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Criteria for Design of Integrated Flight/Propulsion Control Systems for STOVL Fighter Aircraft

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SUMMARY

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 U.S./U.K. STOVL Joint Assessment and Ranking Team. The control-system designs have been evaluated throughout the powered-lift flight envelope on the Vertical Motion Simulator (VMS) at Ames Research Center. 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
IGE	in-ground effect
IMC	instrument meteorological conditions
LIDS	lift-improvement devices
MFVT	mixed-flow vectored thrust
OGE	out-of-ground effect
PIO	pilot-induced oscillation
rms	root mean square
SCAS	stabilization and command augmentation system
T	propulsion-system vertical thrust, lb
VC	velocity command
VMS	Vertical Motion Simulator
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
ζ	damping ratio
θ	temperature ratio as a function of wheel height; pitch attitude, deg
θ_c	commanded aircraft attitude, deg
θ_1	aircraft attitude at one second after control input, deg
σ	standard deviation
τ	time constant, sec
ω	natural frequency, rad/sec

INTRODUCTION

NASA has been involved in a collaborative program with government agencies in the U.S. and with the United Kingdom Ministry of Defence to develop technology for supersonic short takeoff and vertical landing (STOVL) aircraft. As a result, a wide variety of airframe and propulsion system concepts have been assessed through analytical studies, and critical technical issues have been identified for further investigation (ref. 1). The preferred design approach identified by the U.S./U.K. STOVL Joint Assessment and Ranking Team for the airframe and propulsion system is known as mixed-flow remote-lift, an example of which is shown in figure 1. This configuration features mixed fan and core flows that can be directed forward or aft to generate lift and thrust forces and to provide (partially or exclusively) control moments. The propulsion system will have forward-thrust-producing devices 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 nozzles that provide a thrust component for pitch control and may also deflect about the vertical axes. 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 the STOVL 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 the Vertical Motion Simulator (VMS) at Ames Research Center. Included in the control-system evaluation were assessments of maximum control power used in transition and vertical flight, control-system dynamic response associated with control bandwidth and thrust transfer rates for attitude control, thrust margin in the presence of ground effect and hot-gas ingestion, and

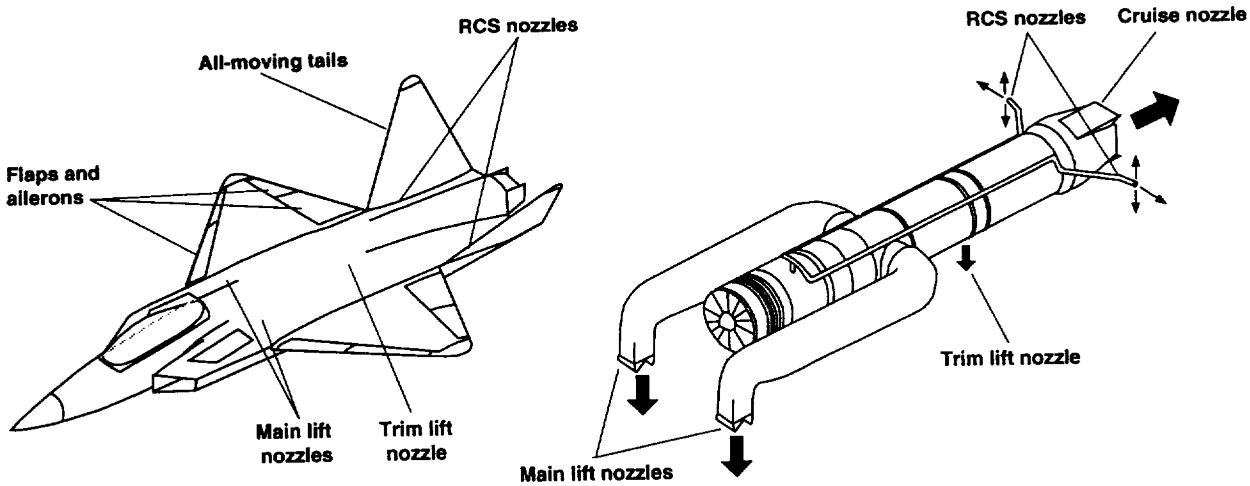


Figure 1. Mixed-flow remote lift STOVL aircraft.

dynamic thrust response for the engine core. Effects of wind, turbulence, and ship airwake disturbances were incorporated in the assessment. Results of these assessments provide the basis for possible revisions or extensions of flying-qualities design criteria for STOVL aircraft.

This report includes a description of the aircraft and the simulation facility, and the experiments 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 deg and an 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 the pitching moment of the lift nozzles. Lift-nozzle thrust can be deflected up to ±20 deg about a nominal rearward cant angle of 8 deg. The cruise nozzle can be deflected laterally or vertically ±20 deg. In conventional flight, the mixed flow is directed aft through the cruise nozzle; while 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 conventional to hover flight, the flow is smoothly transferred from the lift nozzle 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 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 the deflection of lift nozzle thrust.

To achieve the desired level of flying qualities during low-speed flight, stabilization and command augmentation (SCAS) modes were provided in the flight control system as noted in table 1. During transition, either attitude or flightpath SCAS modes were 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

Table 1. Flight-control modes

Control axis	Transition		Hover	
	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 (trim)
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

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 (HUD) 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 VMS (fig. 2) at Ames Research Center. This simulator provides six-degree-of-freedom motion with large excursions in the vertical and longitudinal axes. Large acceleration bandwidths are provided 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. The visual scene consisted either of an airfield scene or a shipboard scene 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 tasks evaluated by the pilots during the simulation were those considered to be 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 divided into two phases. The first phase was initiated under instrument meteorological conditions (IMC) in the landing configuration in level flight at 1100 ft and 200 knots. Capture of a 3 deg glide slope ensued, followed by initiation of a 0.1 g deceleration and a turn to align with the final approach course. The first phase terminated at the final stage of deceleration to the initial hover. The second phase of the approach involved completing the deceleration and acquiring a stable hover over the hover point. Vertical landings were accomplished either on a 100- by 200-ft landing zone marked on the main runway or on a 40- by 70-ft pad on the aft deck of the ship. Six pilots with vertical and short takeoff and landing (V/STOL) and powered-lift aircraft experience participated in the program.

Experiment Configurations

Experiment variables for the decelerating approach and vertical landing included control system configuration, control system dynamics, thrust/weight ratio, jet-induced ground effect and hot-gas ingestion, and environmental conditions (wind, turbulence, and sea

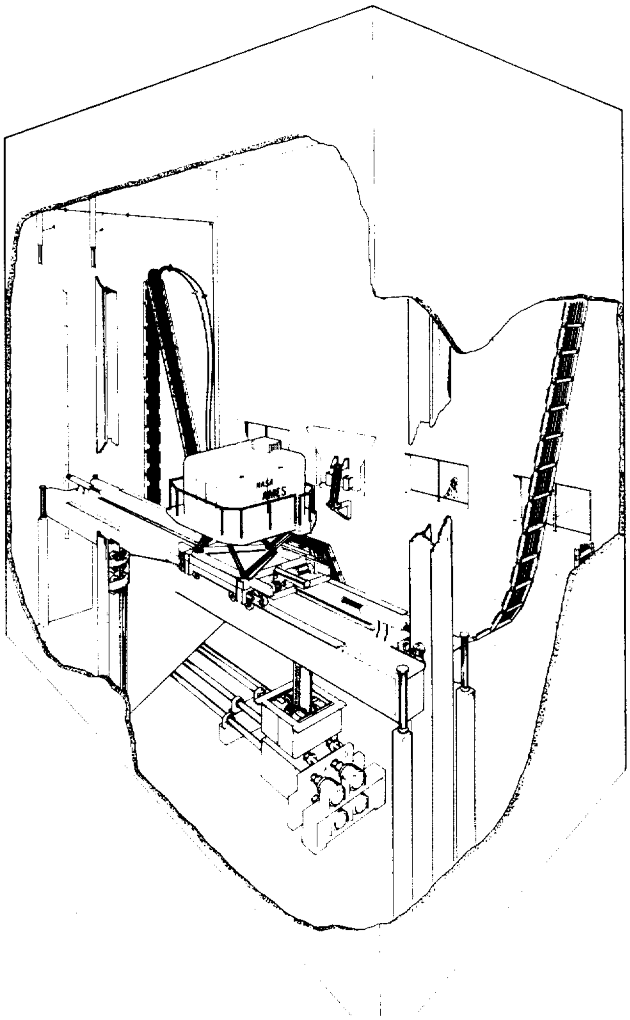


Figure 2. Vertical Motion Simulator (VMS).

state). Both the attitude SCAS and attitude-plus-flightpath SCAS were investigated through both phases of the decelerating approach. Attitude SCAS and attitude-plus-velocity SCAS were evaluated for the vertical landing. System dynamics variations included control-system authority and system bandwidth (refs. 4 and 5), thrust transfer rates, and engine-core thrust-response bandwidth and core acceleration rate. Nine ground-effect and ingestion profiles representative of STOVL aircraft lift and temperature characteristics as a function of height (four were representative of the YAV-8B Harrier with lift-improvement devices (LIDS) on and off) were included for airfield and shipboard landings (refs. 2 and 6). Wind conditions for the approach and airfield landing were calm, 15 and 34 knots, with crosswind components of 30 and 20 deg, respectively. 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 the deck (WOD) of 15, 27, and 46 knots, respectively, from 30 deg 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 7 and 8. Additional information from short takeoff and landing (STOL) aircraft experience which applies to the V/STOL transition is provided in reference 9. The flight and simulation data on which the referenced 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 that follow relate to control power for maneuvering and suppressing disturbances and have the control required for trim removed. They are presented to reflect the influence of the flight phase, including effects of control augmentation and magnitude of atmospheric disturbance, and the bandwidth of the control system. 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 design. Control power usage is presented in terms of individual maximum values (plus or minus with respect to 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 the frequency of occurrence for control use, expected maximum values would be three to four times the standard deviation. Two standard deviations represent a level of control use that is exceeded 4.6 percent of the time over the ensemble of data runs. Aircraft response specifications from references 7 and 9 were translated to measures of control power for direct comparison with the current results. Reference 7 criteria were translated from attitude change in one second using an attitude control bandwidth of 2 rad/sec for an attitude command response that is critically damped or is using a first-order response with a time constant appropriate to the axis being controlled. Examples of the conversion between attitude response and control power are presented in the appendix.

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, as they phase from the former to the latter at progressively higher speeds.

Pitch Control

Effect of flight phase– 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, hover, airfield vertical landing, and shipboard landing are presented in figure 3. For the transition (fig. 3(a)), 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 8 for STOL operations (which can be related to the transition phase of this simulation). Two standard deviation (2σ) levels are well below the reference 8 maximum. Peak values generally equate to 3–4σ levels. The influence of turbulence on the additional control required for disturbance suppression is apparent. For root mean square (rms) turbulence of 6 ft/sec, a few instances of control usage exceed the maximum recommended level in reference 8. Thus, to allow for maneuvering and the effects of turbulence, a control power of 0.2–0.25 rad/sec^2 would provide for at least 99 percent of all demands encountered.

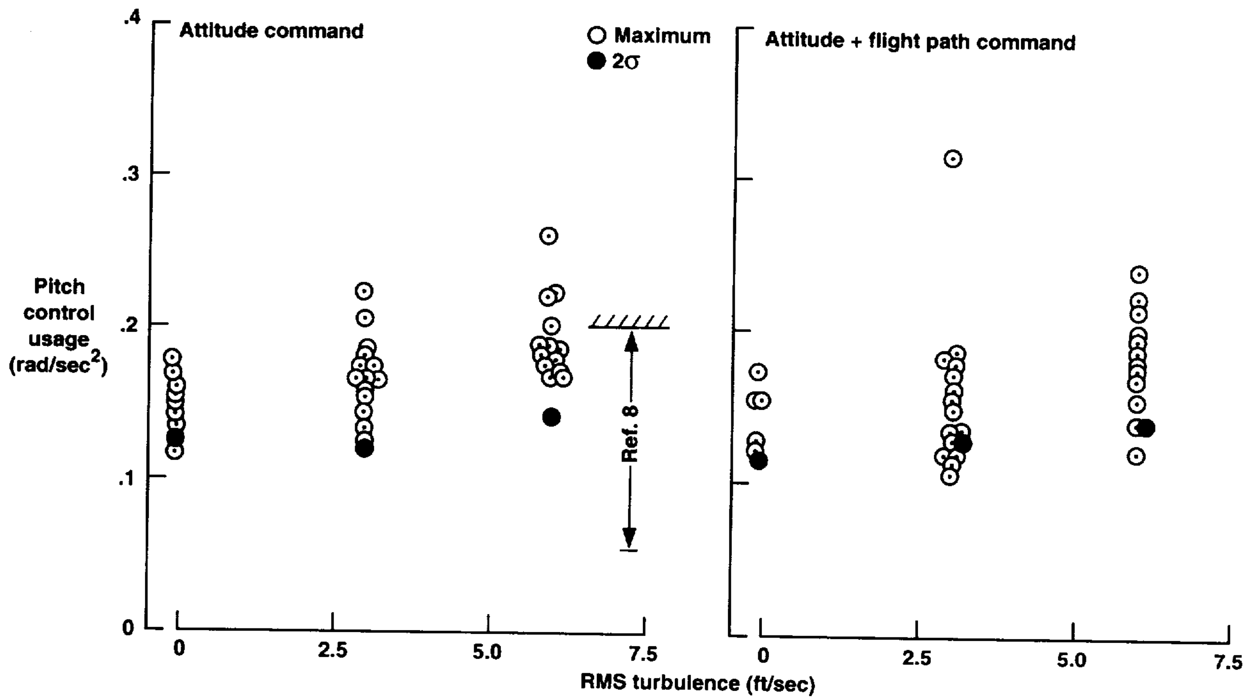
Results in transition for the attitude-plus-flightpath SCAS are comparable to those for the attitude SCAS, reflecting the fact that the pilot's pitch-control task is similar for the two systems during transition. The pilot uses the pitch-attitude changes for flightpath control during the early stages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

Pitch control to the hover point and during the vertical landing with the attitude SCAS (figs. 3(b) and 3(c)) show levels of peak-control usage that are less than the requirements of references 7 and 8. Calm-air maneuvering with the attitude SCAS uses no more than 0.09 rad/sec^2 (the 3–4σ level would be 0.05–0.06 rad/sec^2, reflecting a non-Gaussian tail for the control distribution) and, even at the heaviest level of turbulence, no more than 0.14 rad/sec^2 of control is required in the worst case. For position keeping during vertical landings on the runway, 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 accommodates most of the demands for hover and vertical landing with the attitude SCAS. By comparison, the 3 deg attitude change in one second required by reference 7 converts to a peak pitch-control power of 0.29 rad/sec^2 for a 2 rad/sec attitude-command bandwidth (as extracted from fig. 16).

