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James A. Franklin and Seth B. Anderson

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James A. Franklin
Seth B. Anderson, Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

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V/STOL MANEUVERABILITY AND CONTROL

James A. Franklin and Seth B. Anderson
Ames Research Center, NASA
Moffett Field, California, 94035, U.S.A.

SUMMARY

This paper deals with maneuverability and control of V/STOL aircraft in powered-lift flight, and in addition, with specific considerations of maneuvering in forward flight. A review of maneuverability for representative operational mission tasks is presented and covers takeoff, transition, hover and landing flight phases. Maneuverability is described in terms of the ability to rotate and translate the aircraft and is specified in terms of angular and translational accelerations imposed on the aircraft. Characteristics of representative configurations are reviewed, including experience from past programs and expectations for future designs. The review of control covers the characteristics inherent in the basic airframe and propulsion system and the behavior associated with control augmentation systems. Demands for augmented stability and control response to meet certain mission operational requirements are discussed. Experience from ground-based simulation and flight experiments that illustrates the impact of augmented stability and control on aircraft design is related by example.

NOTATION

a_y	lateral acceleration
a_z, Δg	incremental normal acceleration
C_D	drag coefficient
C_L	lift coefficient
C_Z	normal force coefficient
C_{Z_w}	normal force coefficient derivative with vertical velocity
d_e	equivalent jet exhaust diameter
g	acceleration due to gravity
h, z	altitude, vertical position
IMC	instrument meteorological conditions
$j\omega$	imaginary component of complex root
$K_{(\ )}$	feedback gain for variable ( )
M_q	pitch damping derivative
M_u	pitch acceleration derivative with axial velocity
M_{δ_e}	longitudinal control sensitivity derivative
OVC	outside visual cues
q	freestream dynamic pressure
q_{jet}	local dynamic pressure in jet
s	Laplace operator
T	total thrust
T/W	thrust-to-weight ratio
T_h	vertical velocity mode time constant
T_λ	longitudinal velocity mode time constant
T_1	engine inlet temperature
$t_{\phi = 30^\circ}$	time for 30° bank angle change
$t_{\psi = 15^\circ}$	time for 15° heading change
$t_{50\% \Delta\gamma_{MAX}}$	time to reach 50% of peak flightpath increment
$t_{0.9\Delta\gamma_{SS}}$	time to reach 90% of steady-state flightpath increment

$\dot{u}_{SHEAR}$	rate of change of wind velocity (wind shear gradient)
V	airspeed
VMC	visual meteorological conditions
V_{e_j}	equivalent jet velocity ratio $(q/q_{jet})^{1/2}$
W/S	wing loading
X_u	axial acceleration derivative with axial velocity
X_w	axial acceleration derivative with vertical velocity
x, x_c	actual and commanded longitudinal position
Y_{p_θ}	pilot transfer function for attitude control
Z_w	vertical velocity (heave) damping derivative
Z_{δ_T}	throttle sensitivity derivative
α	angle of attack
β	sideslip angle
γ	flightpath angle
$\Delta(\ )$	incremental value of ( )
$\Delta L/T$	normalized lift in ground effect
$\Delta \mathcal{L}/Td_e$	normalized rolling moment in ground effect
ΔV_A	airspeed change due to wind shear
$(\Delta V/\Delta T)_\theta$	steady-state change in airspeed with thrust at constant pitch attitude
$(\Delta\gamma/\Delta V)_T$ $(d\gamma/du)$	steady-state change in flightpath with airspeed at constant thrust
$(\Delta V/\Delta\gamma)_{SS}$	steady-state flightpath-airspeed coupling in response to thrust at constant attitude
$(\Delta V/\Delta\theta)_T$	steady-state change in airspeed with pitch attitude at constant thrust
ΔX	incremental axial force
ΔZ	incremental normal force
δ_H	stabilator (tailplane) position
δ_{LAT}, δ_a	lateral control position
δ_{MP}, δ_{LONG}, δ_e	longitudinal control position
δ_r	directional control position
δ_T, σ_T	throttle position, main engine throttle position
δ_v	nozzle angle
ζ	damping ratio
θ	pitch attitude
$\theta(1)$	pitch attitude change in 1 sec
θ_T	thrust vector inclination
ρ	air density
σ	real component of a complex root
σ_{FC}	lift engine fuel control position
σ_M	nozzle lever position
τ_e	thrust response time constant
τ_u	time constant for airspeed response to wind shear

τ_x	translational velocity time constant
ϕ	bank angle
$\phi_{(1)}$	bank angle change in one second
ψ	heading change
$\psi(1)$	heading change in one second
ω	natural frequency
$(\dot{\ })$	d ( )/dt
$(\ddot{\ })$	$d^2($ $)/dt^2$

1. INTRODUCTION

The operational requirements for an aircraft's mission define the aircraft's flight envelope and the ability to change from one flight condition to another within this envelope. Maneuverability is associated with the capability to execute these changes in flight condition through changes in the aircraft's attitude, translational velocity, and position in space as demanded by the mission requirement. V/STOL aircraft, in particular, have unique operational maneuvering requirements in addition to those for conventional aircraft. These include the need to hover precisely; move fore and aft, sideways, and vertically for landing; air taxi; transition from powered lift to aerodynamic lift; and perform relatively steep descents and climbouts from confined areas. The precision with which these maneuvers can be accomplished and the effort that the pilot must exert to execute them determines the aircraft's controllability. It is inevitable that certain V/STOL configurations are difficult to control at low-speeds due to low levels of angular damping, little angle-of-attack or directional stability, and too much dihedral effect (Ref. 1). Control is also influenced by the need to counteract forces and moments associated with thrust-induced effects, ground-effect, and flap and speed changes. Environmental effects place extremely severe demands on control for certain V/STOL tasks, such as landing on a small ship in a high sea state with a rolling, pitching, and heaving deck; wind gusts; and wakes from the ship's superstructure. Providing sufficient control to compensate for the lack of inherent stability and to counteract various sources of disturbances is not without penalty because control for low speed operation must be extracted in some form from the propulsion system.

