrust (MFVT) and is described in further detail in Reference 2. The aircraft is a single-place, single-engine fighter/attack aircraft with supersonic dash capability. It features a blended wing-body configuration with a canted empennage that provides longitudinal and directional control. The wing is characterized by a leading edge sweep of 50° and aspect ratio of 2.12. The propulsion system concept uses a turbofan engine where the mixed fan and core streams are either ducted forward to the lift nozzles or aft to a thrust deflecting cruise nozzle. A ventral nozzle diverts some of the mixed flow to provide pitching moment to counter that of the lift nozzles. Lift nozzle thrust can be deflected up to ±20° about a nominal rearward cant angle of 8°. The cruise nozzle can be deflected laterally or vertically ±20°. In conventional flight, the mixed flow is directed aft through the cruise nozzle, whereas in hover it is diverted from the cruise nozzle to the forward lift nozzles, with a small portion reserved for the ventral nozzle. During transition from hover to conventional flight, the flow is smoothly transferred from the lift to the cruise nozzle to provide acceleration.

The basic flight control system uses a variety of control effectors: ailerons, a fully deflecting empennage, reaction control system nozzles located in the tail, differential thrust transfer between the lift nozzles and ventral nozzle, longitudinal deflection of lift nozzle thrust, and vertical and lateral deflection of cruise nozzle thrust. Pitch control is achieved by a combination of symmetric empennage deflection, reaction controls, thrust transfer between the lift and ventral nozzles, and vertical deflection of the cruise nozzle. Roll control is produced by the ailerons and by lateral thrust transfer (differential lift nozzle thrust). Yaw control is derived from the combination of differential empennage deflection, reaction control, and lateral cruise nozzle deflection. Longitudinal acceleration is achieved through thrust transfer between the lift and cruise nozzles and by deflection of lift nozzle thrust.

To achieve the desired level of flying qualities during low-speed flight, stabilization and command augmentation modes were provided in the flight control system as noted in Table 1. During transition, either attitude or flightpath SCAS mode was available. Both modes offer rate-command/attitude hold for pitch and roll control and dutch roll damping and turn coordination for the yaw axis. When only the attitude SCAS is selected, the pilot must control thrust magnitude and deflection. When flightpath SCAS is engaged, the pilot commands flightpath angle and flightpath acceleration directly; the control system coordinates thrust magnitude and deflection to achieve the desired response. Either the attitude or velocity SCAS may be selected in hover. Both modes provide pitch and roll attitude command/attitude hold and yaw rate command. With attitude SCAS, the pilot controls longitudinal and lateral translation through changes in pitch attitude and bank angle. Thrust is used for height control. For the velocity SCAS, longitudinal, lateral, and vertical velocities are commanded directly. A thorough description of the control system is included in Reference 2.

A head-up display presented the primary flight information for these experiments. The display format was a flightpath centered, pursuit presentation in transition. In hover, the display switched to a format that superimposed vertical and horizontal command and situation information in a pursuit tracking presentation. A complete description of the display is included in Reference 3.

SIMULATION EXPERIMENT

Simulation Facility

The experiments on which these criteria are based were conducted on the Vertical Motion Simulator (Fig. 2) at NASA Ames Research Center. This simulator provides six degree-of-freedom motion, with large excursions in the vertical and longitudinal axes, and acceleration bandwidths in all axes that encompass the bandwidths of motion that are expected to be of primary importance to the pilot in vertical flight tasks. A three-window, computer generated image system presented the external view to the pilot, which consisted of either an airfield scene or a shipboard scene consisting of a Spruance-class destroyer. An overhead optical combining glass projected the HUD for the pilot. Control inceptors consisted of a center stick, rudder pedals, and a left-hand quadrant that contained throttle and thrust vector deflection handles.

Evaluation Tasks and Procedure

The pilot's tasks for evaluation during the simulation were those considered the most demanding for precision control of the aircraft—curved decelerating approaches to hover followed by a vertical landing. For evaluation purposes, the decelerating approach was initiated under instrument meteorological conditions (IMC) in level flight at 1100 ft and 200 knots in the landing configuration. Capture of a 3° glide slope ensued, followed by initiation of a 0.1 g deceleration, a turn to align with the final approach course, and acquisition of a stable hover over the hover point. Vertical landings were accomplished either on a 100 by 200 ft landing zone marked on the airfield's main runway or on a 40 by 70 ft pad on the ship's aft deck. Six pilots with V/STOL and powered-lift aircraft experience participated in the program.

Experiment Configurations

Experiment variables for the decelerating approach and vertical landing included the control system configuration, control system dynamics, thrust/weight ratio, jet-induced ground effect and hot-gas ingestion, and environmental conditions (wind, turbulence, and sea condition). Both the attitude SCAS and attitude-plus-flightpath SCAS were investigated for the decelerating approach; attitude SCAS and attitude-plus-velocity SCAS were evaluated for the vertical landing. System dynamics variations included control system authority, thrust transfer rates, engine core thrust response bandwidth and acceleration rate. Nine ground effect and ingestion profiles representative of a broad range of STOVL aircraft characteristics of lift and temperature profile as a function of height (four of which were representative of the YAV-8B Harrier with LIDS on and off) were included for both airfield and shipboard landings. Wind conditions for the approach and airfield landing were calm, 15 knots, and 34 knots, with crosswind components of 30° and 20°, respectively, for the latter two wind conditions. Turbulence of 0, 3, and 6 ft/sec rms accompanied the respective wind cases. Conditions for shipboard recovery included sea states of 0, 3, and 4 with wind over deck of 15, 27, and 46 knots from 30° to port.

CONTROL POWER

Existing design specifications and guidance for pitch, roll, and yaw control power for fixed-wing V/STOL aircraft are contained in References 4 and 5.

Additional information from STOL aircraft experience that would apply to the V/STOL transition is provided in Reference 6. Flight and simulation data on which these publications are based date back to the late 1960s. Given the present capability for achieving highly augmented stability and control characteristics and the necessity for operating in IMC, it is worthwhile to reassess the validity of the control power requirements derived from the earlier data. The results which follow relate to control power for maneuvering and for suppressing disturbances and have control required for trim removed. These results are presented to reflect the influence of flight phase, including effects of control augmentation and magnitude of atmospheric disturbance. The breakdown related to flight phase is important not only because of the difference in the pilot's tasks, but because of the demands placed on different control effectors (aerodynamic surfaces and propulsion system components) that, in turn, place different demands on the aircraft's design. Control power usage is presented in terms of individual maximum values (plus or minus about the mean value) for each run and an aggregate value of two standard deviations for the ensemble at that condition. For a Gaussian distribution of frequency of occurrence of control use, expected maximum values would be three to four times the standard deviation. Two standard deviations represents a level of control use that is exceeded 4.6% of the time over the ensemble of data runs. Aircraft response specifications of References 4 and 6 were translated to measures of control power for direct comparison with the current results. These criteria were converted from attitude change in 1 sec using an attitude control bandwidth of 2 rad/sec for an attitude command response that is critically damped, or using a first-order response with a time constant appropriate to the axis being controlled.

Maximum demands for pitch control during hover and vertical landing are pertinent to sizing requirements for the aircraft's reaction control system or for thrust transfer between components of the propulsion system. Demands for roll control generally size the amount of thrust transfer required between the lift nozzles. Yaw demands contribute to sizing of the reaction control system. During transition, the requirements on control sizing would incorporate both the propulsion system and the aerodynamic effectors.

Pitch Control

Effect of Flight Phase. A collection of results of pitch control usage for both attitude command and attitude-plus-flightpath command SCAS over a range of wind and turbulence for the tasks of transition, airfield vertical landing, and shipboard landing is presented in Figure 3. For the transition (Fig. 3a), results in calm air, which are indicative of maneuvering demands, show that, for attitude command SCAS, pitch control power maximums fall within the range considered to be satisfactory in Reference 5 for STOL operations (which can be related to the transition phase of this simulation). Two standard deviation levels are well below the Reference 5 maximum. Peak values generally equate to 3–4σ levels. The influence of turbulence on the additional control required for disturbance suppression is apparent. For rms turbulence of 6 ft/sec (Turb6), a few instances of control usage exceed the maximum recommended level of Reference 5. Thus, to cater for maneuvering and the effects of turbulence, a control power of 0.2–0.25 rad/sec^2 would provide for at least 99% of all demands encountered.

Results for the attitude-plus-flightpath SCAS are comparable to those for the attitude SCAS, reflecting the fact that the pilot's pitch control task is similar for the two systems during transition. The pilot uses pitch attitude changes for flightpath control during the early stages of the approach, where a frontside control technique is appropriate, as well as to regulate against disturbances arising from wind and turbulence.

Pitch control during the vertical landing with the attitude SCAS (Fig. 3b) shows levels of peak control usage that are less than the requirements of References 4 and 5. The maximum control required was 0.27 rad/sec^2 (3–4σ values of 0.14–0.18 rad/sec^2). Turbulence disturbances did not impose additional demands on control authority. Consequently, control authority of 0.14–0.27 rad/sec^2 would accommodate most of the demands for the attitude SCAS. By comparison, the 3° attitude change in 1 sec required by Reference 4 converts to a peak pitch control power of 0.29 rad/sec^2 for a 2 rad/sec attitude command bandwidth.

With the velocity command SCAS, even less pitch control is required, reflecting the difference in the pitch control task between the two SCAS configurations. With attitude SCAS alone, control of longitudinal position and velocity in hover is accomplished through modulation of pitch attitude. When the velocity command system is engaged, control of the longitudinal axis is achieved through deflection of the thrust vector with attitude fixed. In this case, the vertical landing can require a control authority of 0.17 rad/sec^2, independent of winds and turbulence.

Results for hover and vertical landing aboard ship with attitude command alone (Fig. 3c) are comparable to the criteria of Reference 5 and Level 1 handling values in Reference 4 (although neither criterion applies to shipboard operation, but rather to hover out-of-ground effect). Peak control usage is 0.38 rad/sec^2 or less, with 3–4σ levels being 0.12–0.16 rad/sec^2. For the attitude-plus-velocity command system, peak control use is approximately two-thirds of that for attitude command alone, reflecting, as in the airfield vertical landing, the different task required for the pitch axis. For neither system does wind over deck seem to influence the amount of control required for the landing. Thus, for shipboard operations, the control power requirement of References 4 and 5 appear appropriate with attitude SCAS alone, and a requirement for 0.2 rad/sec^2 should suffice for the attitude-plus-velocity command SCAS.