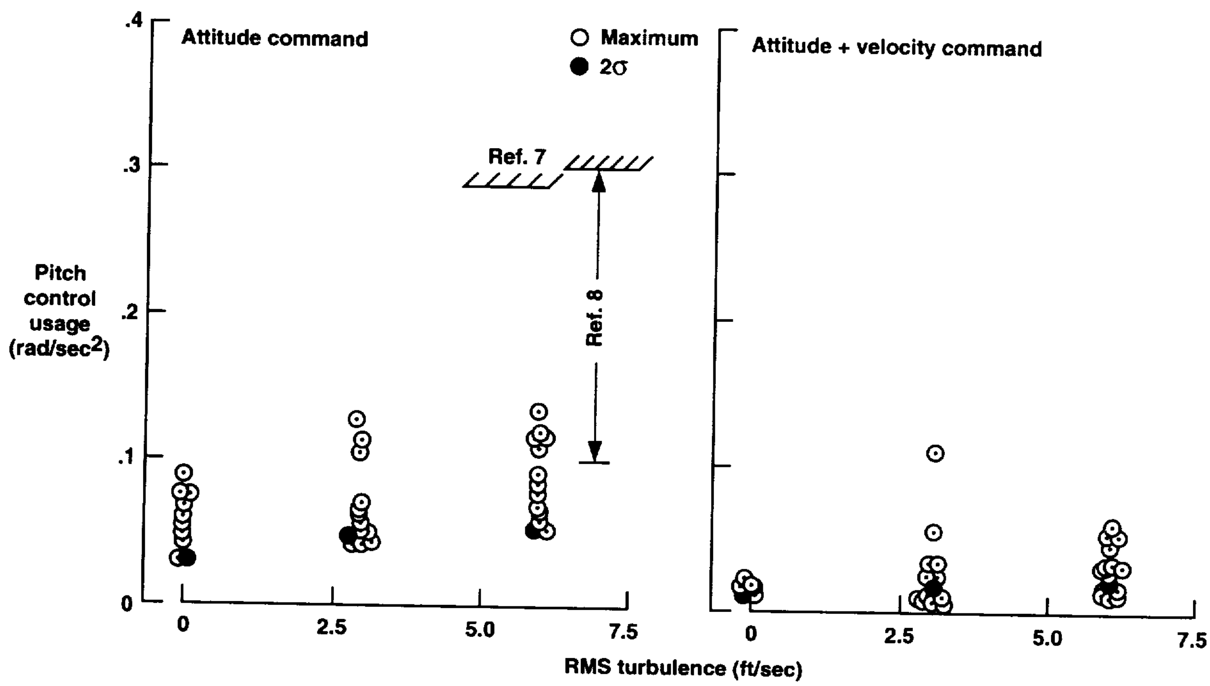
With the velocity-command SCAS, even less pitch control is required, reflecting the difference between the two SCAS configurations in the pitch-control task. With attitude SCAS alone, control of the final deceleration to the hover point and control of longitudinal position and velocity in hover is accomplished 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, hover-point acquisition uses up to 0.06 rad/sec^2 (fig. 3(b)) and the vertical landing can require 0.17 rad/sec^2 (fig. 3(c)), both independent of winds and turbulence.

Results for hover and vertical landing aboard ship with attitude command alone (fig. 3(d)) are comparable to the criteria of reference 8 and Level 1 handling values in reference 7 (although neither criteria applies to shipboard operation, but 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 that for attitude command alone, reflecting, as in the airfield vertical landing, the different task required for the pitch axis. Wind over deck does not seem to influence either system in the amount of control required for the landing. In reference 10, this observation was also made for a simulation evaluation of augmented controls applied to the AV-8 Harrier. Thus, for shipboard operations, the control power requirement of references 7 and 8 appear appropriate with attitude SCAS alone, and a requirement for 0.2 rad/sec^2 should suffice for the attitude-plus-velocity-command SCAS.

Effect of SCAS design bandwidth– The effect of pitch-control bandwidth (the frequency where the peak occurs in the pitch-control effector response) on control usage is illustrated in figure 4, based on the findings of reference 4. Results are presented for attitude-command SCAS alone, assuming that the primary influence of control bandwidth will appear in the primary-control loop with which they are associated. They also are presented only for the 6 ft/sec rms turbulence case. The range of bandwidths explored encompass a practical range for control augmentation designs; below the lowest bandwidth, the aircraft's response to the pilot's control degrades, while no improvements in response to the pilot or in suppression of disturbances is realized at bandwidths above this range. Within this range, the designer has

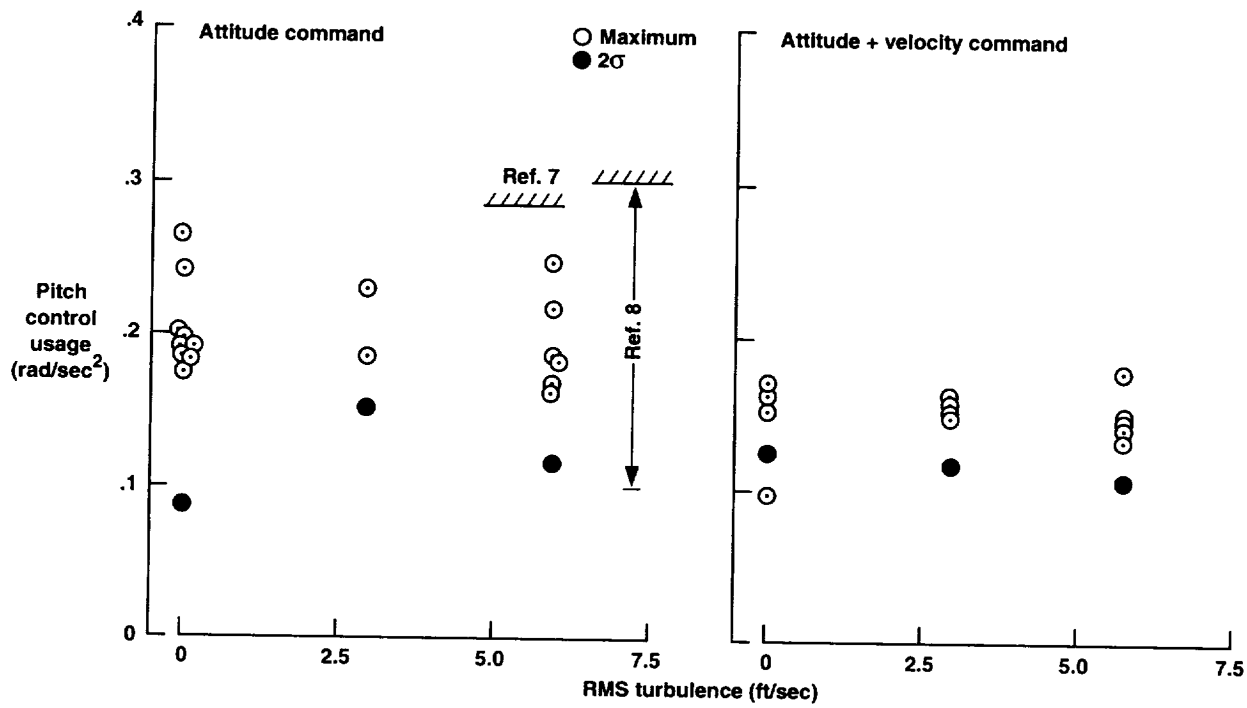


(a) Transition.

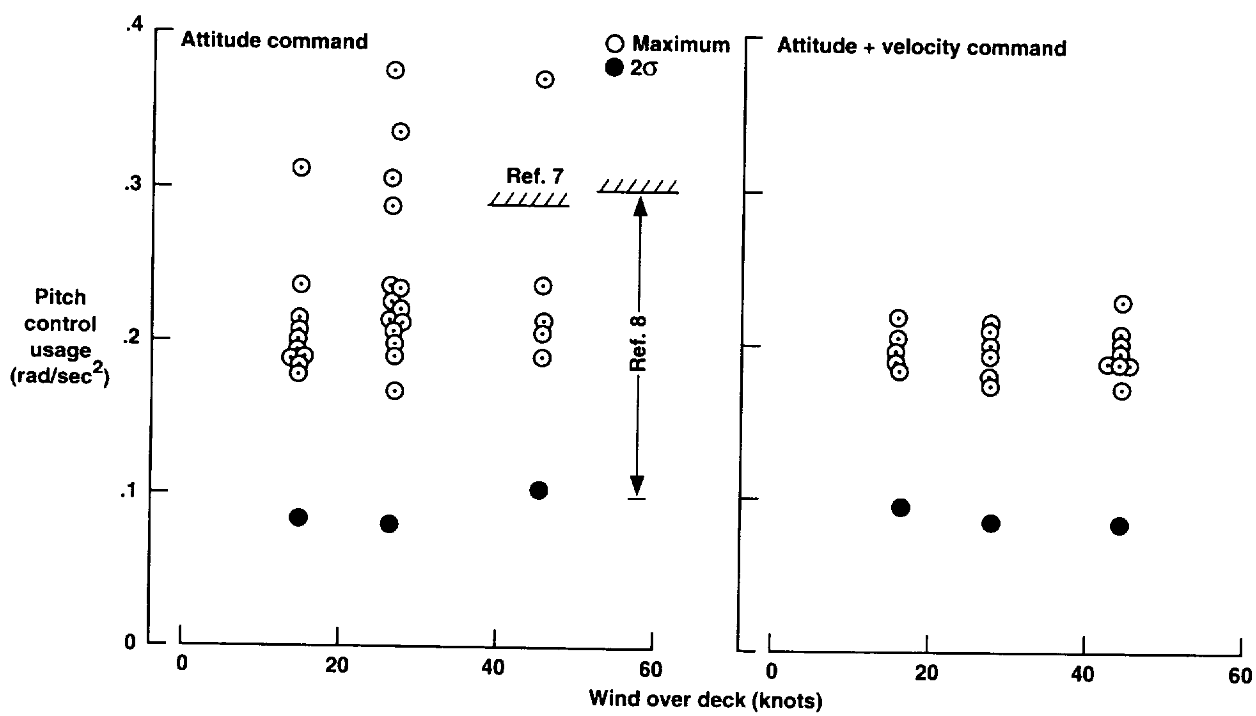


(b) Hover-point acquisition.

Figure 3. Influence of SCAS configuration and wind environment on pitch-control use.



(c) Vertical landing.



(d) Shipboard landing.

Figure 3. Concluded.

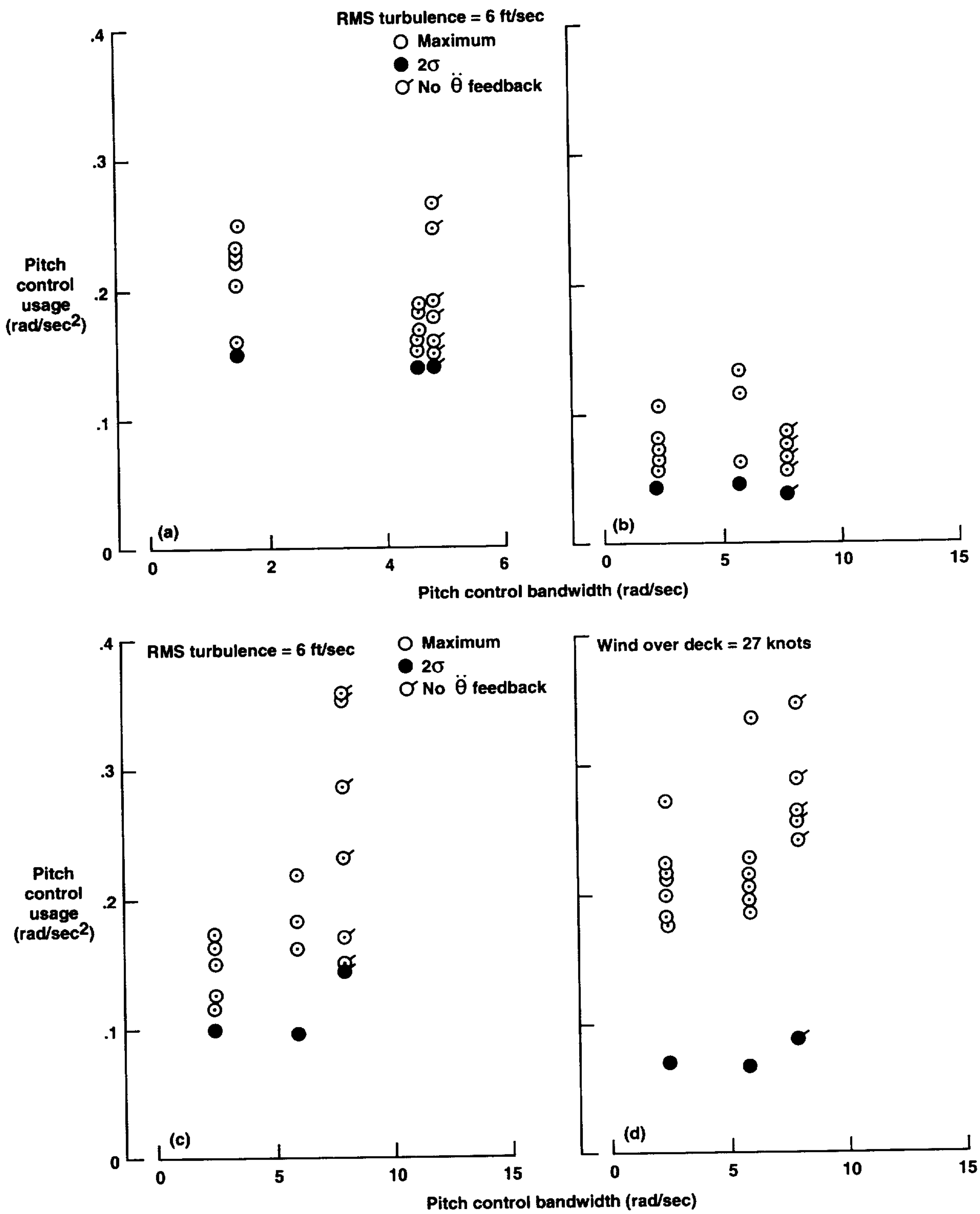


Figure 4. Influence of SCAS bandwidth on pitch-control use. (a) Transition; (b) hover-point acquisition; (c) vertical landing; (d) shipboard landing.

considerable freedom in the choice of closed-loop gain to achieve satisfactory pitch control and disturbance rejection.

As noted in reference 4 and shown in figures 4(a) and 4(b), for the transition and hover-point acquisition tasks, control bandwidth has minimal influence on the maximum pitch-control usage or the 2σ excursions of that control. Levels of use are comparable to those experienced for the baseline SCAS of figures 3(a) and 3(b). However, control use for landbased or shipboard vertical landings show an increase in peak and 2σ levels for a high-bandwidth configuration that only employed attitude and attitude-rate feedback (figs. 4(c) and 4d). The increase is most pronounced for the runway landing. In that case, peak-control usage approaches, and occasionally exceeds, 0.3 rad/sec^2 and represents a sufficient increase in control power that is not desirable unless attitude and attitude rate provide the only feasible feedback available in the control-system design. Over the range of pitch control bandwidths investigated in reference 4, there was no variation in the pilots' ratings for any of the low-speed control tasks, nor did the pilots' comments reflect any awareness of changes in pitch-control response. Therefore, the designer has the latitude to achieve Level 1 flying qualities over a range of control bandwidths without penalizing the aircraft design through demands for excessive control power.

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 7–9, (2) available control power for some relevant V/STOL fighter aircraft designs (refs. 11–13), and (3) earlier fixed-base simulation results for the E-7A STOVL concept (ref. 14), is presented in table 2. 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. For the transition phase, the pertinent criteria are in references 8 and 9; no control power data is available for the individual aircraft. In hover and vertical landing, references 7 and 8 apply; the control power has been tabulated for the Harrier and VAK-191 aircraft.

Table 2. Comparison of pitch-control-power criteria with STOVL aircraft designs

Flight phase	MIL-F 83300 (ref. 7)	AGARD R-577 (ref. 8)	NASA TN 5594 (ref. 9)	AV-8B (ref. 11)	AV-8A (ref. 12)	VAK-191 (ref. 13)	Recent STOVL concepts: MFVT Maneuver	MFVT Turb6	E-7A (ref. 14) Maneuver	E-7A (ref. 14) Turb6
Transition		0.05–0.2	0.5				0.15–0.19	0.2–0.25	0.6	0.6
Hover point	0.29	0.1–0.3		0.53 –0.83	0.8 –0.75	1.0	0.09	0.14(AC) 0.06(VC)		
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)		
Shipboard landing				0.53 –0.83	0.8 –0.75		WOD 15 0.31 0.22	WOD 46 0.37 0.22(VC)	WOD 15 0.3	WOD 34 0.4

Notes:

1. All values expressed in terms of control power in rad/sec^2.
2. References 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 (see appendix).
3. Control power for actual aircraft represent the total available in hover; transition values are not available.
4. Control power for MFVT and E-7A represent maximum used.
5. Turb6 = 6 ft/sec rms turbulence.

In the transition phase, the highest value of the criteria in reference 8 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 9. The greater control activity for the E-7A can be attributed to larger pitching moments imposed by the large air mass flow into the ejector and by a higher degree of angle-of-attack stability for the E-7A. For the hover-point acquisition and the vertical landing, both references 7 and 8 appear to be too demanding. The current results indicate that less control power is used, especially with the velocity-command system that employs thrust deflection for longitudinal control. No criteria are available for shipboard operations. 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 and considerably more than adequate for control with the velocity-command SCAS.

Roll Control

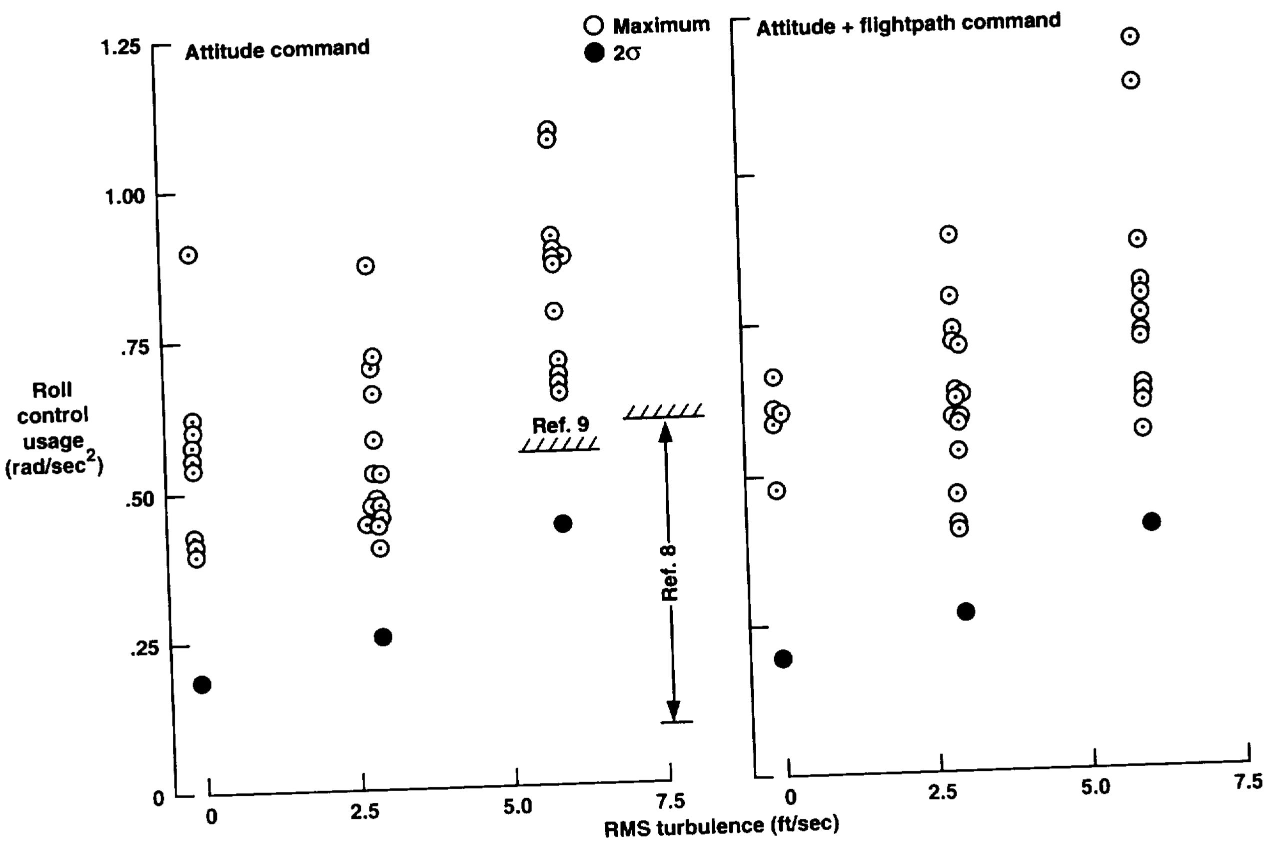
Effect of flight phase– Roll control use for the different flight phases, SCAS modes, and turbulence is shown in figure 5. Maximum roll control use for maneuvering in calm air during transition (fig. 5(a)) substantially exceeds that called for in reference 8, with peaks of 0.4–0.9 rad/sec^2. For control in the heaviest turbulence, demands for as much as 1.2 rad/sec^2 occur, although the range is more typically from 0.6–0.9 rad/sec^2, which is consistent with 3–4σ values. As a further comparison, the Level 1 requirement of reference 9 for maneuver control during STOL operations provides for 30 deg 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 (see appendix). 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 the presence of winds and turbulence. 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.

The level of roll control use is not dependent on whether attitude-command or attitude-plus-flightpath-command SCAS is employed. The contributions of flightpath-command SCAS are pertinent only to the longitudinal control and would not be expected to influence lateral control usage. This is confirmed by the results shown in figure 5.

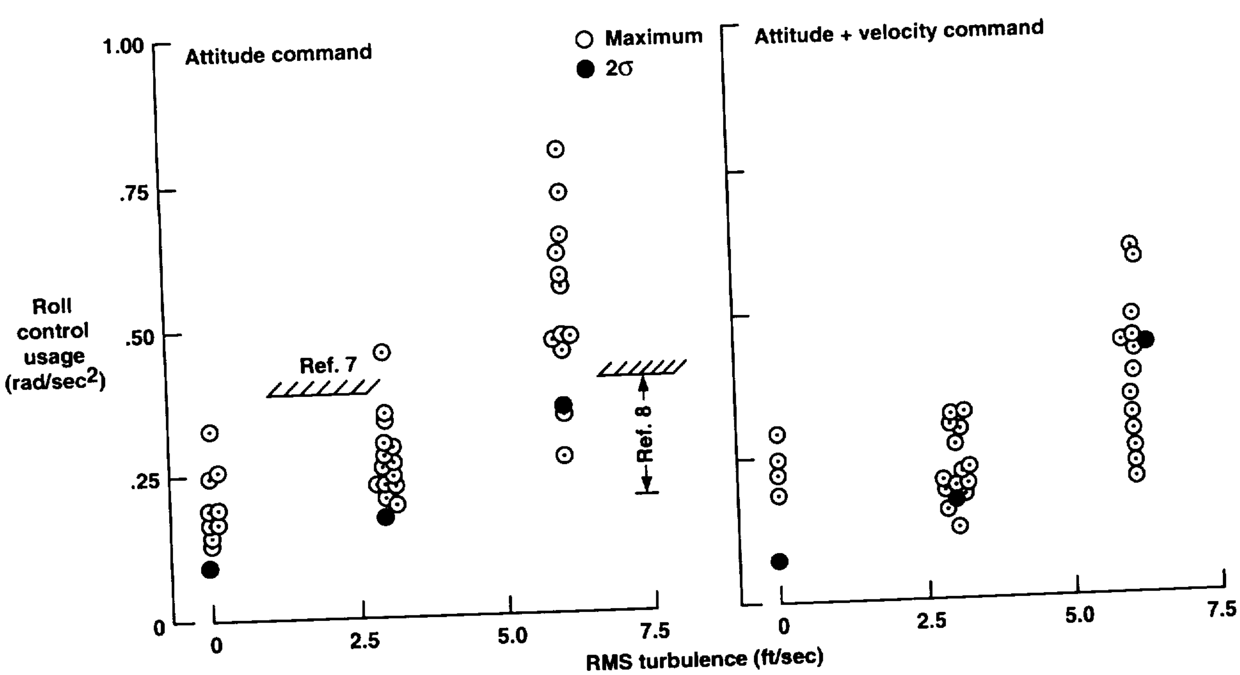
For acquisition of the hover point with the attitude-command SCAS (fig. 5(b)), peak roll control use for calm air and mild turbulence falls within the range recommended in references 7 and 8. The reference 7 requirement for 4 deg in one sec translates to a maximum control power of 0.38 rad/sec^2 for a 2 rad/sec attitude-command bandwidth (see appendix). Maximum maneuvering control ranges from 0.12–0.3 rad/sec^2 in calm air, compared to 3–4σ values of 0.15–0.2 rad/sec^2. However, for rms turbulence of 6 ft/sec, the range of peak control increases substantially to 0.8 rad/sec^2, somewhat in excess of that for the criteria of references 7 and 8. Maximum or 2σ control use is virtually the same for the two SCAS modes, except for the heaviest turbulence condition.

Control use for the vertical landing in either control mode, shown in figure 5(c), is consistently less than the reference 7 requirement in calm air and mild turbulence, and falls within the range suggested in reference 8. Peak maneuvering demands for attitude-command SCAS range from 0.1–0.3 rad/sec^2. The heaviest turbulence increases these levels modestly to 0.2 to 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 (fig. 5(d)) are generally in agreement with the criteria of references 7 and 8, except for high wind-over-deck conditions. In light winds, the peaks vary from 0.2–0.4 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 1.3–2.0 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 the capability to recover to a more actively moving deck. If shipboard operations at these extreme conditions are anticipated, roll-control authority in excess of those given in references 7 and 8 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. 15) and on the aircraft's sensitivity to airwake disturbances and should be qualified accordingly. Previous experience with simulation of helicopter operations in the ship's wake (ref. 16) resulted in the impression that airwake disturbances seemed more severe than those encountered in the actual environment.

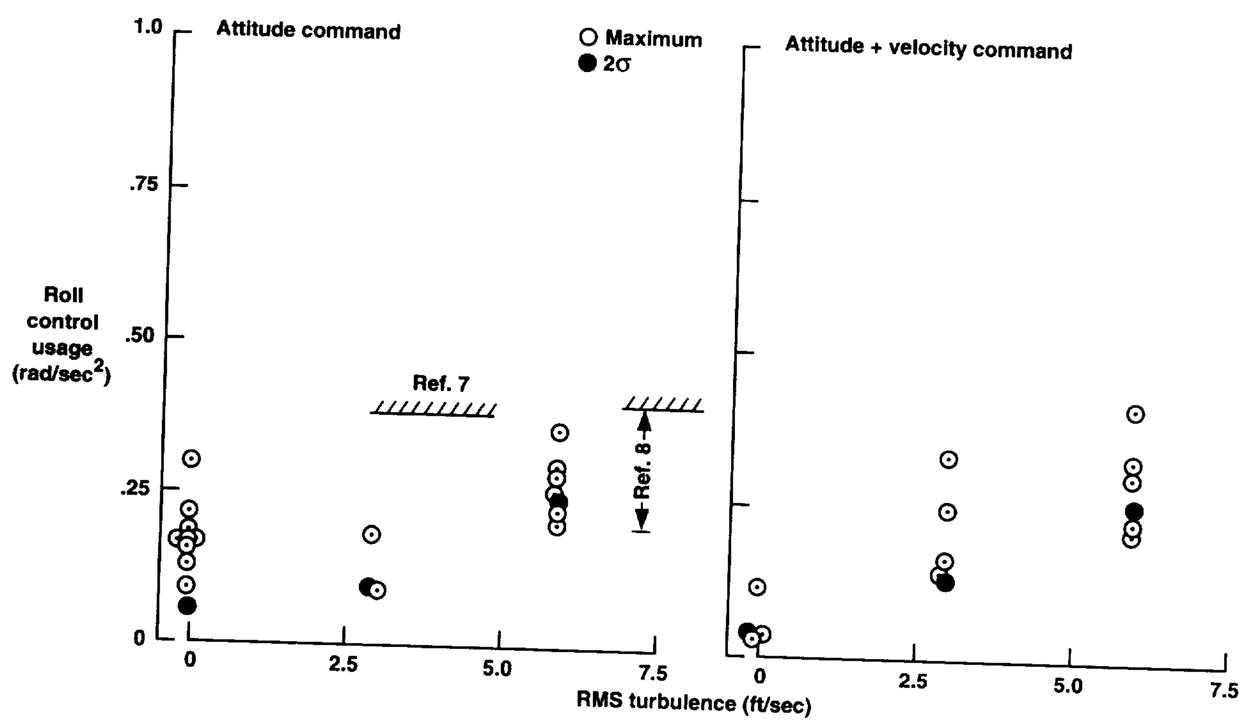


(a) Transition.