Summary of Pitch Control Requirements. A summary of the required pitch control authority determined from these STOVL aircraft simulation results, compared to (1) the Level 1 criteria of References 4, 5, and 6, (2) available control power for some relevant V/STOL fighter aircraft designs (Refs. 7–9), and (3) earlier fixed-base simulation results for the E-7A STOVL concept (Ref. 10), is presented in Table 2. For the transition phase, the pertinent criteria are those of References 5 and 6; no control power data are available for the individual aircraft. For the vertical landing, References 4 and 5 apply; the total available control power has been tabulated for the Harrier and VAK-191.

In the transition phase, the highest value of the criteria of Reference 5 does not quite accommodate the peak control use in turbulence noted for this experiment (MFVT STOVL). Maximum control experienced during the E-7A STOVL simulation was considerably greater, both for maneuvering and control in turbulence, and is more in line with the requirement of Reference 6. For the vertical landing, both References 4 and 5 appear to be too demanding. The current results indicate that less control power is used, especially with a velocity command system that employs thrust deflection for longitudinal control. No criteria are available for shipboard operations. Values shown for the Harrier and VAK-191 aircraft represent total control authority available for trim and maneuvering; actual control used by these aircraft is not available. By comparison, the total control available for the MFVT STOVL aircraft is 0.42 rad/sec^2 in hover, with 0.08 rad/sec^2 of that being used on the average for trim in winds up to 34 knots. Thus, the pitch control for this aircraft was adequate to handle the measured trim and maneuver demands in hover and vertical landing for the attitude SCAS and considerably more than adequate for control with the velocity command SCAS.

Roll Control

Effect of Flight Phase. Roll control use for the different flight phases, SCAS modes, and turbulence is shown in Figure 4. Maximum roll control use for maneuvering in calm air during transition (Fig. 4a) substantially exceeds that called for in Reference 5, with peaks of 0.4–0.9 rad/sec^2. However, the 3–4σ levels of 0.3–0.4 rad/sec^2 are more in line with the criteria. For control in the heaviest turbulence, demands for as much as 1.2 rad/sec^2 occur, although the range is more typically 0.6–0.9 rad/sec^2, which is consistent with 3–4σ values. As a further comparison, the Level 1 requirement of Reference 6 for maneuver control during STOL operations provides for 30° of bank angle change in 2.4 sec, which is satisfied by a control authority of 0.55 rad/sec^2 for a roll damping time constant of 0.5 sec. The latter requirement represents a more specific criterion for operation during transition, particularly where that phase consists of precision path tracking in forward flight during instrument flight conditions in adverse weather. Based on the results of this STOVL aircraft simulation, a roll control authority of 0.9–1.2 rad/sec^2 would be necessary to satisfy demands for maneuvering and control in turbulence.

Control use for the vertical landing, shown in Figure 4b, is consistently less than the Reference 4 requirement, and falls within the range suggested in Reference 5. Peak maneuvering demands for attitude command SCAS range from 0.1 to 0.3 rad/sec^2, and are comparable to 3–4σ values. The heaviest turbulence increases these levels modestly to 0.2–0.4 rad/sec^2. For the attitude-plus-velocity SCAS, which provides lateral velocity command through bank angle control, calm air maneuvering control use is somewhat less than for attitude SCAS alone; however, in turbulence the demands for the two systems are similar.

Results for shipboard recovery are generally in agreement with the criteria of References 4 and 5, except for high wind over deck conditions (Fig. 4c). In light winds, the peaks vary from 0.2 to 0.4 rad/sec^2. In the heaviest winds, maximum control of 0.9–1.1 rad/sec^2 was observed for the attitude command SCAS; for the lateral velocity command SCAS, maximums ranged from 1.3 up to 2.0 rad/sec^2. Based on pilot comments from the subject simulation experiments, operation aboard ship would be precluded at higher sea states because of the limit on capability to recover to a more actively moving deck. If shipboard operations at these extreme conditions are anticipated, roll control authority in excess of that given in References 4 and 5 must be provided. Further, lateral velocity command capability will demand more control authority than that used for attitude command alone. The latter two conclusions are contingent both on the validity of the ship airwake model used in this experiment (Ref. 11) and on the aircraft's sensitivity to airwake disturbances and should be qualified accordingly.

Summary of Roll Control Requirements. Table 3 presents a summary of the required roll control authority determined from these simulation results, compared to the Level 1 criteria of References 4, 5, and 6, to available control power for the V/STOL fighters, and to the E-7A STOVL concept. For the transition phase, the pertinent criteria again are those of References 5 and 6. In the hover and vertical landing, References 4 and 5 are the applicable documents.

During transition, References 5 and 6 accommodate the level of roll control required for maneuvering in calm air, but call for an insufficient level of control to handle the current STOVL configuration in turbulence up to the level shown. Considering experience of the Harrier design evolution, the dominant requirement for roll control during transition may well be associated with countering sideslip excursions. The AV-8B has sufficient lateral control to trim with sideslip angles of 15° or more during transition. The current MFVT configuration can achieve lateral trim with sideslip of 10° or greater over the low speed flight envelope. Criteria of References 4 and 5 are about right for the vertical landing. No criteria are available for shipboard operations. Total control authority available for trim and maneuvering is shown for the Harrier and VAK-191. Total control available for the current STOVL aircraft in its basic configuration in hover is 1.1 rad/sec^2, which was adequate for disturbance suppression and more than adequate for control of the vertical landing. However, it was necessary to augment the baseline roll control system with reaction control to provide sufficient control power to handle the highest wind over deck for recovery to the ship. In the latter case, the total control power was 2.15 rad/sec^2. Control used for maneuvering in calm air and control needed in turbulence for the E-7A were less than those required for the MFVT STOVL and more in line with the criteria of References 5 and 6. It should be noted that for the MFVT STOVL design every 0.1 rad/sec^2 of additional roll control power would require an additional ±170 lb of differential thrust at the lift nozzles in the hover condition, or 2.4 lb/sec of reaction control bleed at the tail mounted reaction control nozzles. If wing tip reaction controls were employed for roll control, this increment of control power would demand 0.7 lb/sec of bleed flow. The bleed flow values are based on an assumption of 90 lb of reaction control thrust per pounds per second of bleed flow rate (Ref. 12), and on minimal nozzle flow losses or adverse jet interference. If the latter two influences are not optimized, bleed flow requirements would increase.

Yaw Control

Effect of Flight Phase. Yaw control use shown in Figure 5 is considerably less than the criteria of References 4 and 5 for any flight phase. For the transition (Fig. 5a), peak demands in calm air range from 0.02 to 0.04 rad/sec^2. In the heaviest turbulence, maximum control usage of 0.04–0.14 rad/sec^2 was observed, with most confined to the range of 0.05–0.07 rad/sec^2, within the 3–4σ band. In contrast, the recommended range is 0.15–0.25 rad/sec^2 from Reference 5. As a further example, the requirement of Reference 6 for a 15° heading change in 2.2 sec translates into a maximum yaw control power of 0.22 rad/sec^2 for a yaw damping time constant of 1 sec. The disparity between these two criteria for yaw control and the recent simulation experience is likely attributable to good yaw stability augmentation employed and the lower sensitivity to disturbances for the recent STOVL fighter concepts compared to the collection of aircraft on which the earlier criteria were based.

Maximum yaw control for the vertical landing (Fig. 5b) is comparable to that for the transition. Maximum maneuvering control in calm air varies from 0.015 to 0.065 rad/sec^2; control in turbulence increases somewhat with an occasional peak excursion as large as 0.1 rad/sec^2. The maximum range in turbulence corresponds to 3–4σ values. The Reference 4 requirement for a heading change of 6° in 1 sec converts to a maximum control power of 0.28 rad/sec^2 for a yaw time constant of 1 sec. For the shipboard landing (Fig. 5c), maximum control use is similar to that for the runway landing, with peaks to 0.1 rad/sec^2 for the highest wind over deck.

Summary of Yaw Control Requirements. Yaw control summaries of authority determined from these STOVL aircraft simulation results, compared to the Level 1 criteria of References 4, 5, and 6, to available control power for other V/STOL fighter designs, and to the E-7A, are provided in Table 4. For the transition phase, the pertinent criteria once more are those of References 5 and 6. For the vertical landing, References 4 and 5 are the pertinent criteria.

For the transition and vertical landing, the criteria of References 4, 5, and 6 all exceed the current experience for yaw control use to a significant degree. Based on the current experience, yaw control power for maneuvering and turbulence suppression could be considerably reduced. As before, shipboard operations are not covered by the existing criteria. Total control authority for the Harrier and VAK-191 are somewhat in excess of that for the current STOVL design (0.28 rad/sec^2). Control used by the E-7A in the fixed-base simulation experiment is comparable to that for the MFVT STOVL tested on the VMS. For this STOVL aircraft design, every 0.1 rad/sec^2 reduction in yaw control power would reduce the reaction control bleed at the tail mounted reaction control nozzles by 4.8 lb/sec.

THRUST TRANSFER RATES

Ability to achieve adequate rates of thrust transfer between propulsion system components for pitch and roll control is an important aspect of control system dynamic response. Maximum thrust transfer rates observed for the different tasks in the simulation program are documented in this section. Results are presented both as maximum rate of change of thrust and, more generally, as the rate of change of pitch and roll angular acceleration. Implications for thrust control bandwidth are also noted.

Pitch Control

Effect of Flight Phase. Thrust transfer rates for pitch control are documented in Figure 6. During the transition (Fig. 6a), maneuvering control in calm air produces peak rates ranging from 0.2 to 1.3 kilopounds (klb)/sec for the attitude command SCAS. Maximum rates of 1.5–3.3 klb/sec are reached under the highest wind and turbulence condition. This maximum range exceeds that for 3–4σ values. Results are independent of SCAS mode. Runway vertical landings appear to be more demanding on maneuver control rates than the previous flight phase, but with no influence of SCAS mode (Fig. 6b). Peak rates ranging from 1 to 2.6 klb/sec are observed in the data. Turbulence has no influence on the rate of control use. The most significant control rates appear for the shipboard landings (Fig. 6c). Maximum rates of 3–4 klb/sec with attitude command and 3–6 klb/sec with longitudinal velocity command SCAS occur at the highest wind over deck.