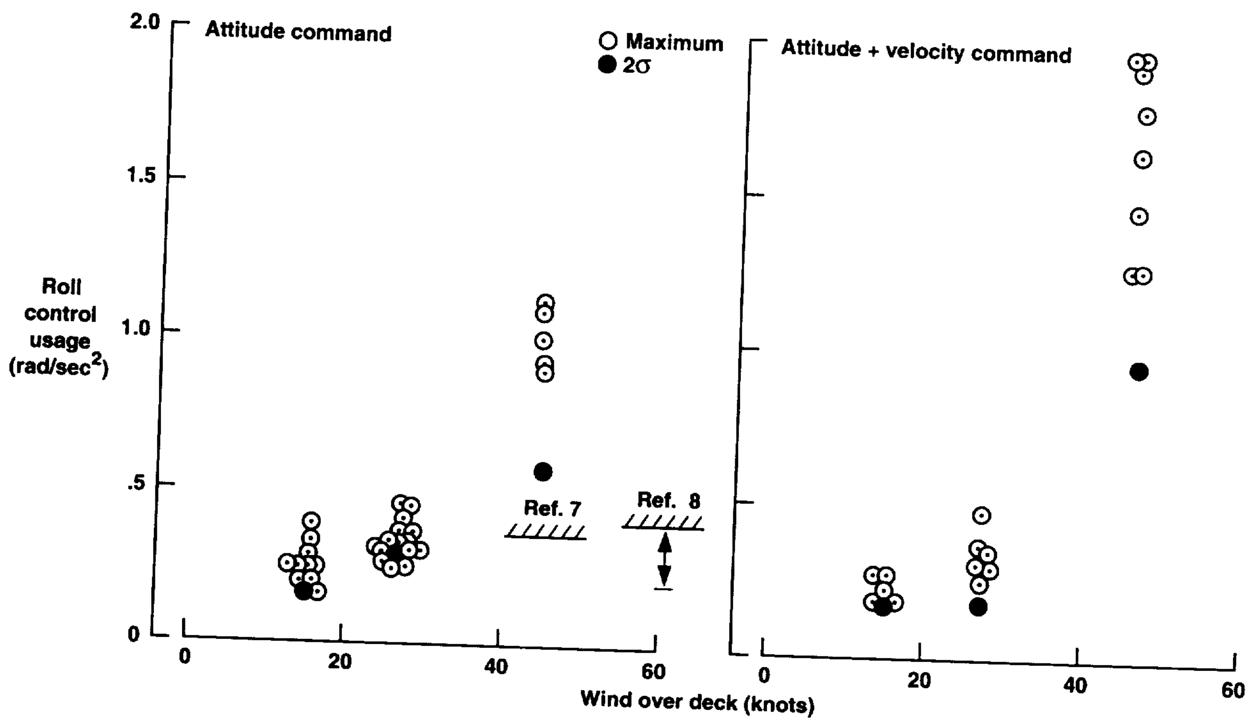


(b) Hover-point acquisition.

Figure 5. Influence of SCAS configuration and wind environment on roll-control use.



(c) Vertical landing.



(d) Shipboard landing.

Figure 5. Concluded.

In a few instances, roll-control configurations for the attitude-command system that had reduced control authority were examined to determine if encountering control limits would provide a view of control authority requirements different from that suggested by peak control use. Control authority limits of 75 and 50 percent of the design maximum were imposed over the transition and hover-flight phases. The maximum control authorities associated with these limits are shown in figure 6. It is apparent that the 100 percent authority exceeds the peak use documented in figure 5, whereas the 50 percent authority represents lower control power than was used in some instances. Based on a limited number of transitions to hover and vertical landings, the reduction in control authority to 75 percent of maximum was not apparent to the pilot either in terms of task performance or control system behavior. However, when the control authority was reduced to 50 percent, control limits were frequently encountered during lateral translations in hover. On occasion, the limiting was sufficient to cause pilot-induced oscillation (PIO) and loss of control. These results indicate that it is not necessary to design for the extreme control authority measured during this series of tests, since occasional excursions that saturate the control momentarily can be tolerated. However, it is necessary to accommodate sustained peak-control demands that are more than a momentary occurrence.

Effect of SCAS design bandwidth– For the transition phase, figure 7(a) shows an increase in maximum roll control usage with increasing control

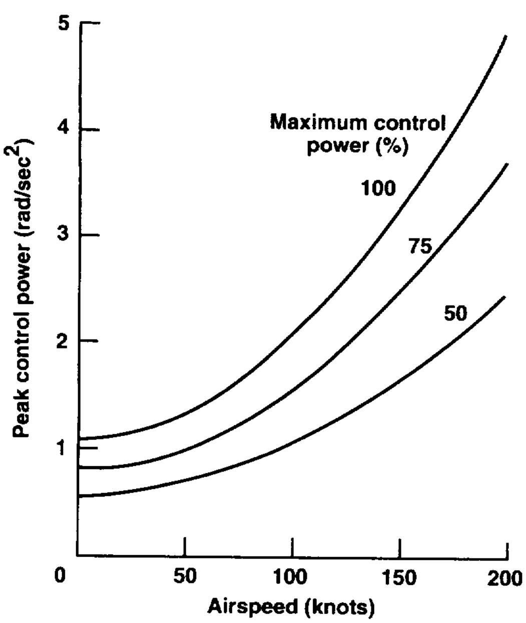


Figure 6. Variation of roll-control power over the low-speed flight envelope.

bandwidth. As was the case for pitch control, control bandwidth is based on the frequency of the peak in roll-control effector response (ref. 5). Over the range of bandwidth shown, a modest increase in peak control is apparent. For hover-point acquisition, runway vertical landing, and shipboard landing (figs. 7(b)–7(d)), no appreciable variation in maximum control usage is observed over the range of bandwidths noted. As was the case for pitch control, in this series of roll-control evaluations, there was no effect on the pilots' ratings for any of the low-speed control tasks as a result of changes in roll-control bandwidth over the range noted in figure 7, nor did the pilots' comments reflect any awareness of changes in roll-control response. Thus, there is merit in reducing the roll-control bandwidth, as long as flying qualities and disturbance rejection are not degraded, because lower roll bandwidths appear to be adequate for the task.

Summary of roll control requirements– Table 3 presents a summary of the required roll-control authority determined from these simulation results, compared to (1) the Level 1 criteria of references 7–9, (2) available control power for the V/STOL fighters of references 11–13, and (3) the E-7A STOVL concept. For the transition phase, the pertinent criteria are those in references 8 and 9. For hover and vertical landing, references 7 and 8 are the applicable documents.

During transition, references 8 and 9 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 the experience gained during 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 deg or more during transition. The current MFVT configuration can achieve lateral trim with sideslip of 10 deg or greater over the low-speed flight envelope. References 7 and 8 do not call for sufficient control for the hover-point acquisition; both criteria are about right for the vertical landing. No criteria are available for shipboard operations. Total control authority available for trim and maneuvering are shown for the Harrier and VAK-191 in references 11 and 13. 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.

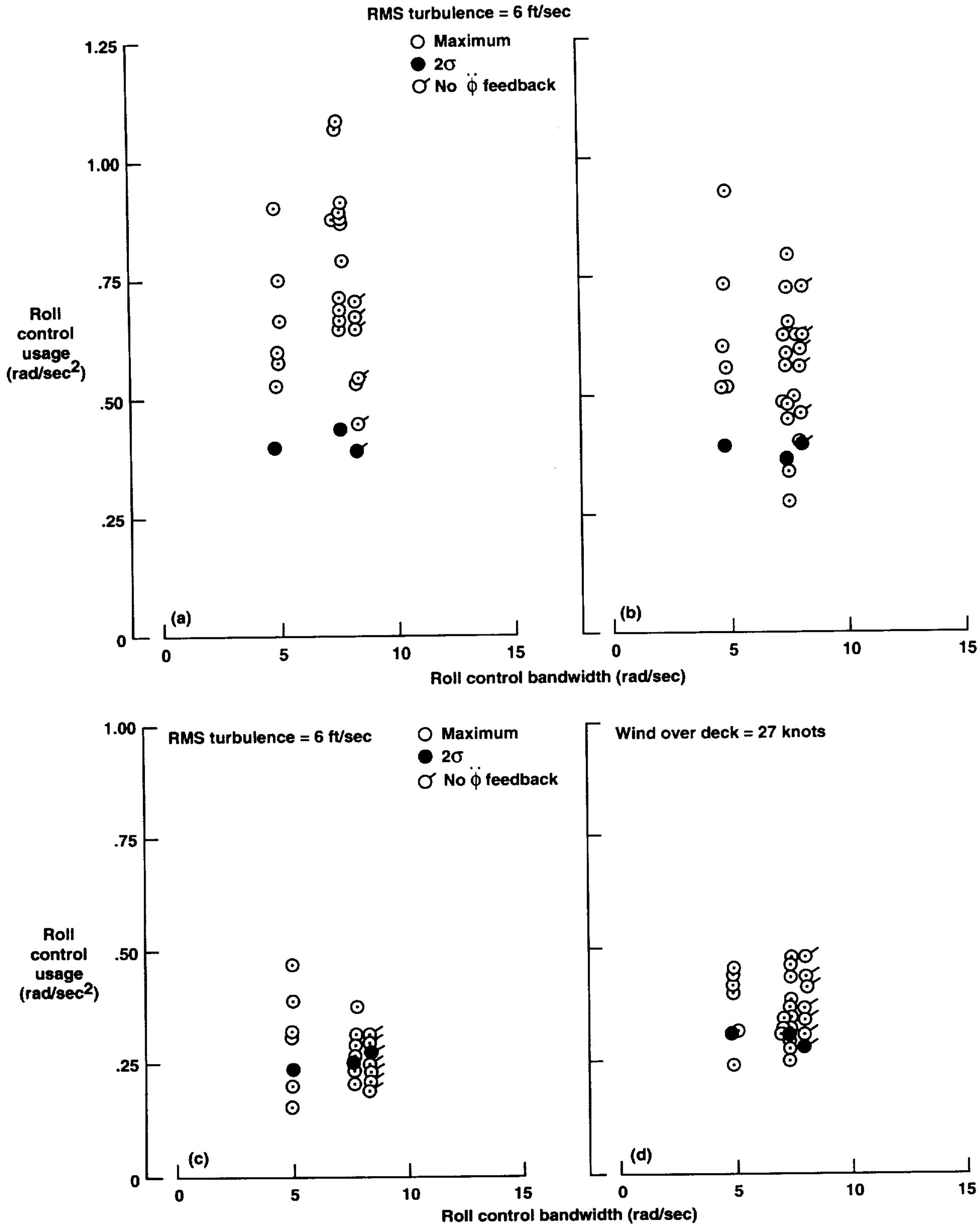


Figure 7. Influence of SCAS bandwidth on roll-control use. (a) Transition; (b) hover-point acquisition; (c) vertical landing; (d) shipboard landing.

Table 3. Comparison of roll-control-power criteria with STOVL aircraft designs

Flight phase	MIL-F 83300 (ref. 7)	AGARD R-577 (ref. 8)	NASA TN 5594 (ref. 9)	AV-8B (ref. 11)	AV-8A (ref. 12)	VAK-191 (ref. 13)	Recent STOVL concepts: MFVT Maneuver	MFVT Turb6	E-7A (ref. 14) Maneuver	E-7A (ref. 14) Turb6
Transition		0.1–0.6	0.55				0.3–0.4	0.9–1.2	0.25	0.6
Hover point	0.38	0.2–0.4		2.2	1.73	1.4	0.15–0.3	0.5–0.8		
Vertical landing	0.38	0.2–0.4		2.2	1.73	1.4	0.1–0.3	0.2–0.4		
Shipboard landing				2.2	1.73		WOD 15 0.2–0.4	WOD 46 0.9–1.1(AC) 1.3–2.0(VC)	WOD 15 0.55	WOD 34 1.8

Notes:

1. All values expressed in terms of control power in rad/sec^2.
2. References 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 (see appendix).
3. Control power for actual aircraft represent the total available in hover; transition values are not available.
4. Control power for MFVT and E-7A represent maximum used.
5. Turb6 = 6 ft/sec rms turbulence.

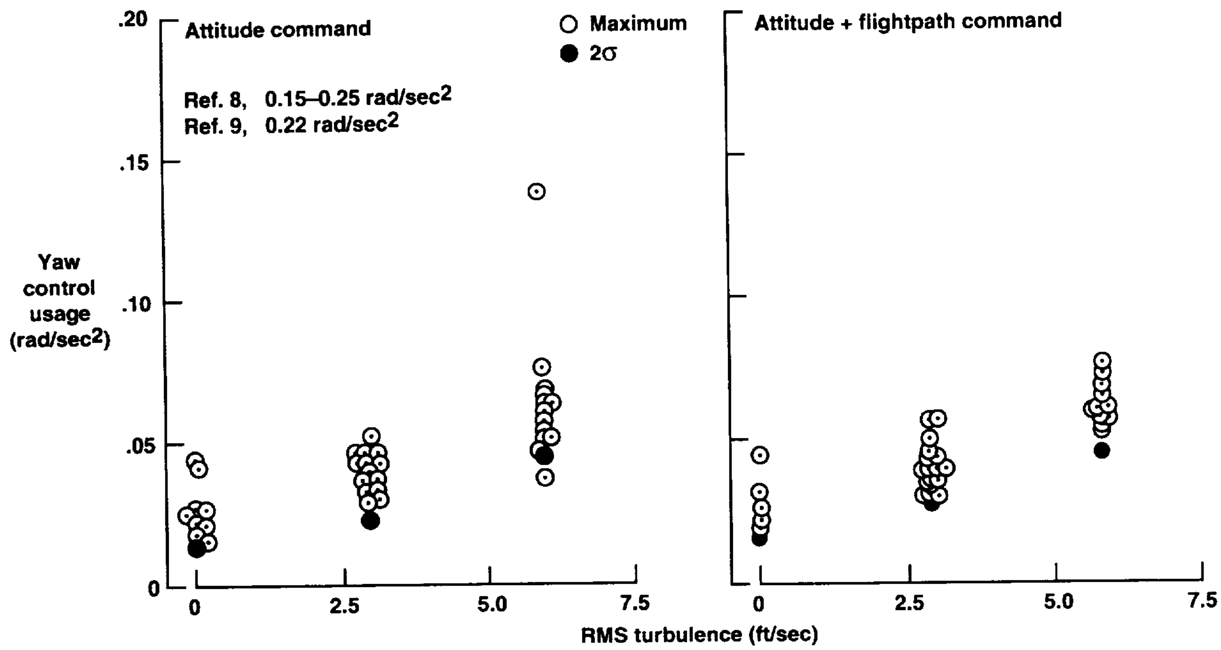
Control used for maneuvering and control of turbulence by the E-7A was less than that required for the MFVT STOVL and is more in line with the criteria of references 8 and 9. It should be noted that, for the MFVT STOVL design, every 0.1 rad/sec^2 of additional roll-control power would require an additional ±170 lb of differential thrust at the lift nozzles at 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 lb/sec of bleed-flow rate (ref. 17), 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

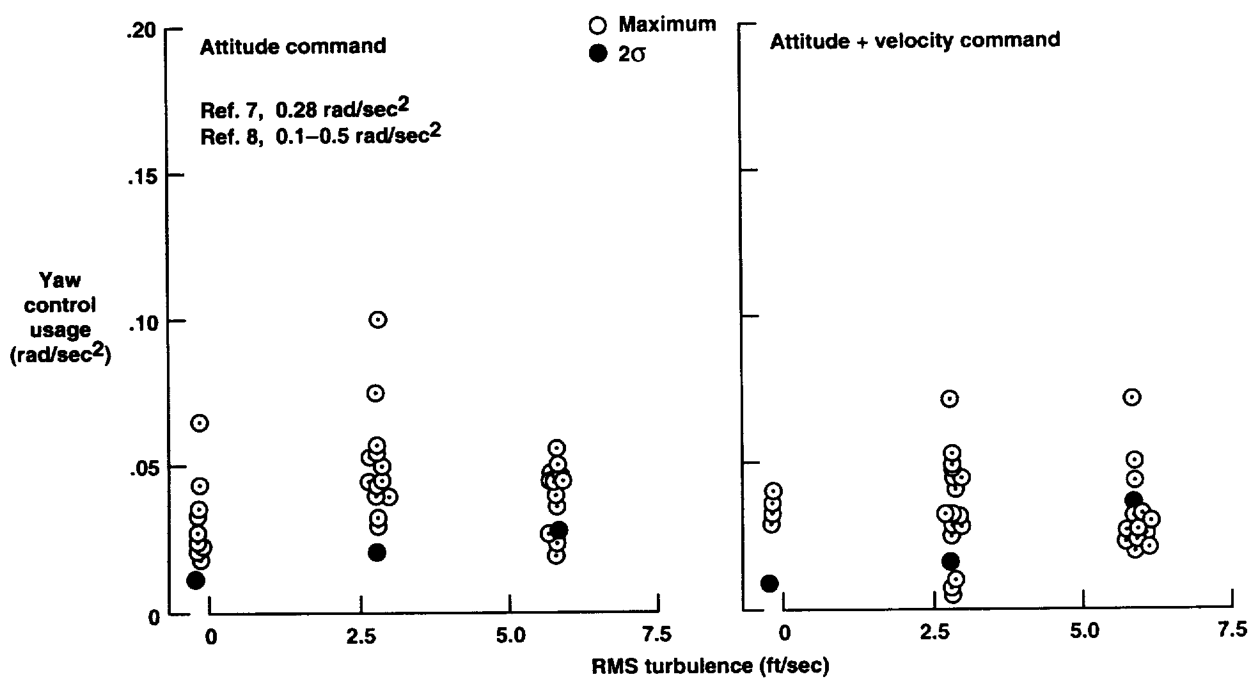
Effect of flight phase– The yaw control use shown in figure 8 is considerably less than the criteria in references 7 and 8 for any flight phase. For the transition (fig. 8(a)), peak demands in calm air range from 0.02 to 0.04 rad/sec^2. In the heaviest turbulence, maximum control usage of 0.04–0.14 rad/sec^2 was observed, with most usage 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 8. As a further example, the requirement of reference 9 for a 15 deg 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 (see appendix). The disparity between these two criteria for yaw control and the recent simulation experience is likely attributable to better yaw-stability augmentation and lower sensitivity to disturbances for the recent STOVL fighter concepts compared to the collection of aircraft on which the earlier criteria were based. As was the case for roll control, incorporation of flightpath SCAS has no influence on the level of yaw-control use.

Maximum yaw control for the hover-point acquisition and vertical landing (figs. 8(b) and (c)) are comparable to those for the transition. Maximum maneuvering control in calm air varies from 0.015–0.065 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 7 requirement for a heading change of 6 deg in 1 sec converts to a maximum control power of 0.28 rad/sec^2 for a yaw time constant of 1 sec. Again, no difference is discernible with or without velocity-command SCAS.

For the shipboard landing (fig. 8(d)), maximum control use with attitude command is similar to that for the runway landing, with peaks to 0.1 rad/sec^2 for the highest wind over deck. The velocity-command SCAS exhibited control use similar to that for attitude command

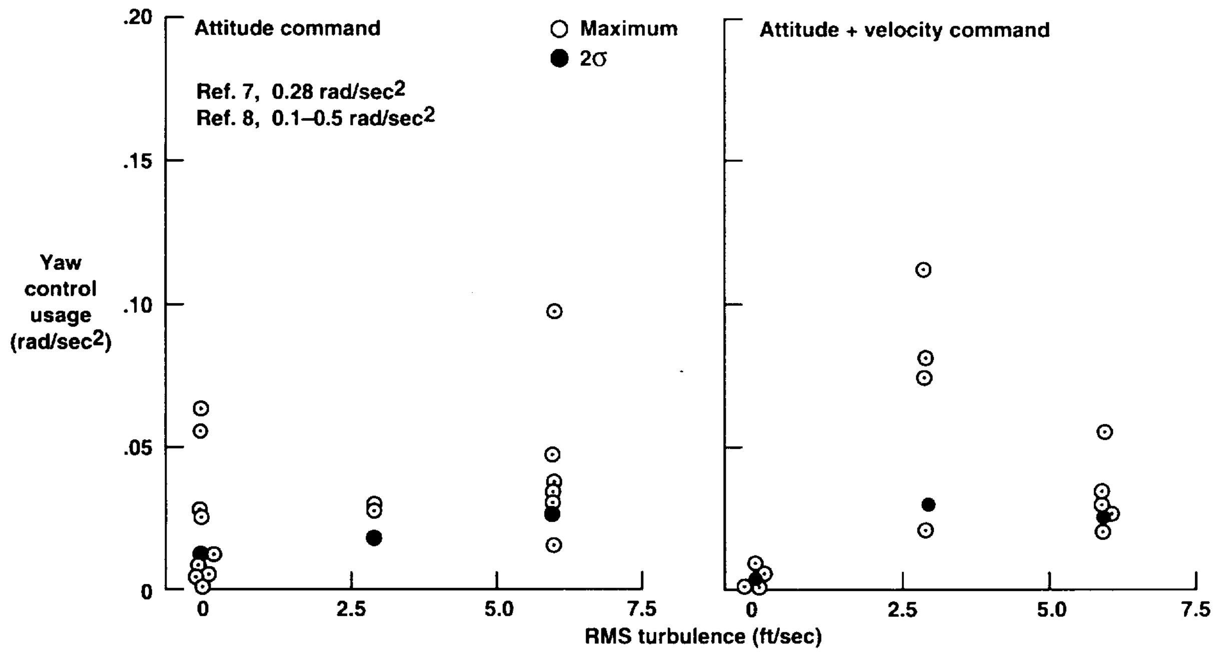


(a) Transition.

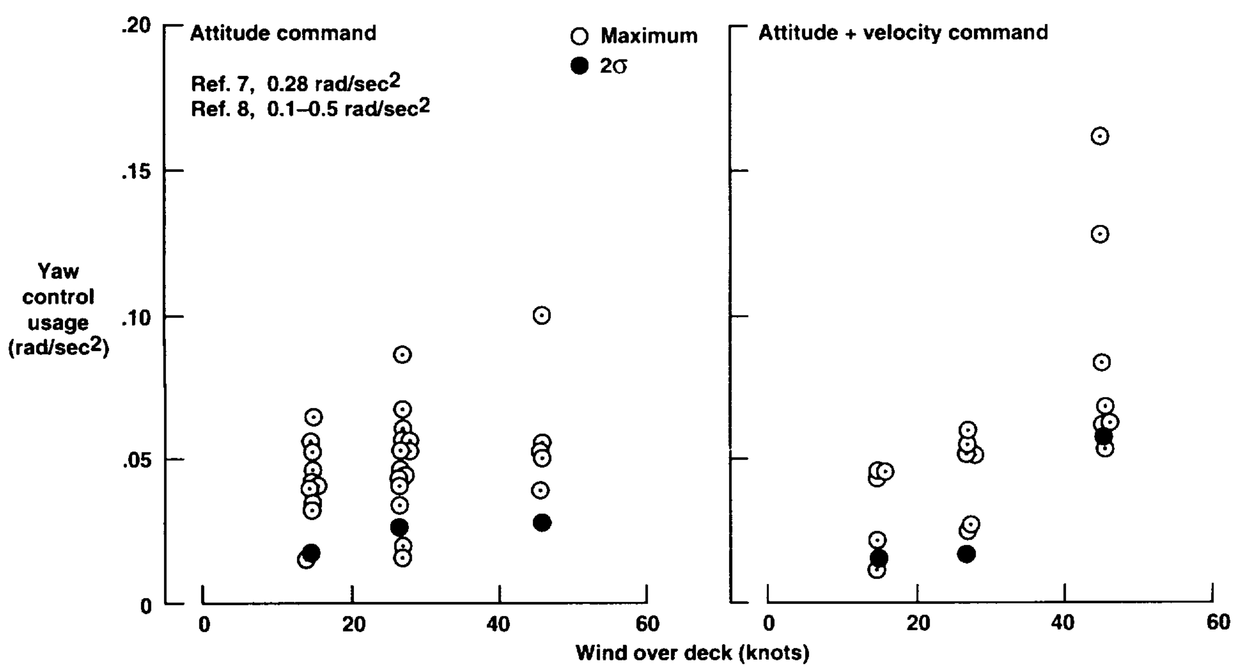


(b) Hover-point acquisition.

Figure 8. Influence of SCAS configuration and wind environment on yaw-control use.



(c) Vertical landing.



(d) Shipboard landing.

Figure 8. Concluded.

in light winds. In the highest winds, the velocity-command SCAS used up to 0.16 rad/sec^2, exceeding that for the attitude SCAS under the same conditions. Effects of yaw-control bandwidth were not examined in this series of experiments.

Summary of yaw-control requirements– Yaw-control summaries of authority determined from these STOVL aircraft simulation results, compared to (1) the Level 1 criteria of references 7–9, (2) available control power for other V/STOL fighter designs, and (3) the E-7A, are provided in table 4. For the transition phase, the pertinent criteria are those of references 8 and 9. In the hover and vertical landing phases, references 7 and 8 are the pertinent criteria.

For the transition, hover, and vertical landing, the criteria of references 7–9 exceed the current experience for yaw-control use to a significant degree. Based on 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 is comparable to that for the MFVT STOVL tested on the VMS. For the MFVT 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.

Table 4. Comparison of yaw-control-power criteria with STOVL aircraft designs

Flight phase	MIL-F 83300 (ref. 7)	AGARD R-577 (ref. 8)	NASA TN 5594 (ref. 9)	AV-8B (ref. 11)	AV-8A (ref. 12)	VAK-191 (ref. 13)	Recent STOVL concepts MFVT Maneuver	MFVT Turb6	E-7A (ref. 14) Maneuver	E-7A (ref. 14) Turb6
Transition		0.15–0.25	0.22				0.02–0.04	0.05–0.07	0.04	0.04
Hover point	0.28	0.1–0.5		0.43	0.46	0.4	0.015–0.065	0.1		
Vertical landing	0.28	0.1–0.5		0.43	0.46	0.4	0.015–0.065	0.1		
Shipboard landing				0.43	0.46		WOD 15 0.065	WOD 46 0.1	WOD 15 0.05	WOD 34 0.12

Notes:

1. All values expressed in terms of control power in rad/sec^2.
2. References 7 and 9 requirements converted from attitude response based on a time constant of 1 sec for rate command systems (see appendix).
3. Control power for actual aircraft represent the total available in hover; transition values are not available.
4. Control power for MFVT and E-7A represent maximum used.
5. Turb6 = 6 ft/sec rms turbulence.

THRUST TRANSFER RATES

The 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 thrust rate of change and, more generally, as the pitch and roll angular acceleration rate of change. Implications for thrust-control bandwidth are also noted.

Pitch Control

Effect of flight phase– Thrust transfer rates for pitch control are documented in figure 9. During the transition (fig. 9(a)), 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 at the highest wind and turbulence condition. This maximum range exceeds that for 3–4σ values. Results are independent of SCAS mode. During hover-point acquisition, maximum rates are somewhat less than during transition and are less dependent on turbulence magnitude (fig. 9(b)). Maneuvering to the hover point uses rates up to 1 klb/sec; in the heaviest turbulence, rates up to 2 klb/sec are encountered. Again, rates are well in excess of 3–4σ levels. The velocity-command SCAS mode requires somewhat less control rate for maneuvering or disturbance suppression than does the attitude SCAS. Runway vertical landings appear to demand more maneuver control rate than the previous two flight phases, but with no SCAS mode influence (fig. 9(c)). Peak rates ranging from 1–2.6 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. 9(d)). 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.

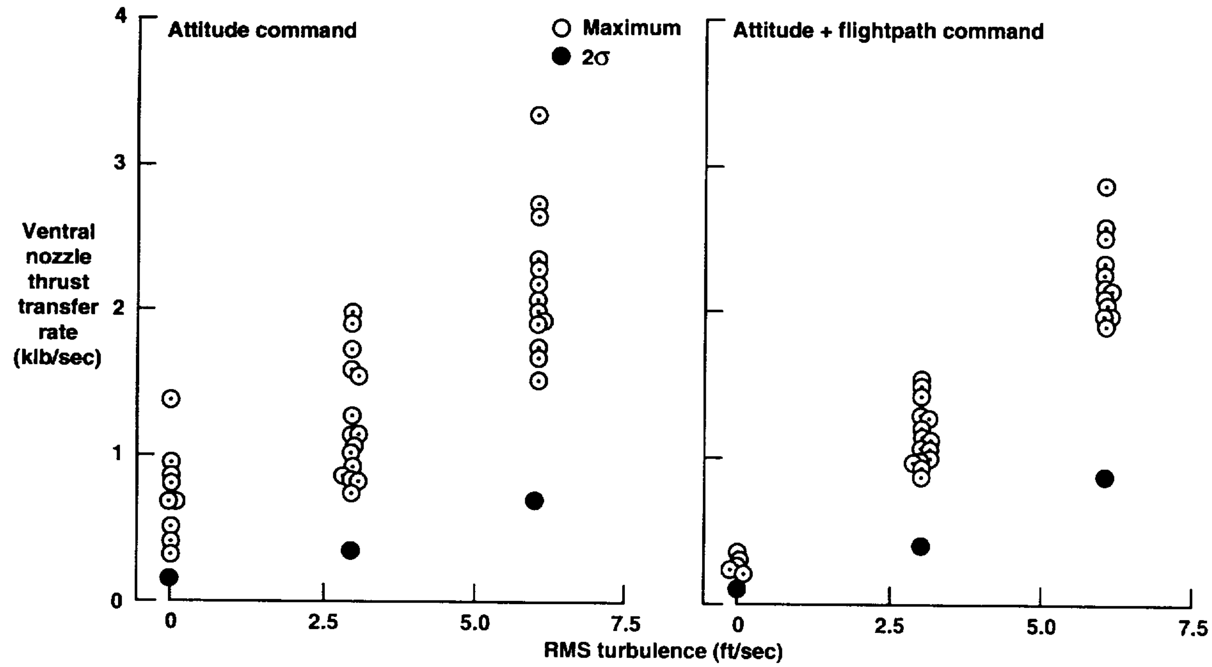
To generalize these results, thrust transfer rates can be expressed in the control power rate of change for this aircraft configuration, where 4 klb/sec is equivalent to 1 rad/sec^3. In turn, the maximum rate of change of control power can be used to define the relationship between peak-control usage and the effective bandwidth of control that can be achieved without encountering the control rate limit. The relationship of maximum rate-limit-free control bandwidth with maximum control power rate and peak-control use is illustrated in figure 10. For example, a maximum thrust-transfer rate of 2 klb/sec (corresponding to an angular acceleration rate change 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.

Effect of SCAS design bandwidth– From the results of reference 4, pitch-control bandwidth had no influence on maximum thrust-transfer rates for the transition or hover-point acquisition (figs. 11(a) and 11(b)). However, for the vertical landing on the runway or aboard ship (figs. 11(c) and 11(d)), the highest bandwidth configuration that relied only on rate and attitude feedback required significantly higher thrust-transfer rates than the configurations that employed angular-acceleration feedback regardless of bandwidth. The higher control rates at this bandwidth were attributed to lower phase margins associated with the negative static-stability configuration and the lesser degree of lead compensation in the absence of acceleration feedback (ref. 4).