To generalize these results, thrust transfer rates can be expressed in time rate of change of control power for this aircraft configuration, where 4 klb/sec is equivalent to 1 rad/sec^3. In turn, the maximum rate of change of control power can be used to define the relationship between peak control usage and the effective bandwidth of control that can be achieved without encountering the control rate limit. For example, a maximum thrust transfer rate of 2 klb/sec (corresponding to a rate of change of angular acceleration of 0.5 rad/sec^3) and a peak control usage of 0.05 rad/sec^2 (representative of 1σ level of control use for closed-loop regulation) would imply a rate limit free control bandwidth of 10 rad/sec. Conversely, for the same thrust transfer rate and a representative control bandwidth of 5 rad/sec, rate limit free operation could be sustained up to a control authority of 0.1 rad/sec^2.

Roll Control

Effect of Flight Phase. In Figure 7, the rates of thrust transfer employed for roll control are indicated for the different flight phases. Throughout the transition (Fig. 7a), typical maximum rates for maneuver control ranged from 1 to 2 klb/sec with the exception of two cases which demanded 4.5–6.5 klb/sec. In the heaviest turbulence, rates of 3–4 klb/sec occur frequently, with occasional peaks from 5 to 8 klb/sec. For roll control, a thrust transfer rate of 10 klb/sec is equivalent to 3 rad/sec^3.

Maneuver control rates for the runway vertical landing (Fig. 7b) generally ranged from 2 to 4 klb/sec. Turbulence did not affect control rates up to the magnitude of disturbances evaluated. For shipboard landings (Fig. 7c), peak rates of 7–8 klb/sec are observed for the attitude SCAS with significant wind over deck and represent a substantial increase over other phases of operation. With the attitude-plus-velocity SCAS, wind over deck has a strong influence on thrust transfer rates, with peaks of 10 klb/sec (3 rad/sec^3) reached on occasion for the highest wind over deck. In lighter winds, transfer rates are comparable for the two SCAS modes.

As an example for roll control, a maximum thrust transfer rate of 5 klb/sec (corresponding to a rate of change of angular acceleration of 1.5 rad/sec^3) and a peak control usage of 0.2 rad/sec^2 would imply a rate limit free control bandwidth of 7.5 rad/sec. For the same thrust transfer rate and a bandwidth of 5 rad/sec, a peak control authority of 0.3 rad/sec^2 could be achieved without reaching the control rate limit.

THRUST CONTROL

Influence of Ground Effect and Ingestion

Vertical axis control power in vertical flight is associated with the margin of thrust in excess of that required to equilibrate the aircraft's weight. The requirements for thrust margin during vertical landing are influenced by the disturbances imposed by jet-induced aerodynamic forces in proximity to the ground and degradation in engine thrust that results from temperature rise at the engine inlet due to the recirculation of hot gas exhaust from the propulsion system. Experiments have been conducted on the VMS to evaluate in general the influence of ground effect and hot gas ingestion on thrust margin necessary to control height and sink rate during airfield vertical landings (Ref. 2). In turn, these results were validated with specific simulation assessments of vertical landings with the YAV-8B Harrier, an aircraft whose vertical landing characteristics are well known and have been related to the simulation experience. Results from these simulations are presented in Figure 8. The boundaries shown define acceptable and unacceptable regions for combinations of mean ground effect and ingestion and thrust/weight ratio. One boundary was extracted from the generalized evaluations reported in Reference 2. Data from the YAV-8B ground effect evaluation are also presented with an appropriate fairing to illustrate the trend. The YAV-8B data correspond to configurations with and without lift improvement devices (LIDS) and for two levels of hot gas ingestion, and span the range of mean ground effect covered in the previous generalized investigations. Thrust/weight ratio is determined out-of-ground effect. Mean ground effect and ingestion are defined here by the relationship

$$\frac{1}{43}\int_0^{43} (\Delta L/T)'dh$$

where $(\Delta L/T)'$ incorporates jet induced aerodynamic ground effect as well as thrust variations with inlet temperature and is defined as

$$(\Delta L/T)' = \{[1 + \Delta L/T][1 + (\Delta F_G/\Delta\theta)(\Delta\theta/W)] - 1\}$$

The altitude range over which the mean ground effect and ingestion are based is 43 ft and represents the range over which ground effect exists for the Harrier. For the earlier generalized ground effect simulation, the integral defining mean ground effect was based on an altitude range of 15 ft, where ground effect did not vary above that altitude. The mean ground effect that defined the boundary for that experiment (Ref. 2) was adjusted by the ratio 15:43 to bring it into conformity with the definition of mean ground effect used herein.

The shape of the boundaries is established by height control out-of-ground effect for positive ground effect, on abort capability at decision height for neutral to moderately negative ground effect and ingestion, and on control of sink rate and hover position to touchdown for larger negative ground effect. Results from simulation evaluation of the YAV-8B Harrier are somewhat less conservative than the boundary derived from the evaluation of generalized ground effect and are consistent with Harrier flight experience as described in the aircraft's operations manuals (Refs. 13 and 14). The boundary correlates over much of its range with an analytical prediction of the trend of thrust/weight with mean ground effect required to arrest a nominal sink rate of 4 ft/sec prior to touchdown with an application of maximum thrust at an altitude of 21 ft. This analytical relationship is expressed as

$$\left(\dot{h}_i^2 - \dot{h}_o^2\right)/2g = \int_0^{43} (\Delta L/T)'dh + \int_0^{h_i} (\Delta T/W)dh$$

and can be used in synthesis of new STOVL designs to determine the required thrust margin for anticipated levels of mean ground effect and ingestion. Finally, based on the results of Reference 2, it was noted that the employment of a vertical velocity command control did not shift the boundary shown in Figure 8, which was obtained for attitude SCAS alone. However, as noted in Reference 2, vertical velocity command does reduce the chance for abuse of sink rate control during the descent to landing and, hence, improves the control margin for vertical landing.

Influence of Engine Dynamics

Effects of thrust response dynamics on the pilot's assessment of control of the vertical landing are shown in Figure 9. These data come from Reference 2 and apply to manual control of thrust with only attitude SCAS available. It is apparent that bandwidth of thrust response of the engine core of 4–5 rad/sec is sufficient to achieve satisfactory ratings for height and sink rate control. For bandwidths below 3 rad/sec, the control task deteriorates rapidly. Both the transition and hover point acquisition tasks were less sensitive to variations in thrust control bandwidth than was the vertical landing (Ref. 2). Vertical velocity command in addition to attitude SCAS insulates the pilot from the dynamics of the propulsion system response and results in toleration of slower engine response (providing the overall airframe response is not altered) than for attitude SCAS alone.

To a point, the vertical landing is insensitive to maximum rate of change of core thrust, which is associated with engine acceleration limits imposed by maximum allowable temperatures in the core. Thrust rates varying from 25% of maximum thrust/sec down to nearly 10%/sec were tolerable for height control. However, at about 10%/sec, thrust rate limiting and loss of control were encountered on occasion for such slow acceleration characteristics. These acceleration rate limits can be related to surge margin in design of the propulsion system control. Deceleration rate limits are important to the ability to rapidly reduce thrust at touchdown, as well as to the dynamic control of vertical velocity in the hover. Vertical velocity command does not seem to alter these results.

CONCLUSIONS

A program has been conducted to define and experimentally evaluate control system concepts for STOVL fighter aircraft in powered-lift flight. The control system designs have been evaluated in Ames Research Center's Vertical Motion Simulator. Items assessed in the program were maximum control power, control system dynamic response associated with thrust transfer for attitude control, thrust margin in the presence of ground effect and hot gas ingestion, and dynamic thrust response for the engine core. Results provide the basis for a reassessment of existing flying qualities design criteria for this class of aircraft.

This experience shows that pitch control power used in transition is in general accord with existing criteria, whereas that used for vertical landing is somewhat lower. When a translational velocity command system using deflected thrust for longitudinal force control is employed, pitch control use is considerably less than the criteria suggest. No criteria, except that for hover, exist for shipboard recovery.

In the roll axis, control power recommended by current design criteria is insufficient to cover demands for transition. Agreement is good with criteria for vertical landing. Again, no criteria are available for shipboard operations. For these operations, lateral velocity command through bank angle control typically used greater control power than did an attitude command system alone.

For the transition and vertical landing, the existing criteria all exceed the current experience for yaw control use. As before, shipboard operations are not covered by the existing criteria.

Thrust transfer rates for pitch and roll control were observed to be greatest for shipboard operations, with the decelerating transition placing the next greatest demand. Control mode did not have a strong influence on these results.

Thrust margins for vertical landing in the presence of ground effect and hot gas ingestion were defined based on results from simulation of the YAV-8B Harrier. The shape of the boundaries is established by height control out-of-ground effect for positive ground effect, on abort capability at decision height for neutral to moderately negative ground effect and ingestion, and on control of sink rate and hover position to touchdown for larger negative ground effect. The boundary correlates with an analytical prediction of the trend of thrust/weight with mean ground effect required to arrest a nominal sink rate with an application of maximum thrust at decision height. The employment of a vertical velocity command control does not alter the thrust margin requirement.

Bandwidth of thrust response of the engine core of 4–5 rad/sec is sufficient to achieve satisfactory ratings for height and sink rate control. For bandwidths below 3 rad/sec, the control task deteriorates rapidly. Vertical velocity command systems can tolerate somewhat slower engine response (providing the overall airframe response is not altered) than can be accepted by the pilot for manual control of thrust. To a point, the vertical landing is insensitive to maximum rate of change of core thrust; however, loss of control appears at the lowest thrust transfer rates. Vertical velocity command does not seem to alter these results.

REFERENCES

1. Levine, J. and Inglis, M., "US/UK Advanced Short Takeoff and Vertical Landing Program," AIAA Paper 89-2039, July 1989.

2. Franklin, J. A., Stortz, M. W., Engelland, S. A., Hardy, G. H., and Martin, J. L., "Moving Base Simulation Evaluation of Control System Concepts and Design Criteria for STOVL Aircraft," NASA TM-103843, June 1991.

3. Merrick, V. K., Farris, G. G., and Vanags, A. A., "A Head-Up Display Format for Application to V/STOL Approach and Landing," NASA TM-102262, Sept. 1989.

4. Chalk, C. R., Key, D. L., Kroll, J. Jr., Wasserman, R., and Radford, R. C., "Background Information and User Guide for MIL-F-83300 – Military Specifications – Flying Qualities for Piloted V/STOL Aircraft," AFFDL-TR-70-88, Nov. 1971.

5. "V/STOL Handling, I – Criteria and Discussion," AGARD R-577-70, Dec. 1970.

6. Innis, R. C., Holzhauser, C. A., and Quigley, H. C., "Airworthiness Considerations for STOL Aircraft," NASA TN D-5594, Jan. 1970.

7 Anon., "AV-8B Aircraft Stability, Control and Flying Qualities," McDonnell Douglas Corporation Report MDC A5192, Aug. 1981.

8. Lacey, T. R., "MIL-F-83300, View from an Aircraft Designer," Proceedings of the Navy/NASA VSTOL Flying Qualities Workshop, April 1977.

9. Fortenbaugh, R., Hutchins, D., Miller, D., Schweinfurth, R., Traskos, R., and Tumilowicz, R.,"USN/FMOD FRG VAK-191B Joint Flight Test Program – Stability and Control," Final Report, Vol. 4, NAVAIR-4R-76, Aug. 1976.

10. Franklin, J. A., Stortz, M. W., Gerdes, R. M., Hardy, G. H., Martin, J. L., and Engelland, S. A., "Simulation Evaluation of Transition and Hover Flying Qualities of the E-7A STOVL Aircraft," NASA TM-101015, Aug. 1988.

11. Fortenbaugh, R. L., "Mathematical Models for the Aircraft Operational Environment of DD-963 Class Ships," Vought Corp. Rep. 2-55800/8R-3500, Sept. 1978.

12. Hange, C. and Gelhausen, P., "An Investigation Into Sizing the Reaction Control System in Conceptual STOVL Aircraft," NASA TM-103990, 1993.

13. Anon., "NATOPS Flight Manual Navy Model AV-8B," A1-AV8B-NFM-000, Dec. 1984.

14. Anon., "NATOPS Flight Manual Navy Model AV-8A and TAV-8A," NAVAIR 01-AV8A-1, June 1978.

Table 1. Flight Control Modes

	Transition		Hover	
Control axis	Attitude SCAS	Flightpath SCAS	Attitude SCAS	Velocity SCAS
Pitch/roll	Rate command-attitude hold	Rate command-attitude hold	Attitude command-attitude hold	Attitude command-attitude hold
Yaw	Turn coordination	Turn coordination	Yaw rate command	Yaw rate command
Vertical	Thrust magnitude	Flightpath command	Thrust magnitude	Velocity command
Longitudinal	Thrust deflection	Acceleration command-velocity hold	Thrust deflection	Velocity command
Lateral				Velocity command

Table 2. Comparison of Pitch Control Power Criteria with STOVL Aircraft Designs

Flight phase	MIL-F 83300 Ref. 4	AGARD R-577 Ref. 5	NASA TN 5594 Ref. 6	AV-8B Ref. 7	AV-8A Ref. 8	VAK-191 Ref. 9	Recent STOVL Concepts			
							MFVT		E-7A (Ref. 10)	
							Maneuver	Turb6	Maneuver	Turb6
Transition		0.05–0.2	0.5				0.15–0.19	0.2–0.25	0.6	0.6
Vertical landing	0.29	0.1–0.3		0.53 –0.83	0.8 –0.75	1.0	0.16–0.27 0.17	0.16–0.27 (AC) 0.17 (VC)		
							WOD 15	WOD 46	WOD 15	WOD 34
Shipboard landing				0.53 –0.83	0.8 –0.75		0.31 0.22	0.37 0.22 (VC)	0.3	0.4

Notes: (1) All values expressed in terms of control power in rad/sec^2.

(2) Reference 7 and 9 requirements converted from attitude response based on a time constant of 0.5 sec for rate command systems or a natural frequency of 2 rad/sec for a critically damped attitude command system.

(3) Control power for actual aircraft represent total available in hover; transition values not available.

(4) Control power for MFVT and E-7A represent maximum used.

Table 3. Comparison of Roll Control Power Criteria with STOVL Aircraft Designs

Flight phase	MIL-F 83300 Ref. 4	AGARD R-577 Ref. 5	NASA TN 5594 Ref. 6	AV-8B Ref. 7	AV-8A Ref. 8	VAK-191 Ref. 9	Recent STOVL Concepts			
							MFVT		E-7A (Ref. 10)	
							Maneuver	Turb6	Maneuver	Turb6
Transition		0.1–0.6	0.55				0.3–0.4	0.9–1.2	0.25	0.6
Vertical landing	0.38	0.2–0.4		2.2	1.73	1.4	0.1–0.3	0.2–0.4		
							WOD 15	WOD 46	WOD 15	WOD 34
Shipboard landing				2.2	1.73		0.2–0.4	0.9–1.1 (AC) 1.3–2.0 (VC)	0.55	1.8

Notes: (1) All values expressed in terms of control power in rad/sec^2.

(2) Reference 7 and 9 requirements converted from attitude response based on a time constant of 0.5 sec for rate command systems or a natural frequency of 2 rad/sec for a critically damped attitude command system..

(3) Control power for actual aircraft represent total available in hover; transition values not available.

(4) Control power for MFVT and E-7A represent maximum used.

Table 4. Comparison of Yaw Control Power Criteria with STOVL Aircraft Designs

Flight phase	MIL-F 83300 Ref. 4	AGARD R-577 Ref. 5	NASA TN 5594 Ref. 6	AV-8B Ref. 7	AV-8A Ref. 8	VAK-191 Ref. 9	Recent STOVL Concepts			
							MFVT		E-7A (Ref. 10)	
							Maneuver	Turb6	Maneuver	Turb6
Transition		0.15–0.25	0.22				0.02–0.04	0.05–0.07	0.04	0.04
Vertical landing	0.28	0.1–0.5		0.43	0.46	0.4	0.15–0.065	0.1		
							WOD 15	WOD 46	WOD 15	WOD 34
Shipboard landing				0.43	0.46		0.065	0.1	0.05	0.12

Notes: (1) All values expressed in terms of control power in rad/sec^2.

(2) Reference 7 and 9 requirements converted from attitude response based on a time constant of 1 sec for rate command systems.

(3) Control power for actual aircraft represent total available in hover; transition values not available.

(4) Control power for MFVT and E-7A represent maximum used.