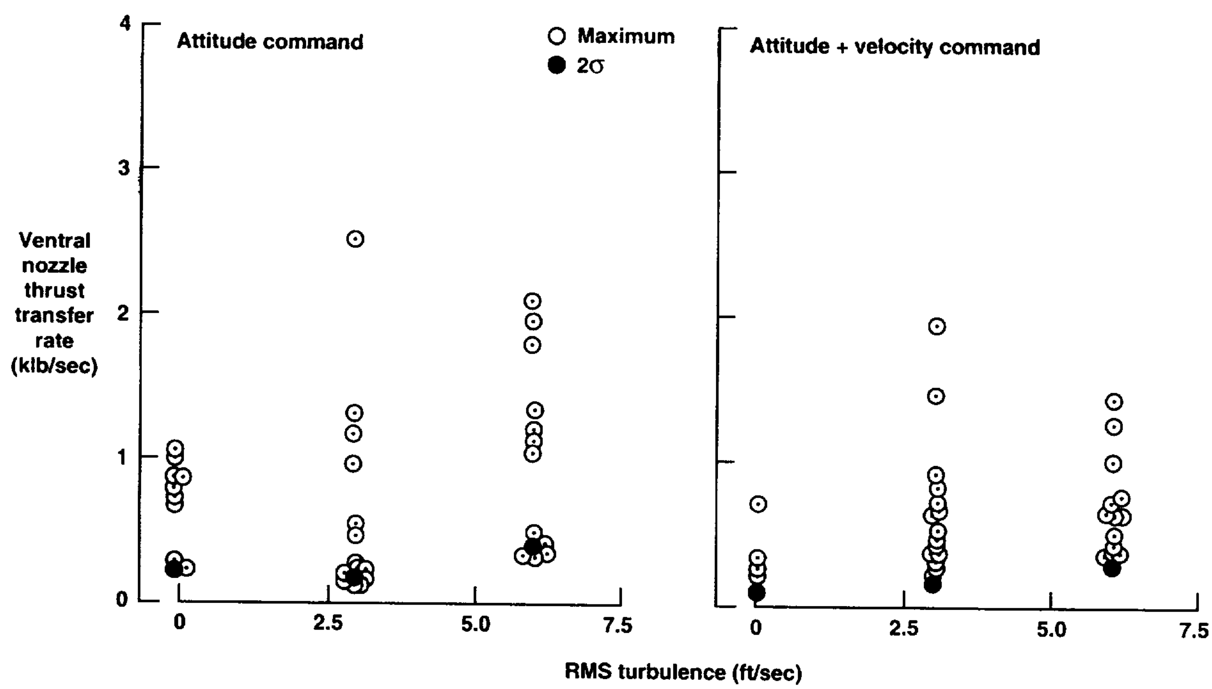
Roll Control

Effect of flight phase– In figure 12, the rates of thrust transfer employed for roll control are indicated for the different flight phases. Throughout the transition (fig. 12(a)), typical maximum rates for maneuver control ranged from 1–2 klb/sec for either the attitude or attitude-plus-flightpath SCAS, with the exception of two cases for the attitude SCAS which demanded 4.5–6.5 klb/sec. In the heaviest turbulence, 3–4 klb/sec occur frequently for the attitude-command SCAS, with occasional peaks from 5–8 klb/sec. For roll control, a thrust-transfer rate of 10 klb/sec is equivalent to 3 rad/sec^3. For the attitude-plus-flightpath SCAS, the maximum transfer rates are in the heavier turbulence range from 3–7 klb/sec with a single peak at 9 klb/sec.

During hover-point acquisition (fig. 12(b)), transfer rates for maneuvering ranged from 2–5 klb/sec for the attitude-SCAS configuration. Turbulence did not affect the maximum-control rate up to the magnitude of disturbances evaluated. Maximum rates were somewhat less for the velocity-command SCAS than for attitude SCAS. Maneuver-control rates for the runway vertical landing (fig. 12(c)) were comparable to those for hover-point acquisition for both SCAS modes. The velocity-command SCAS has a somewhat greater requirement for control rates in turbulence than the attitude SCAS.

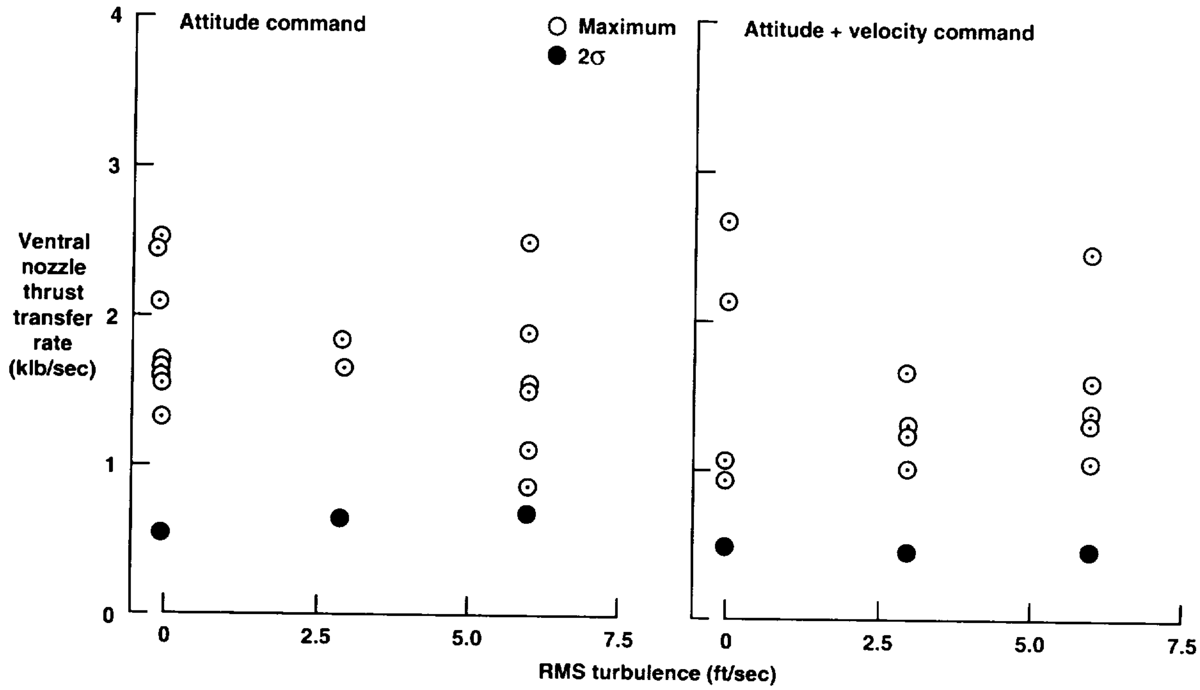


(a) Transition.

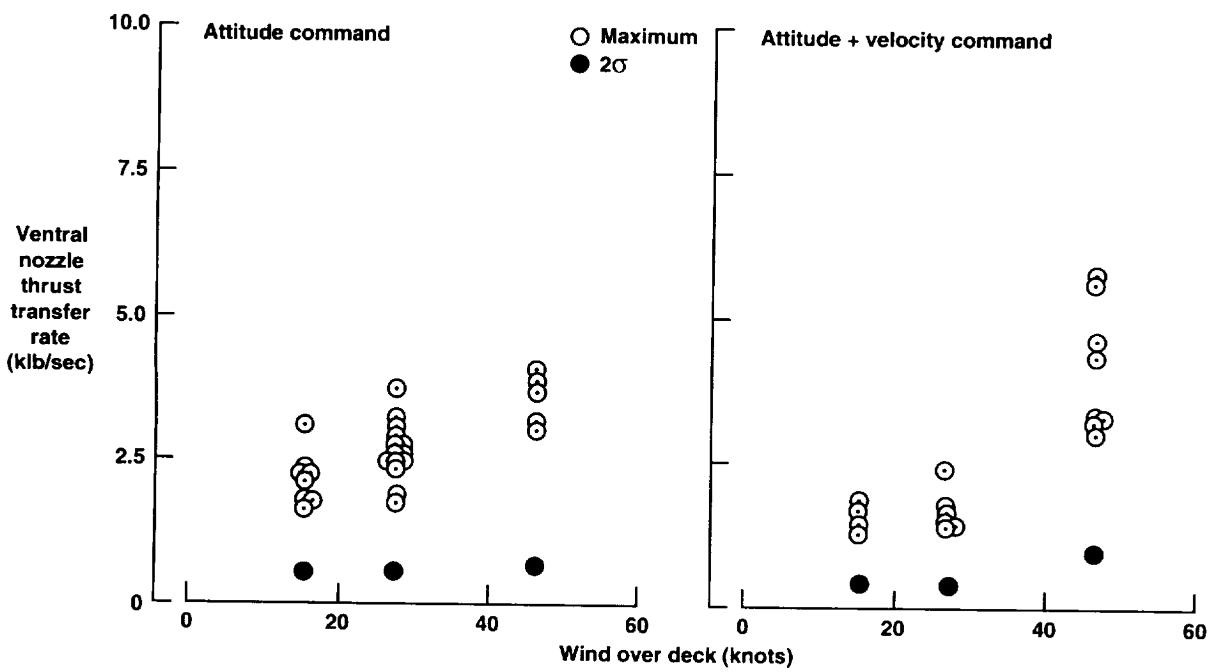


(b) Hover-point acquisition.

Figure 9. Influence of SCAS configuration and wind environment on thrust-transfer rate for pitch control.



(c) Vertical landing.



(d) Shipboard landing.

Figure 9. Concluded.

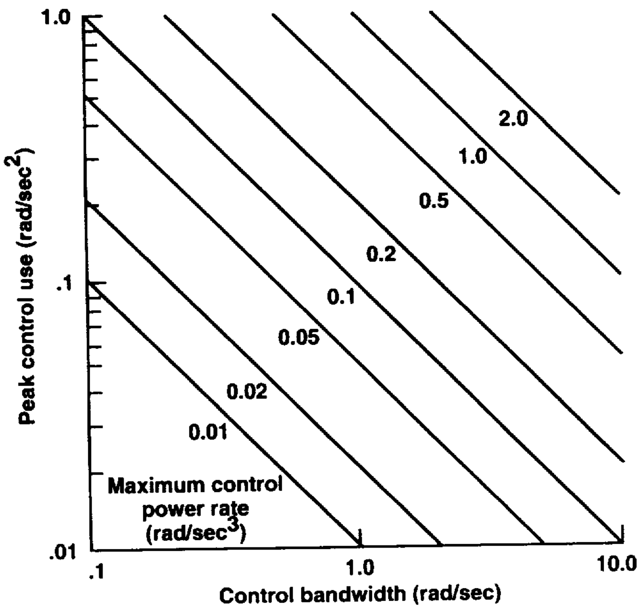


Figure 10. Influence of peak-control use and control power rate on rate-limit-free control bandwidth.

For shipboard landings (fig. 12(d)), 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 greatly influenced thrust-transfer rates, with peaks of 10 klb/sec (3 rad/sec^3) occasionally reached for the highest wind over deck. In lighter winds, transfer rates are comparable for the two SCAS modes.

The maximum available thrust-transfer rate was 10 klb/sec for these conditions. Evaluations were made for cases where the maximum available transfer rate was reduced to 6 klb/sec without encountering loss of control: lower maximum transfer rates would consistently produce limit cycling in the roll control leading to PIO and loss of control.

As an example, for roll control (fig. 10), a maximum thrust-transfer rate of 5 klb/sec (corresponding to an angular acceleration rate change 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.

Effect of SCAS design bandwidth– Control bandwidth has less influence on thrust-transfer rate than on control usage (fig. 13). In the transition phase (fig. 13(a)), a modest increase in peak rate appears at the highest bandwidth, and no change in the 2σ level is observed. No significant change appears in peak values for hover-point acquisition, runway vertical landing, or shipboard landings (figs. 13(b)–13(d)), and the 2σ values actually decrease at the highest bandwidth in the shipboard case. The cause for this decrease is not apparent; it would be conservative to interpret bandwidth as having no effect on thrust-transfer rate in this case.