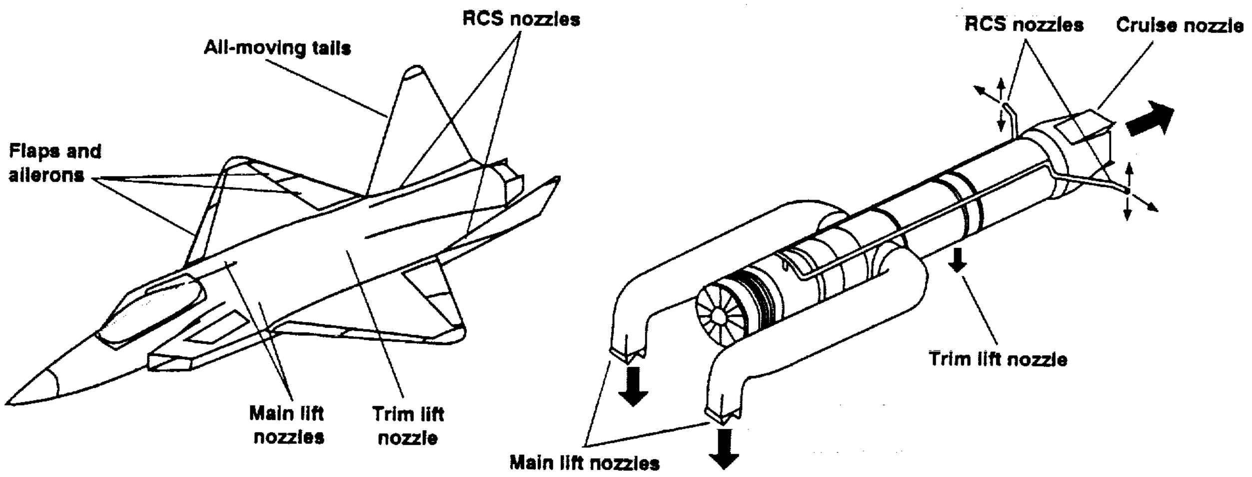


Figure 1. Mixed-Flow Remote Lift STOVL Aircraft

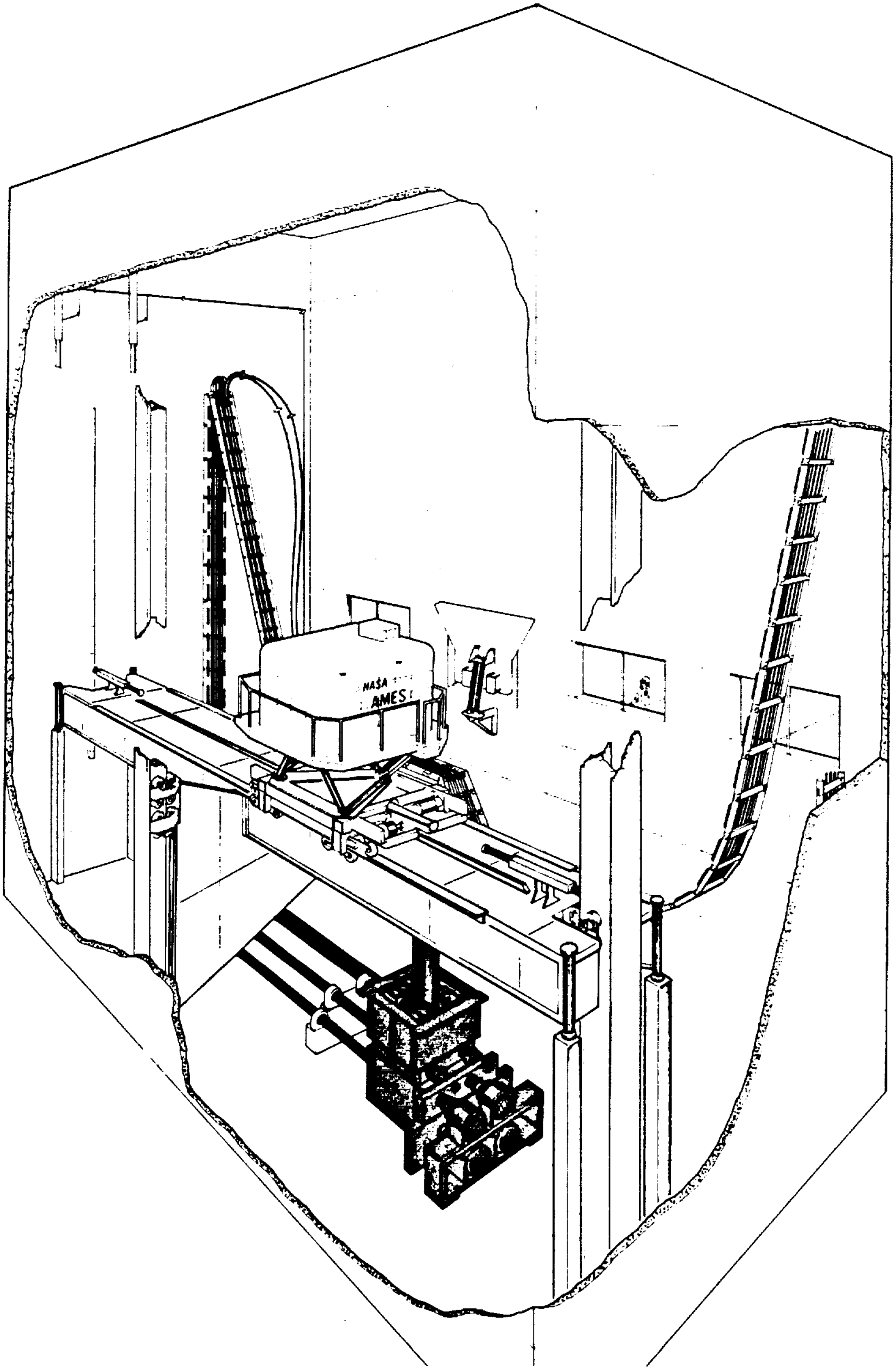
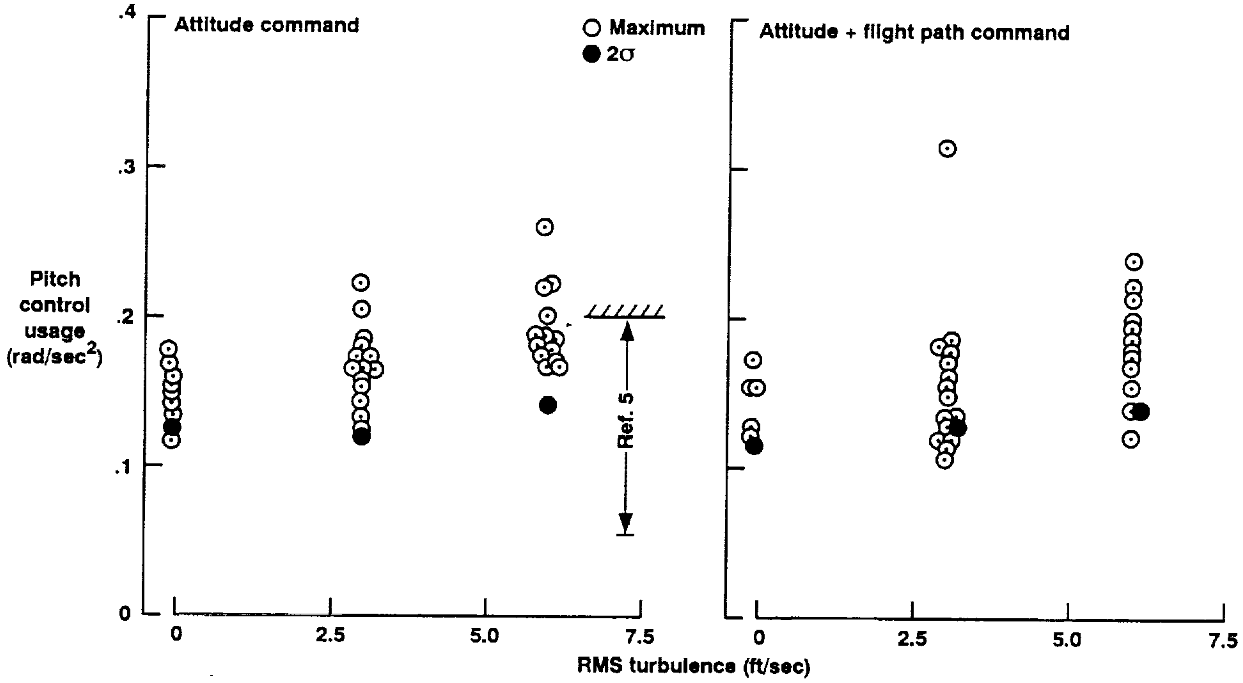
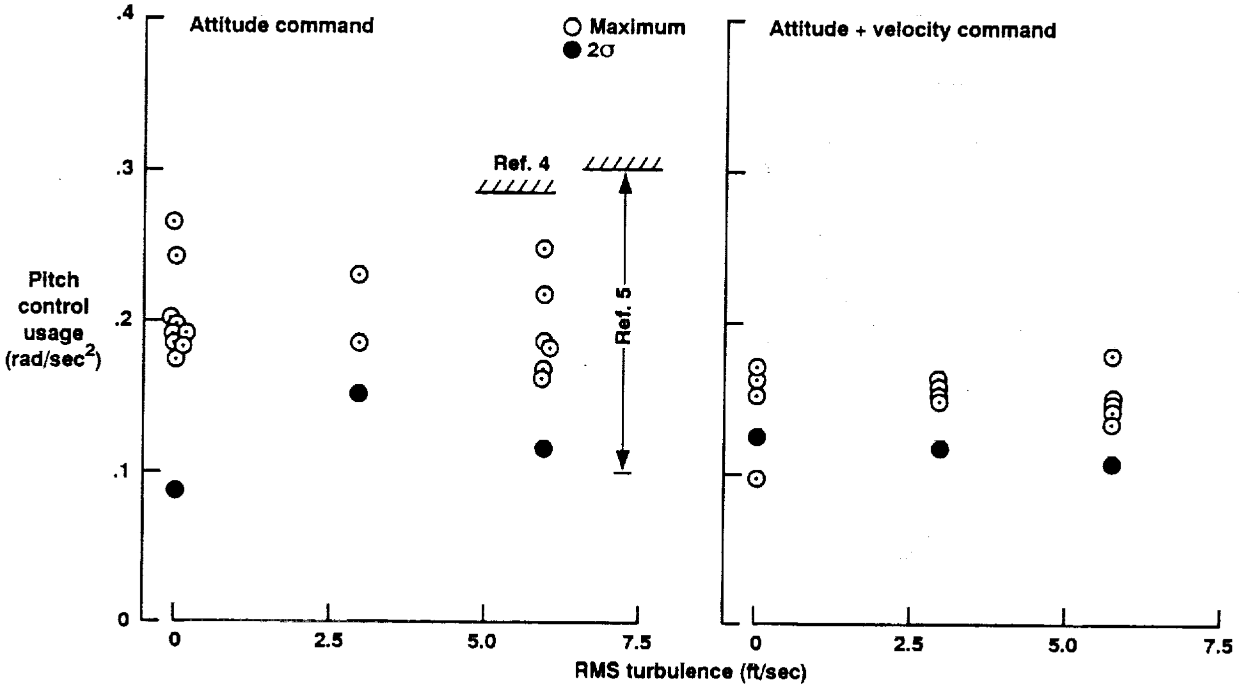


Figure 2. Vertical Motion Simulator

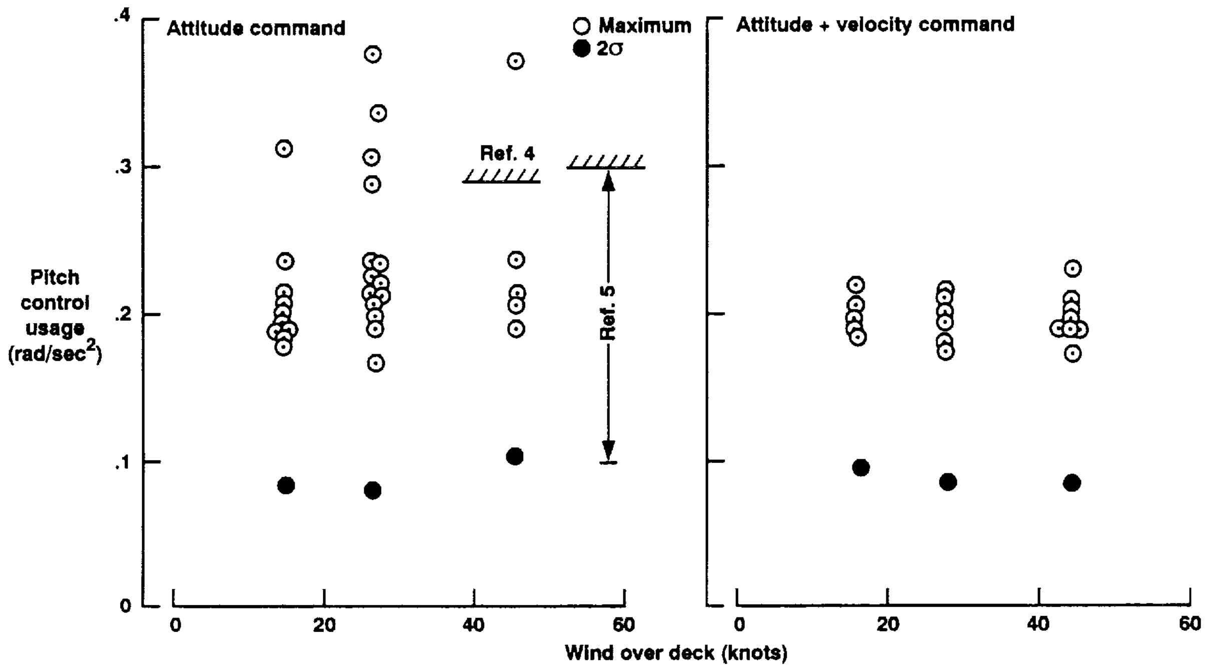


(a) Transition



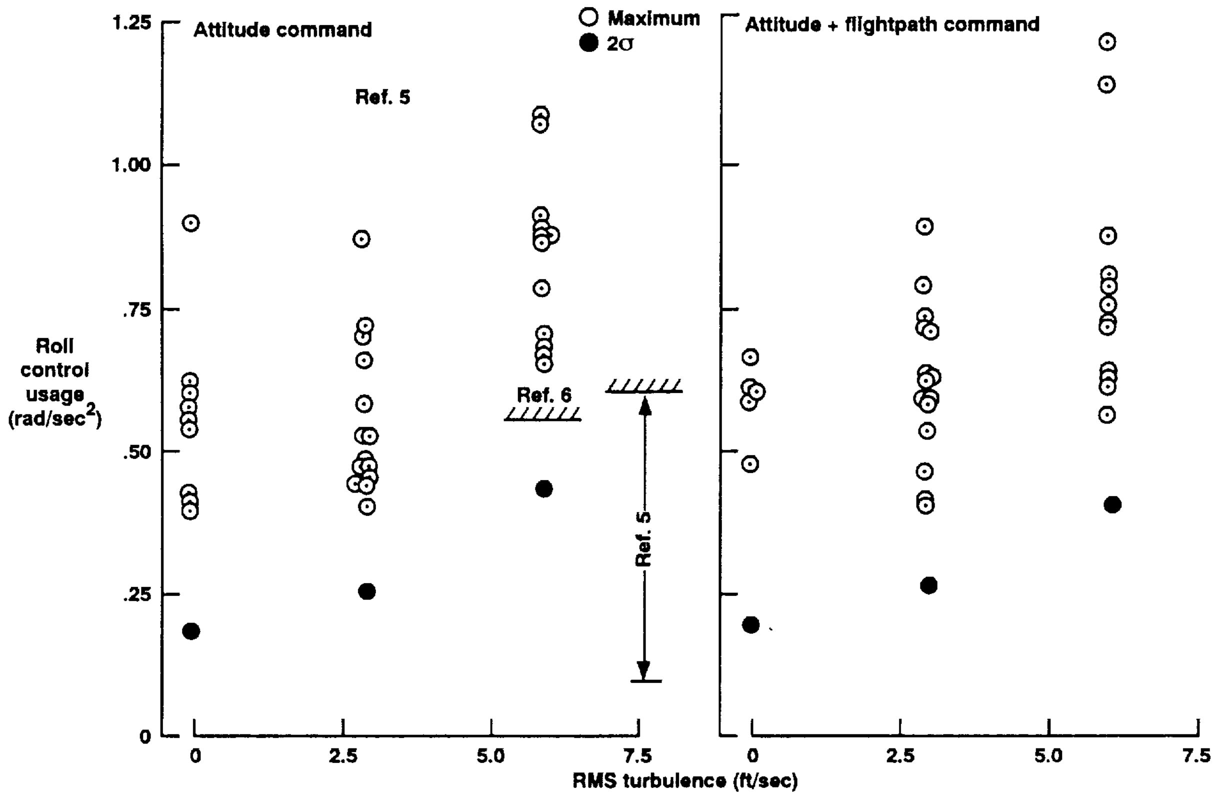
(b) Vertical Landing

Figure 3. Influence of SCAS Configuration and Wind Environment on Pitch Control Use.



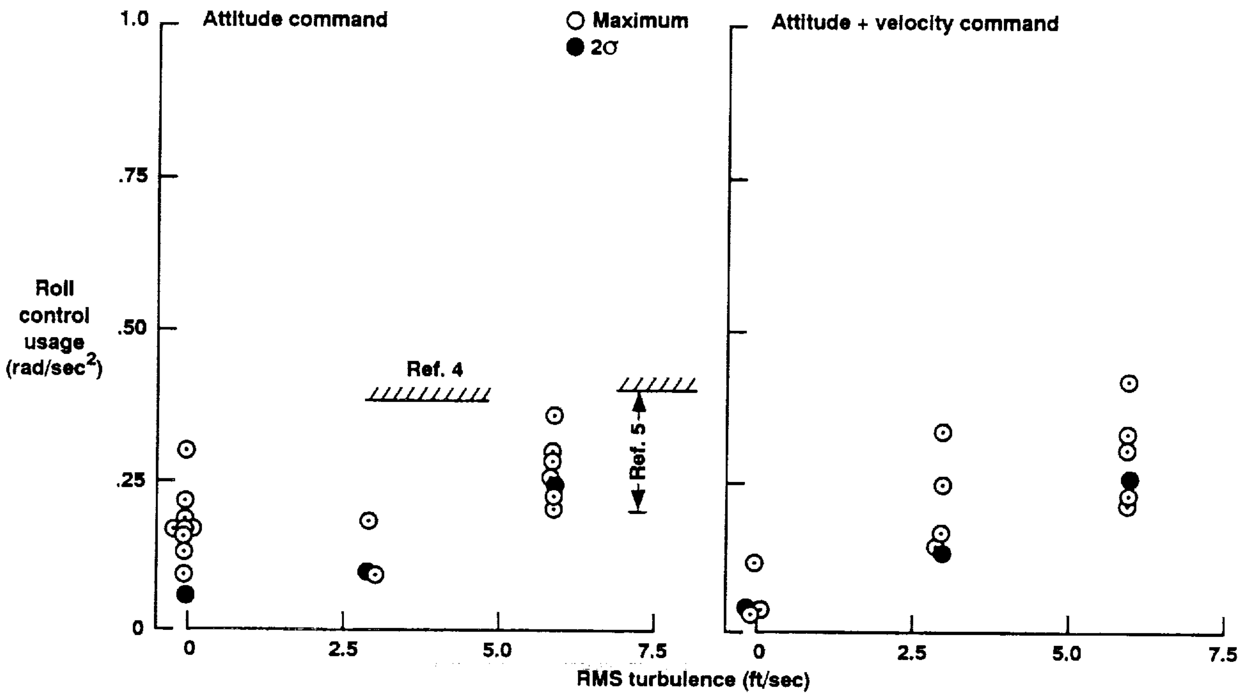
(c) Shipboard Landing

Figure 3. Concluded.

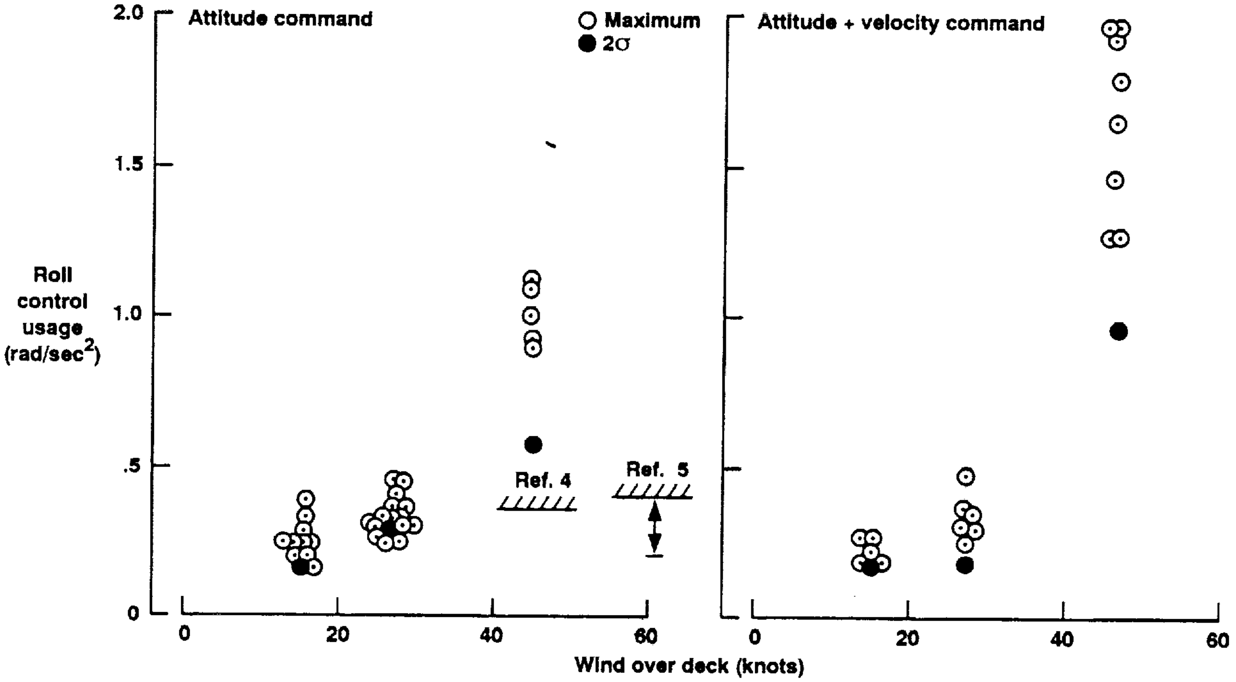


(a) Transition

Figure 4. Influence of SCAS Configuration and Wind Environment on Roll Control Use.