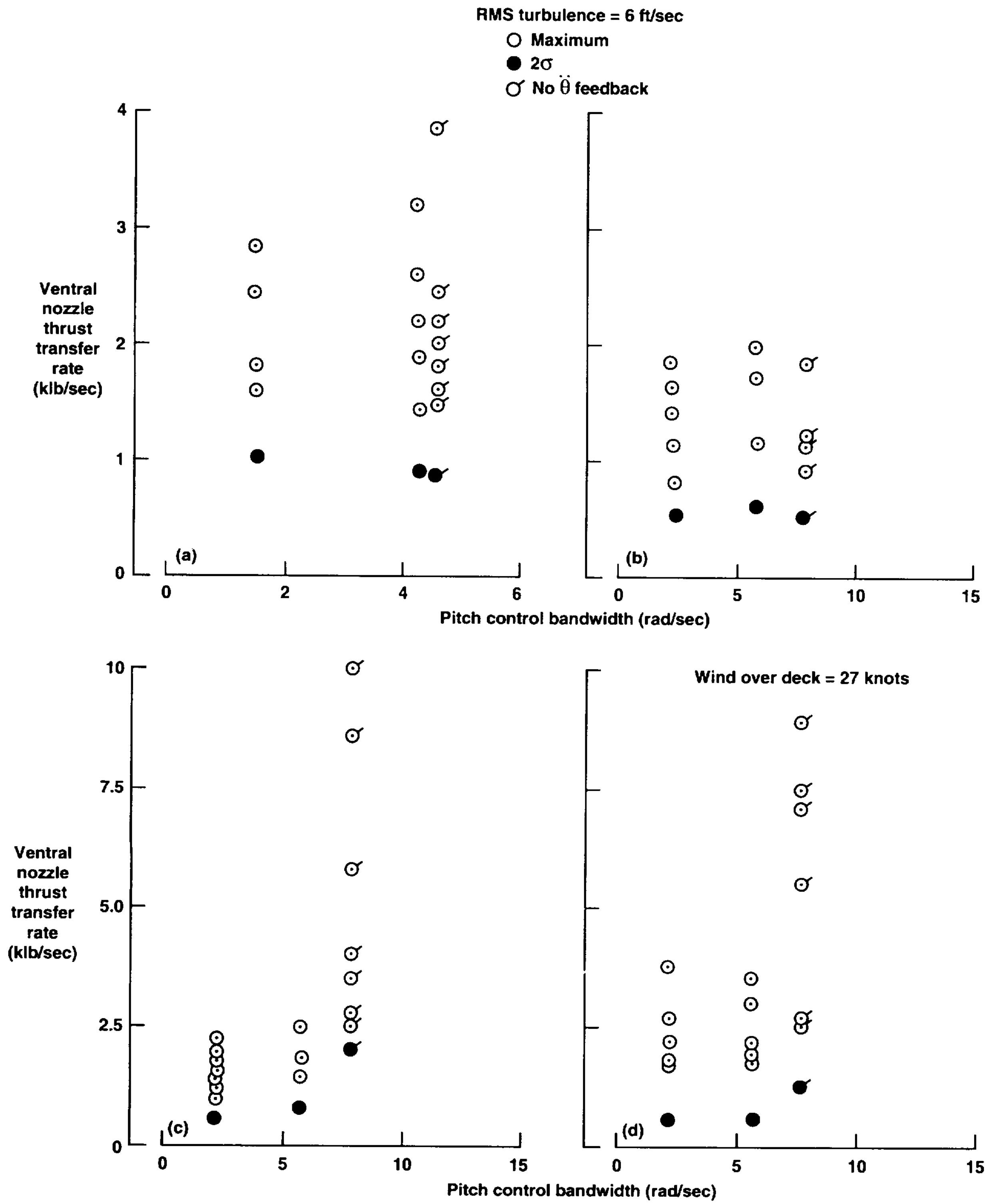
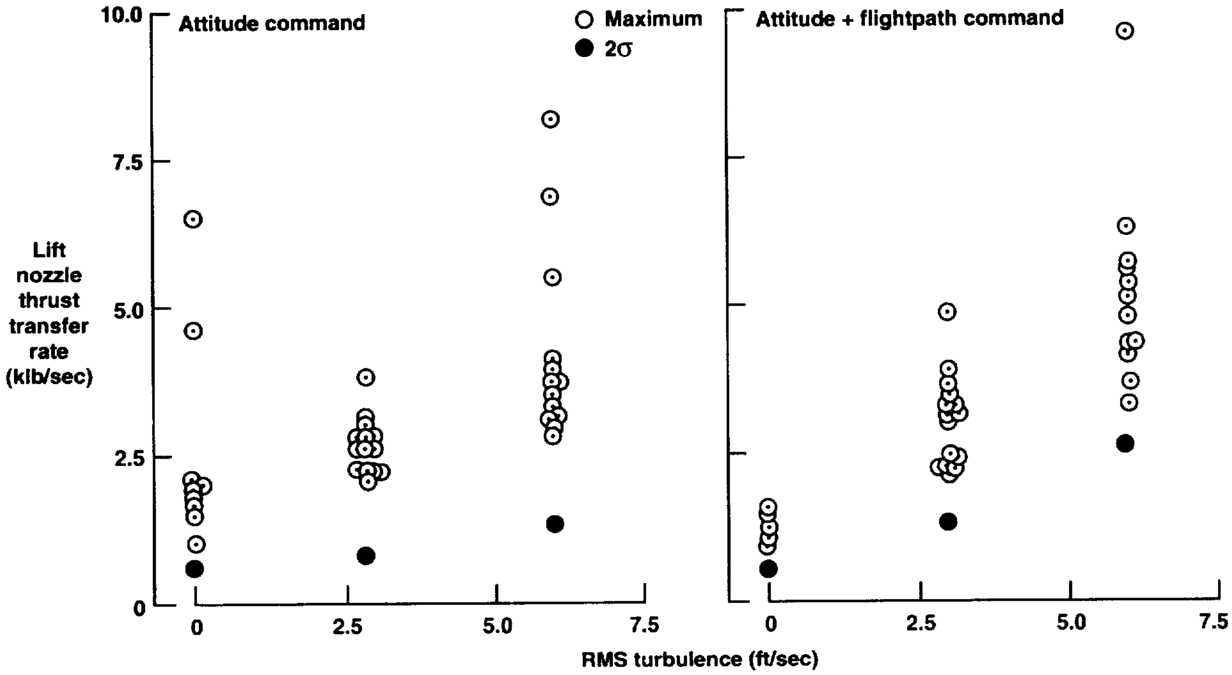
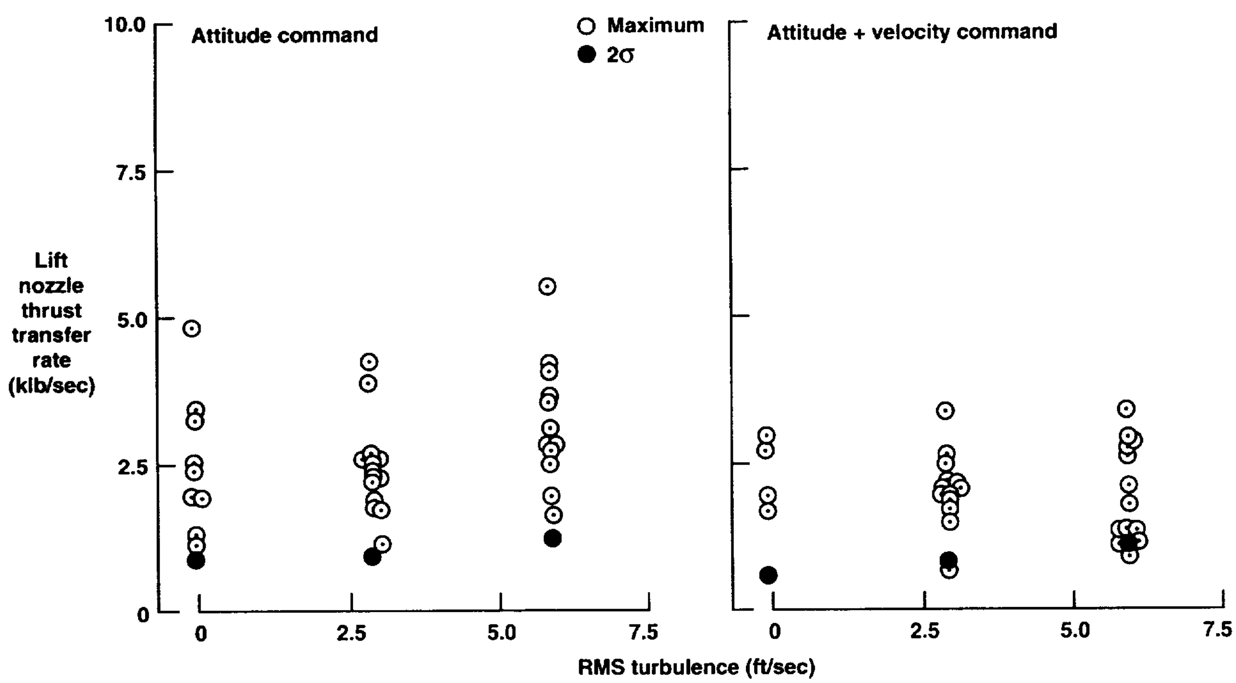


Figure 11. Effect of SCAS bandwidth on thrust-transfer rates for pitch control. (a) Transition; (b) hover-point acquisition; (c) vertical landing; (d) shipboard landing.

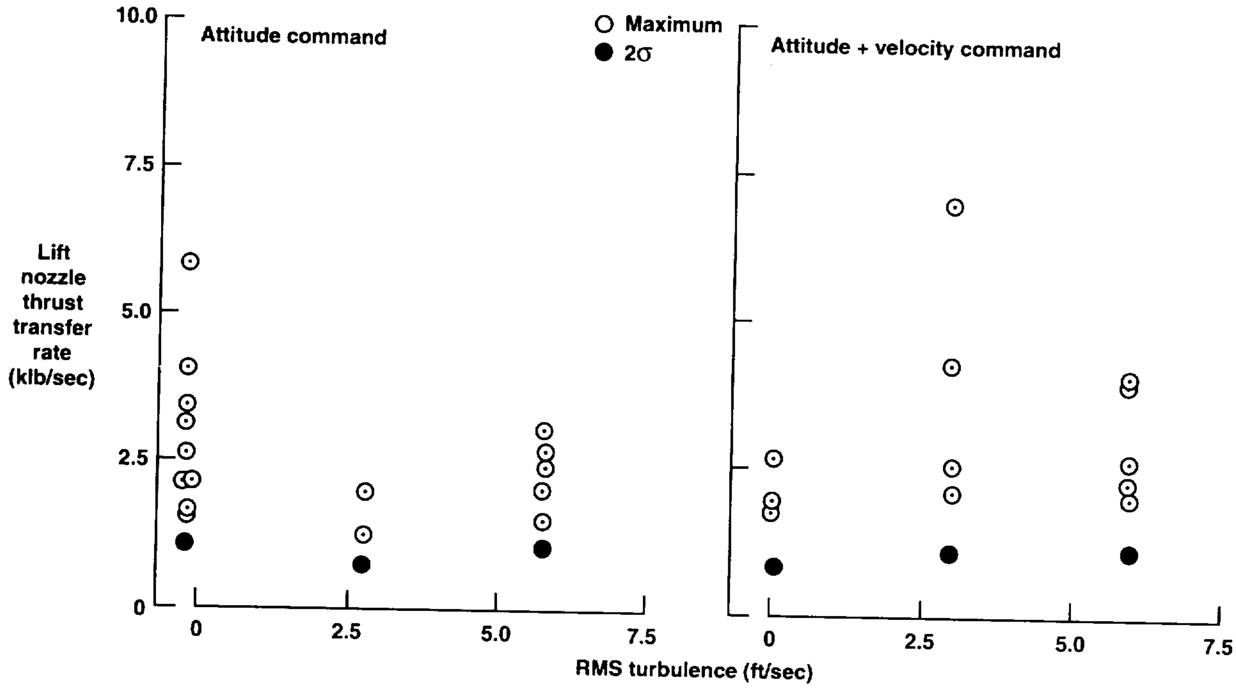


(a) Transition.

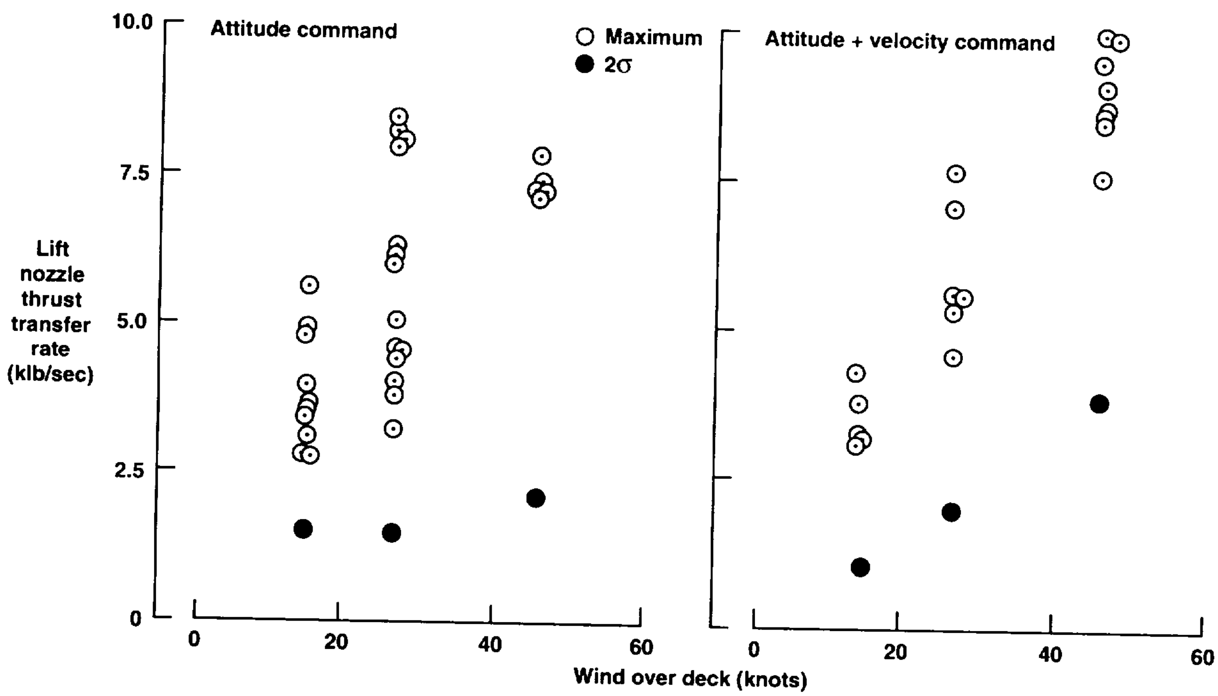


(b) Hover-point acquisition.

Figure 12. Influence of SCAS configuration and wind environment on thrust-transfer rates for roll control.



(c) Vertical landing.



(d) Shipboard landing.

Figure 12. Concluded.

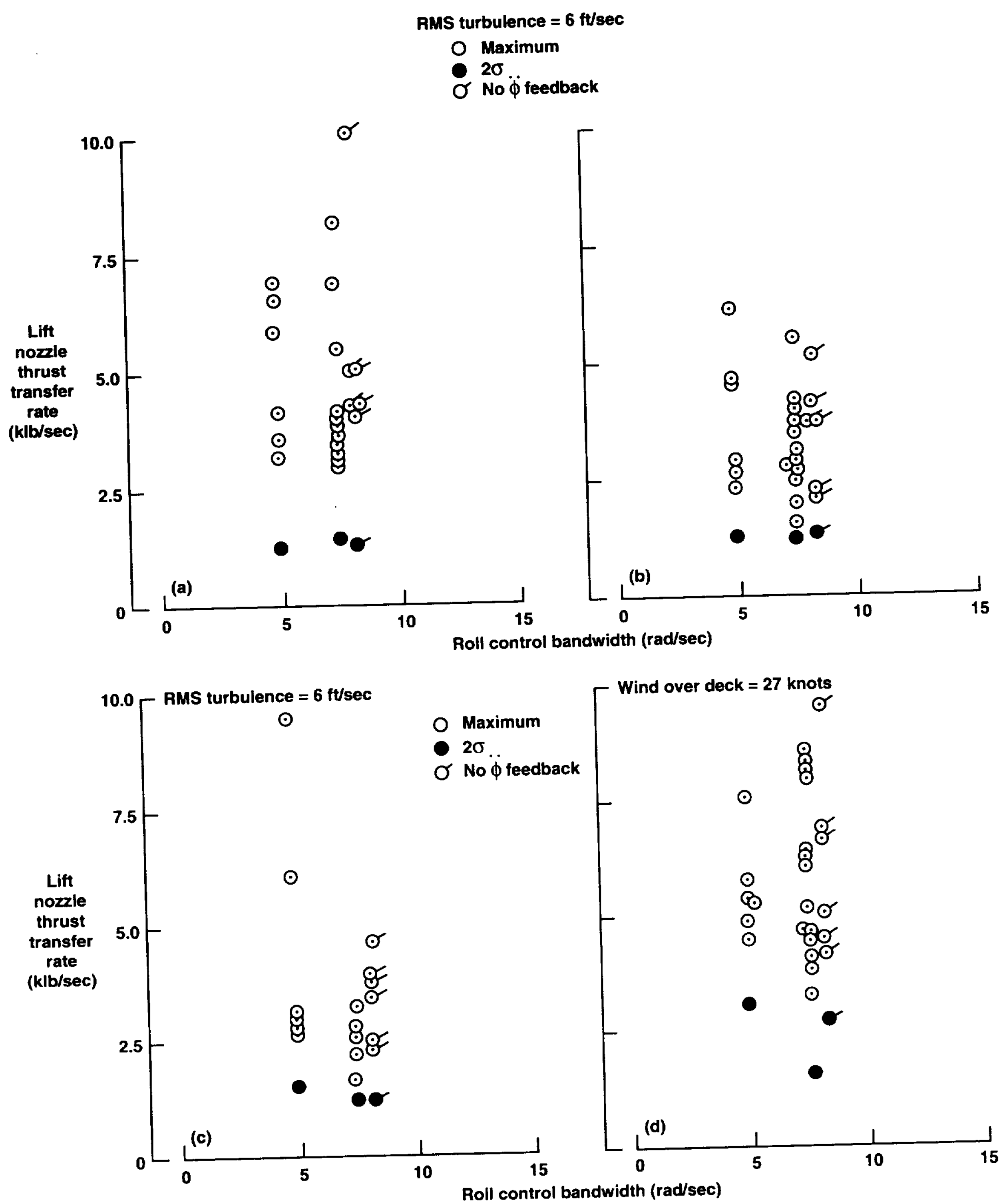


Figure 13. Effect of SCAS bandwidth on thrust-transfer rates for roll control. (a) Transition; (b) hover-point acquisition; (c) vertical landing; (d) shipboard landing.