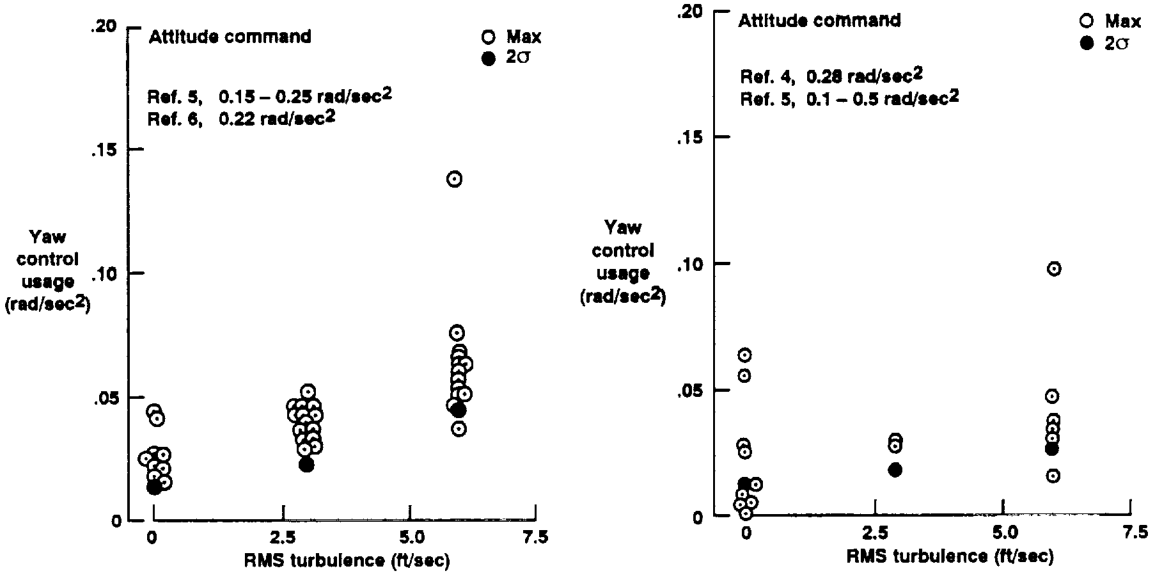


(b) Vertical Landing



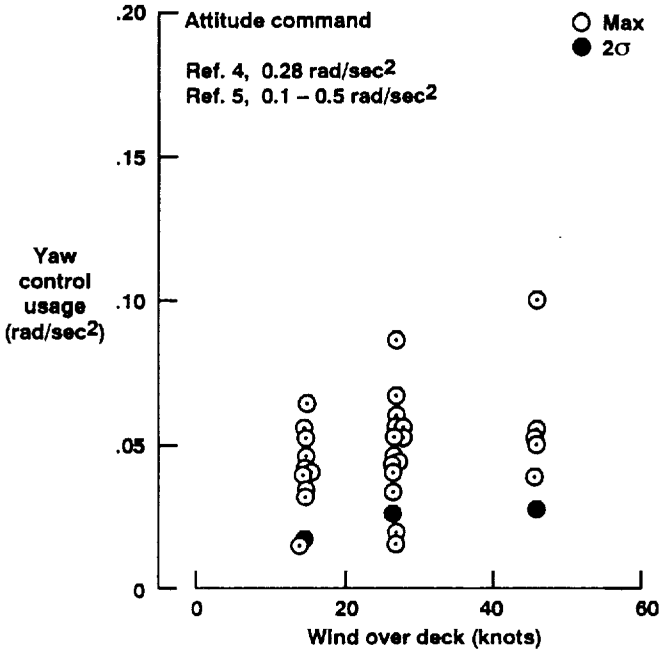
(c) Shipboard Landing

Figure 4. Concluded.



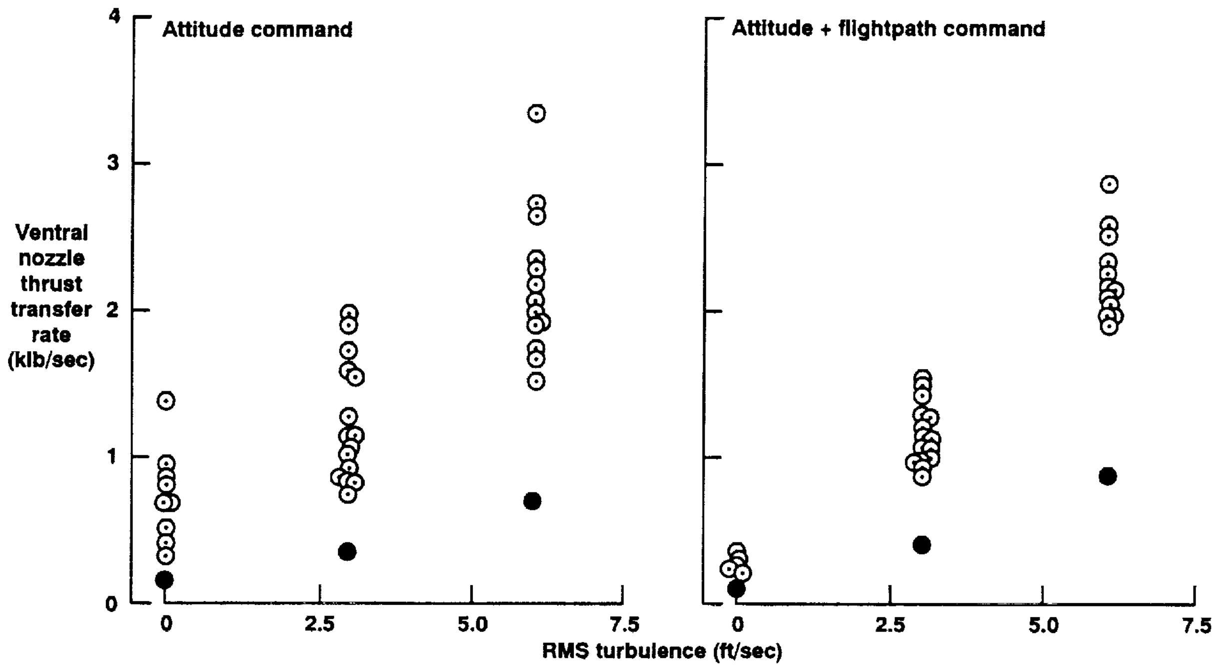
(a) Transition

(b) Vertical Landing

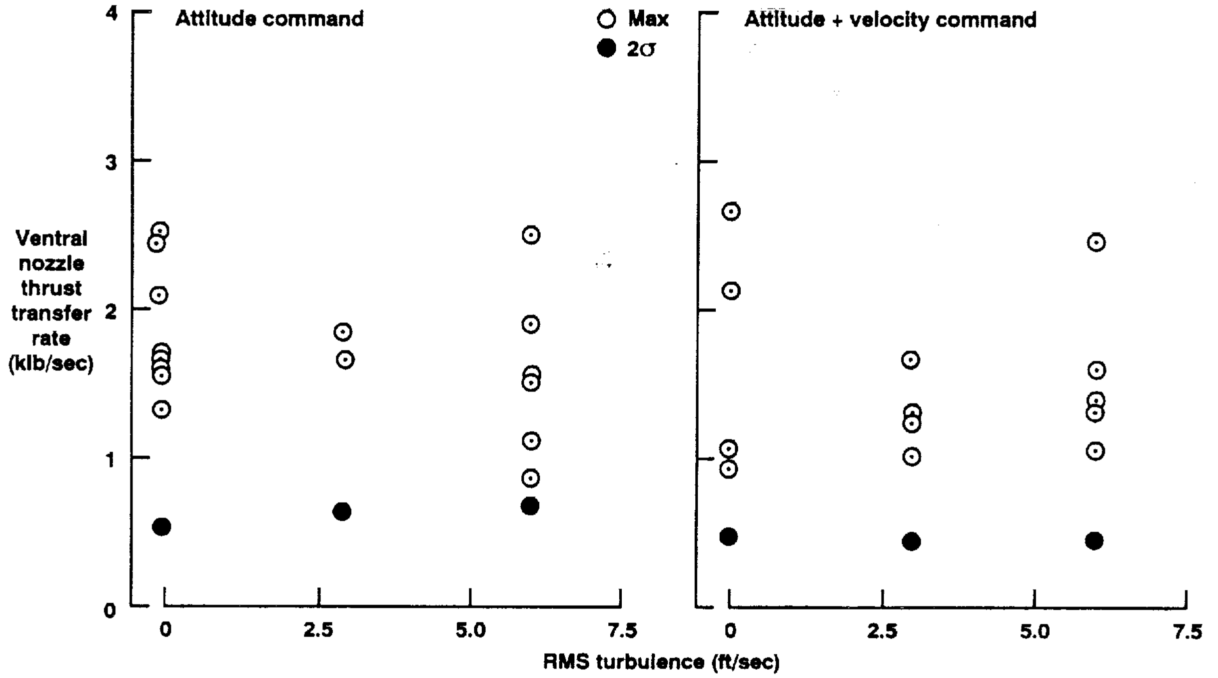


(c) Shipboard Landing

Figure 5. Influence of Wind Environment on Yaw Control Use.

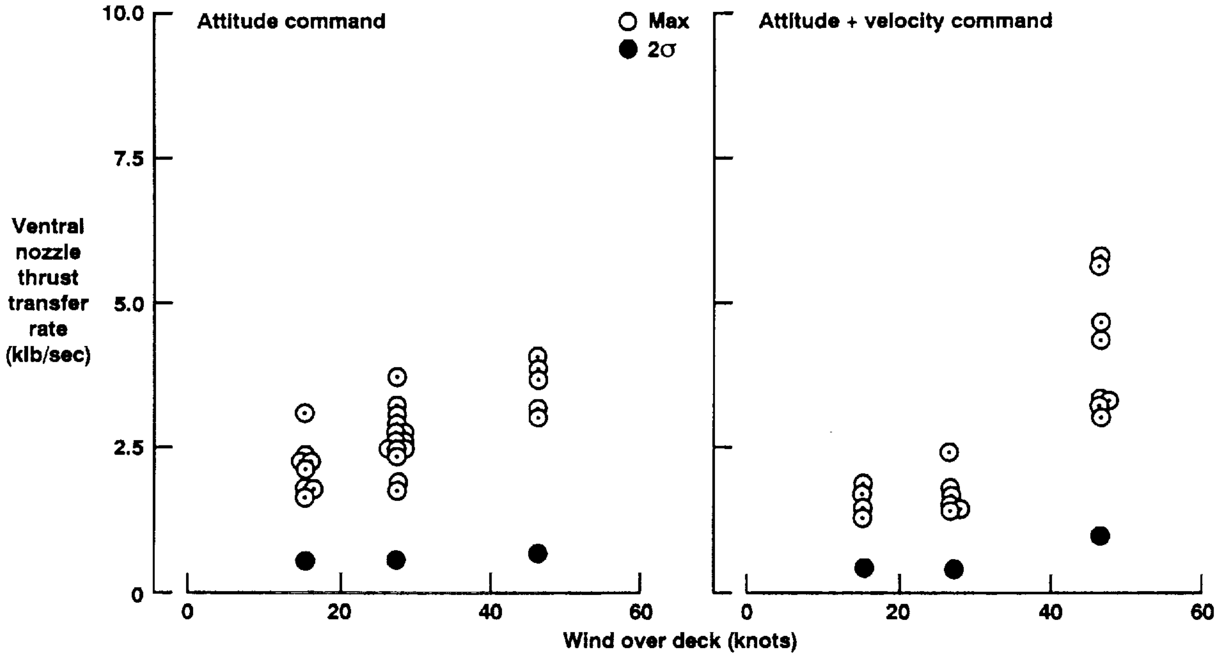


(a) Transition



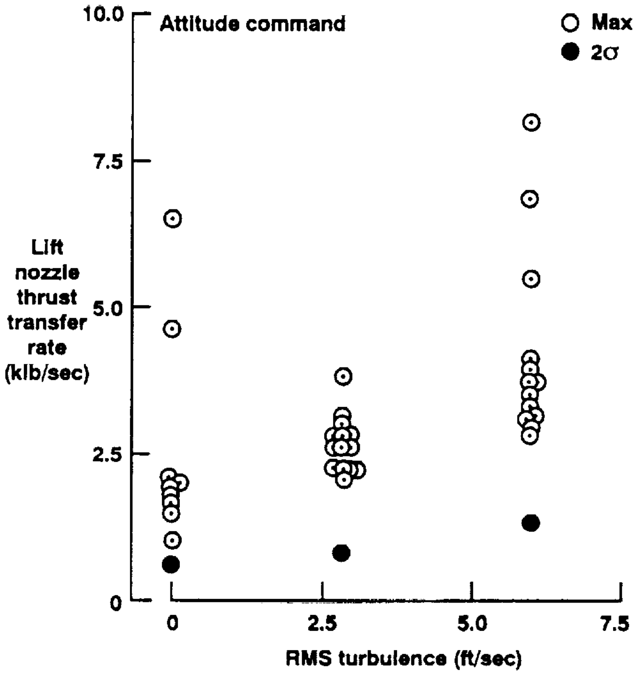
(b) Vertical Landing

Figure 6. Influence of SCAS Configuration and Wind Environment on Thrust Transfer Rate for Pitch Control.



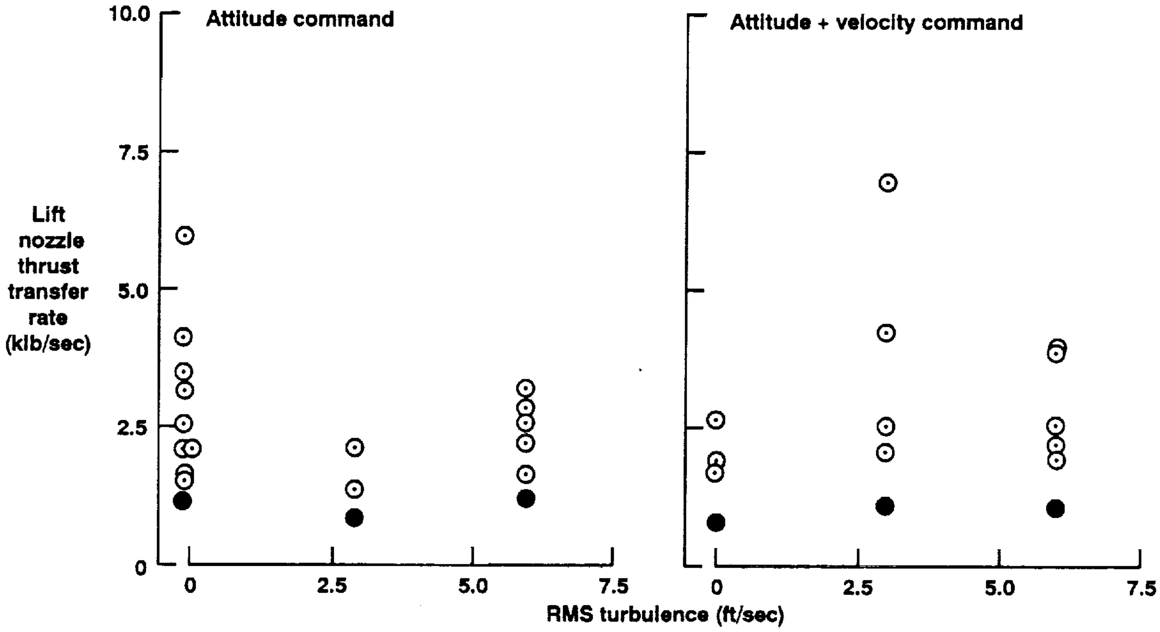
(c) Shipboard Landing

Figure 6. Concluded.

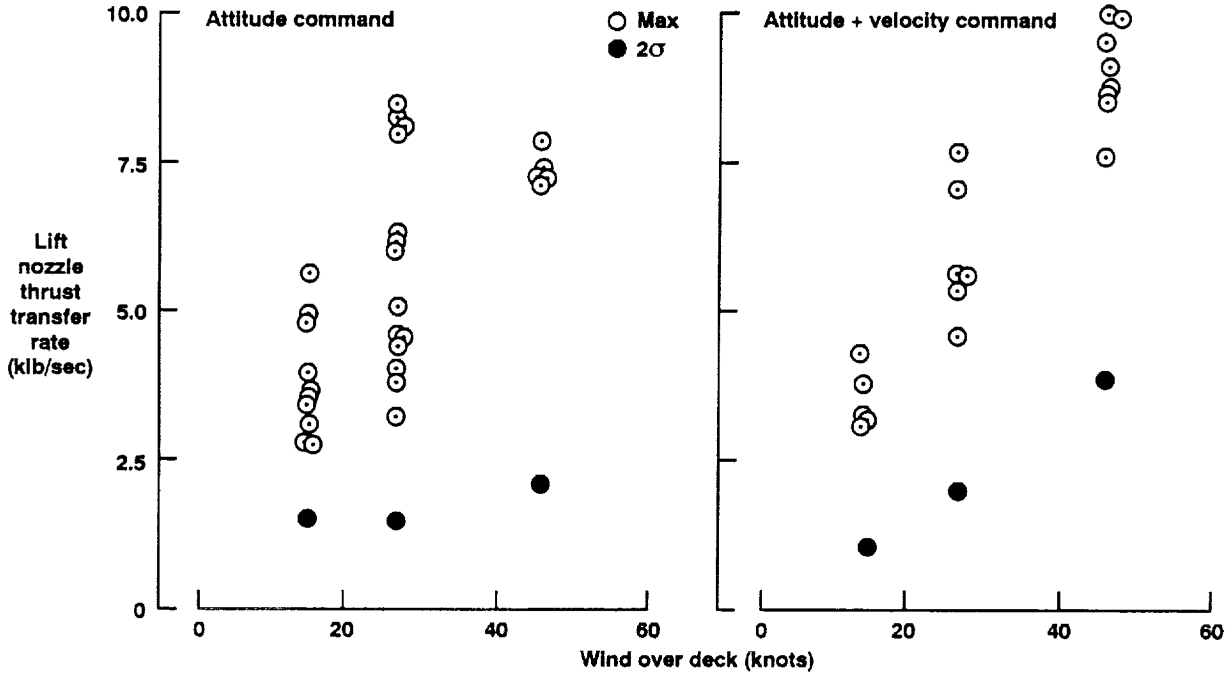


(a) Transition

Figure 7. Influence of SCAS Configuration and Wind Environment on Thrust Transfer Rates for Roll Control.



(b) Vertical Landing



(c) Shipboard Landing

Figure 7. Concluded.

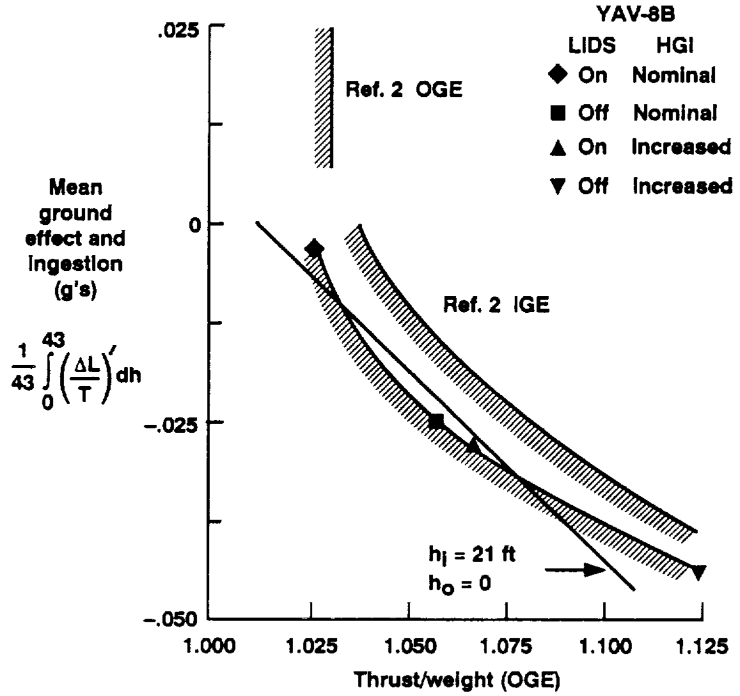


Figure 8. Influence of Ground Effect and Hot Gas Ingestion on Thrust Margin for Vertical Landing

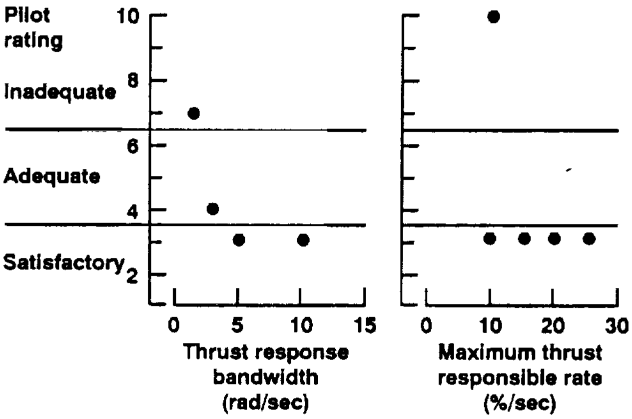


Figure 9. Effect of Thrust Response Bandwidth and Response Rate on Control of Vertical Landing