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 result from temperature rise at the engine inlet due to the recirculation of hot exhaust gas from the propulsion system. Generalized experiments have been conducted on the VMS to evaluate 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). 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 (ref. 6). Results from these simulations are presented in figure 14. 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 in reference 6 are also presented with an appropriate data fairing to illustrate the trend. The YAV-8B data correspond to configurations with and without LIDS and for two levels of hot-gas ingestion, spanning the range of mean ground effect covered in previous generalized investigations. Thrust–weight ratio is determined out of ground effect. Mean ground effect and ingestion are defined here by the relationship

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

where $(\Delta L/T)'$ incorporates jet-induced aerodynamic ground effect as well as thrust variations with inlet temperature. It is derived from the normal force equation:

$$(1 + \Delta L/T)T - W = ma_z \qquad (2)$$

where

$$T = W + (\Delta F_G/\Delta N_F)(\Delta N_F/\Delta\theta)\Delta\theta \qquad (3)$$

After collecting terms, the normal force equation is

$$\{[1+ \Delta L/T][1+ (\Delta F_G/\Delta\theta)(\Delta\theta/W)] - 1\} = a_z/g \qquad (4)$$

and the term on the left side of the equation is $(\Delta L/T)'$.

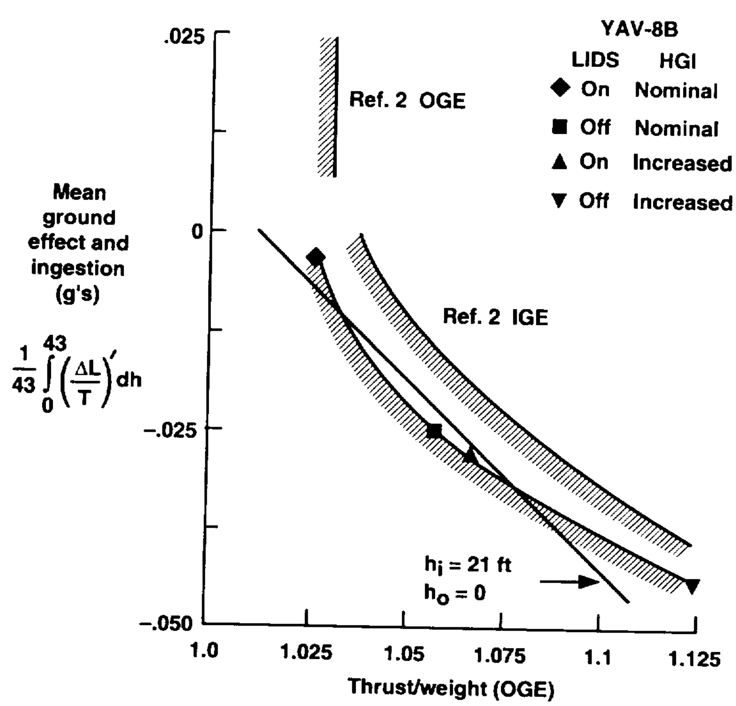


Figure 14. Influence of ground effect and hot-gas ingestion on thrust margin for vertical landing.

The range of wheel height over which the mean ground effect and ingestion is based is 0–43 ft, which represents ground effect for the YAV-8B Harrier. For the earlier generalized ground-effect simulation, the defining mean ground effect was based on an altitude range of 0–15 ft, where ground effect did not vary above that wheel height. 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 are established by (1) height control out of ground effect for positive ground effect, (2) on abort capability at decision height for neutral to moderately negative ground effect and ingestion, and (3) on control of sink rate and hover position to touchdown for larger negative ground effect. Results from the simulation evaluation of the YAV-8B Harrier (ref. 6) are less conservative than the boundary derived from the evaluation of generalized ground effect and are consistent with Harrier flight experience described in their operations manuals (refs. 18 and 19). The boundary correlates over much of its range with an analytical prediction of the thrust–weight trend with mean ground effect required to arrest a nominal sink rate of 4 ft/sec prior to touchdown when maximum thrust is applied at an altitude of 21 ft. This analytical relationship is expressed as

$$\left(\dot{h}_i^2 - \dot{h}_o^2\right)/2g = \int_0^{43} (\Delta L/T)'\,dh + \int_0^{h_i} (\Delta T/W)\,dh \qquad (5)$$

and can be used in the 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 obtained for attitude SCAS and shown in figure 14. However, as noted in reference 2, vertical-velocity command reduces 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

The effects of thrust response dynamics on the pilot's assessment of vertical landing control are shown in figure 15. These data are from reference 2 and apply to manual control of thrust with only attitude SCAS available. Thrust response bandwidth of 4–5 rad/sec for the engine core is sufficient to achieve satisfactory ratings for height and sink rate control. For bandwidths below 3 rad/sec, the control task deteriorates rapidly. By comparison, reference 7 requires a first-order time constant of 0.3 sec or less for satisfactory hover-control thrust response, while reference 8 recommends a time constant of 0.5 sec or less. 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 added to attitude SCAS insulates the pilot from the dynamics of the propulsion-system response and results in the toleration of slower engine response. As long as thrust rate limits (engine acceleration limits) permit, the vertical-velocity-command system can drive engine thrust to produce the desired vertical-velocity response to the pilot's commands.

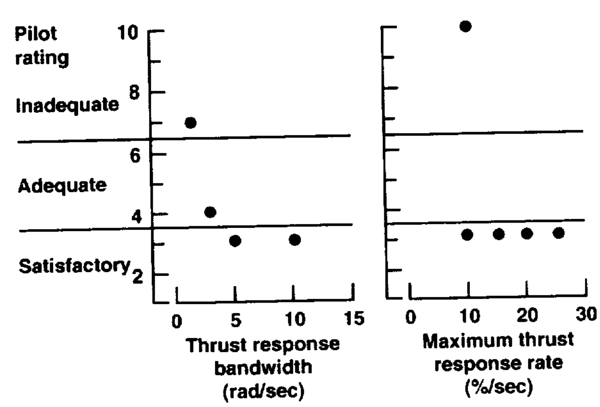


Figure 15. Effect of thrust-response bandwidth and response rate on control of vertical landing.

To a point, the vertical landing is insensitive to maximum core thrust rate of change, which is associated with engine acceleration limits imposed by maximum allowable temperatures in the core. Thrust rates varying from 25 percent of maximum thrust/sec to nearly 10 percent thrust/sec were tolerable for height control. However, at about 10 percent thrust/sec, thrust-rate limiting and loss of control were occasionally encountered for slow acceleration characteristics. These acceleration rate limits can be related to the surge margin in the design of the propulsion system control. Deceleration rate limits are important to rapidly reduce thrust at touchdown and to the dynamic response of vertical velocity in the hover. Vertical-velocity command does not seem to alter these results. Furthermore, the basic engine response bandwidth would be expected to affect the acceptable acceleration rate since the ability of the velocity command to compensate for lower-bandwidth thrust response is dependent upon the rate that the system can change engine thrust.

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 on Ames Research Center's Vertical Motion Simulator. Items assessed in the program were maximum control power, control-system dynamic response associated with control bandwidth and 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, while pitch-control power used for hover and 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 criteria suggest. No criteria, except those for hover, exist for shipboard recovery. Within the range of control bandwidth that provides satisfactory flying qualities, the control designer has considerable latitude in closed-loop system design to achieve reasonable control activity and disturbance rejection.

In the roll axis, the control power recommended by current design criteria is insufficient to cover demands for transition and hover-point acquisition. Agreement with criteria for vertical landing is good. 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. There is merit in reducing roll-control bandwidth, up to the point of deterioration in pilot ratings, to reduce control usage. For this particular aircraft 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.

For the transition, hover, and vertical landing, the existing criteria exceed the current experience for yaw-control use. As before, shipboard operations are not covered by the existing criteria. 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 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; however, control bandwidth was a factor on pitch-control rate for vertical landing. The designer has considerable latitude in choice of bandwidth for the closed-loop control system to achieve satisfactory flying qualities while avoiding excessive control use or actuation rates.

Thrust margins for vertical landing in the presence of ground effect and hot-gas ingestion were defined based on results from a simulation of the YAV-8B Harrier. The shape of the boundaries were 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.

An engine-core thrust response bandwidth 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 the pilots can accept for manual control of thrust. To a point, the vertical landing is insensitive to maximum core thrust rate of change; however, a loss of control appears at the lowest thrust transfer rates. Vertical-velocity command does not seem to alter these results.

APPENDIX

The relationship between attitude response and the angular acceleration of the control effector required to produce that response is dependent on the attitude-control mode employed. Two control modes are considered in this report, attitude command and rate command. For an attitude-command system, attitude response can be represented in the frequency domain by the second order transfer function

$$\frac{\theta}{\theta_c} = \frac{\omega^2}{s^2 + 2\zeta\omega s + \omega^2} \tag{6}$$

and the angular acceleration associated with the control response is

$$\frac{\ddot{\theta}}{\theta_c} = \frac{\omega^2 s^2}{s^2 + 2\zeta\omega s + \omega^2} \tag{7}$$

Examples of attitude and angular-acceleration response to a step-command input, normalized by the input magnitude, are plotted versus nondimensional time in figure 16 for a damping ratio of 0.7. Effects of variations in damping ratio on attitude response are shown in figure 17. The attitude response in 1 sec following a step-command input, defined from the inverse Laplace transform of equation (6), as a function of damping ratio and natural frequency, is given by

$$\frac{\theta_1}{\theta_c} = 1 - \frac{e^{-\zeta\omega}}{\sqrt{1-\zeta^2}} \sin\left(\omega\sqrt{1-\zeta^2} + \psi\right) \tag{8}$$

where

$$\psi = \tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta} \tag{9}$$

The peak angular acceleration required to produce this response (fig. 16) occurs at the initiation of the maneuver. From equation (7), the peak acceleration in proportion to the command input is

$$\frac{\ddot{\theta}_o}{\theta_c} = \omega^2 \tag{10}$$

Finally, the acceleration required to achieve the desired attitude response in 1 sec follows from equations (8) and (9) and is

$$\frac{\ddot{\theta}_o}{\theta_1} = \frac{\omega^2}{1 - \frac{e^{-\zeta\omega}}{\sqrt{1-\zeta^2}} \sin\left(\omega\sqrt{1-\zeta^2} + \psi\right)} \tag{11}$$

For a rate-command system, the transfer functions representing attitude and angular acceleration response to the step-rate command input are

$$\frac{\theta}{\dot{\theta}_c} = \frac{1}{s(\tau s + 1)} \tag{12}$$

$$\frac{\ddot{\theta}}{\dot{\theta}_c} = \frac{s}{(\tau s + 1)} \tag{13}$$

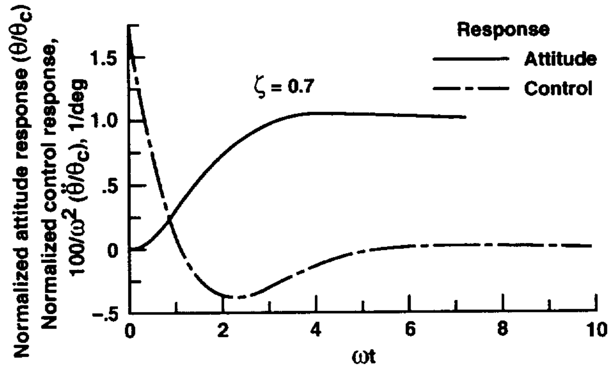


Figure 16. Attitude and control response to step command for an attitude-command system.

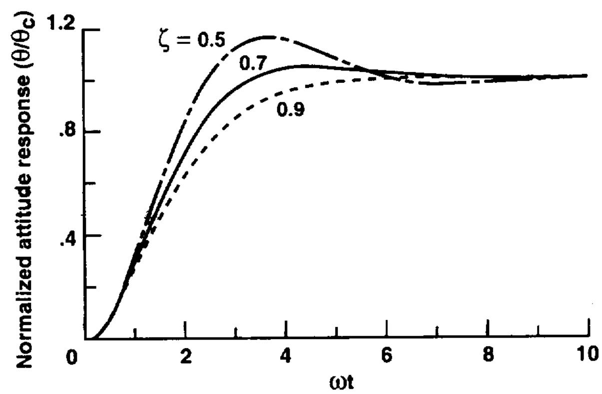


Figure 17. Effect of damping ratio on attitude response for an attitude-command system.

An example time history of attitude and control response is shown in figure 18. Attitude response in 1 sec following a step input, in proportion to that input, is represented as a function of the rate-command time constant by

$$\frac{\theta_1}{\dot{\theta}_c} = \tau\left(e^{-1/\tau} + 1/\tau - 1\right) \tag{14}$$

Peak angular acceleration to achieve this response is

$$\frac{\ddot{\theta}_o}{\dot{\theta}_c} = \frac{1}{\tau} \tag{15}$$

The peak acceleration required to achieve the desired attitude in 1 sec follows from equations (14) and (15).

$$\frac{\ddot{\theta}_o}{\theta_l} = \frac{1}{\tau^2\left(e^{-l/\tau} + l/\tau - 1\right)} \qquad (16)$$

Figure 18 can be used to extract attitude response and control-induced accelerations for different response times.

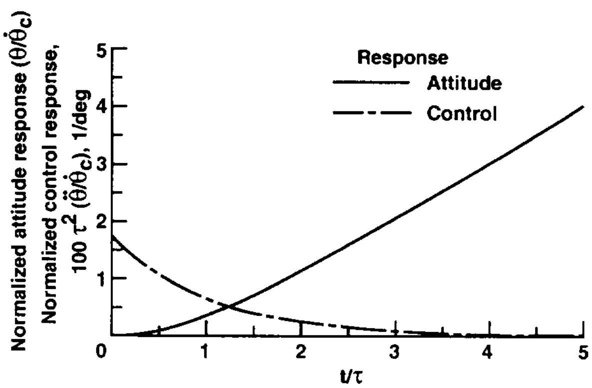


Figure 18. Attitude and control response to step command for a rate-command system.

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13. ABSTRACT *(Maximum 200 words)*

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 U.S./U.K. STOVL Joint Assessment and Ranking Team. The control-system designs have been evaluated throughout the powered-lift flight envelope on the Vertical Motion Simulator (VMS) at Ames Research Center. 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.

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