Requirements for V/STOL flying qualities that attempt to define maneuverability and controllability criteria have been developed from a background of flight experience using a wide variety of V/STOL concepts. The specifications in the two documents, AGARD Report 577 (Ref. 2) and MIL-F-83300 (Ref. 3), have been operationally evaluated for recent V/STOL designs but lack clear definition for shipboard operation. Nevertheless, they have served to guide some V/STOL flight test programs and have been used extensively in recent design studies for advanced V/STOL concepts.

The intent of this paper is to describe the environment in which modern V/STOL aircraft will be expected to operate, to establish the nature of maneuvers that are appropriate to execute tasks associated with these operations, and then to relate these maneuvers to control authority demanded for modern V/STOL designs. Given this maneuver environment and required capability, the controllability to permit the desired precision of maneuvering is assessed. Characteristics of the basic aircraft and control augmentation systems that contribute to or detract from control precision are reviewed. The full V/STOL flight regime will be covered in these assessments, including takeoff, transition, approach, and landing. Furthermore, contributions of V/STOL configurations to combat maneuverability are noted in general terms. The paper describes experience that has been gained since AGARD 577 and MIL-F-83300 were published. The results compiled in these two documents are summarized and recent information from ground-based simulation, flight research, concept evaluations, and development test programs are discussed. Conclusions concerning future requirements for flight control research for V/STOL aircraft are mentioned in closing.

2. OPERATIONAL MANEUVER REQUIREMENTS

2.1 Operational Environment

Maneuver requirements for V/STOL aircraft are predicated on the operational environment to which they are exposed. For military use, these aircraft may be required to operate from major military airfields, austere forward sites, large aircraft carriers, or small aviation-capable vessels. Airfields and aircraft carriers provide ample space for takeoff and landing and precision approach guidance for operations conducted under low-visibility conditions and, as such, pose no great challenge to V/STOL operations. The capability for hover and slow-speed flight and for rapidly accelerating between conventional wing-borne to fully propulsion-borne flight that characterizes V/STOL aircraft permits operation into more confined spaces associated with austere land-based sites and from platforms or decks of small ships. However, these operations enforce a greater precision of control and capability for rapid deceleration to hover than are associated with more generously proportioned facilities. For forward land bases, these aircraft may operate from temporary pads with dimensions of 70x70 ft, in close proximity to trees, buildings, equipment, or other obstacles to flight, as shown in Fig. 1. As a consequence, the ability to position the aircraft, to control height precisely, to stop quickly when approaching obstacles, and to do so under conditions of winds, turbulence, and low visibility is essential to ensure routine operational capability.

Operation at sea may entail vertical takeoff, short takeoff, and ski jump launch and vertical landing, and may take place from the decks of large carriers (70- 80 metric ton) to 15-ton amphibious assault ships, or even destroyers having landing pads of dimensions as small as 40x40 feet. As such, ample space may be available for launch and recovery, or these operations may take place in a confined space surrounded by the ship's structure. Figure 2 illustrates ski jump takeoff from the forward deck of H.M.S. Hermes, and as described by the pilots, is a rather uneventful experience. For vertical takeoffs, the primary concern is to avoid the ship's superstructure at liftoff and at translation away from the ship. For flat-deck, short-takeoff, pitching motion of the deck poses the greatest challenge, since downward excursions reduce clearance margins above the sea and enforce greater maneuver requirements after leaving the deck. In general, however, air operations aboard a ship this size or of that of the U.S.S. Guam, shown in Fig. 3, affords ample space for maneuvering during launch and recovery. When operations take place aboard smaller ships such as those shown in Fig. 4, the proximity of the ship's structure makes it imperative to be able to quickly arrest translational motions when maneuvering during departure or landing on the small pad astern. It should also be noted that, in all cases, air disturbances induced by the ship's superstructure increases the difficulty of precise control, and operation in poor visibility will make the pilot's task of positioning the aircraft in relation to the ship a challenging task.

During recovery to the ship, the vertical, lateral, and rolling motion of the landing pad may present a significant control challenge for the pilot. Figure 5 presents examples of the magnitude of these motions as derived from predictive models of Fortenbaugh (Ref. 4) and Brown et al. (Ref. 5). These motions are shown as functions of significant wave height, which is correlated with the measure of the sea state. For the smaller destroyer-class ship, peak heave motions may reach 10-15 ft, lateral motions as much as 5 ft, and roll amplitudes of nearly 10°, for significant wave heights of 15 to 20 ft. Under current operational guidance, launch and recovery would normally take place in sea states of 4 or less, for which case the ship motion poses much less of a challenge. Although the larger amphibious assault ship has a more benign rolling motion, linear motion at the pad is as large as for the destroyer. Thus, if operations are to be conducted in more adverse weather conditions, it may be necessary for future aircraft to accommodate to the more active deck of the small ship in sea state 5.

V/STOL operation in confined spaces and near obstacles in a steady wind will expose the aircraft to strong wind gradients and turbulence. Figure 6 illustrates the nature of this environment in proximity to the fantail landing spot on a DD-963-class destroyer. In the presence of a 20-knot quartering wind 30 degrees to port, the character of the mean wind for an approach into the wind at an altitude of 100 ft above the sea and during descent onto the landing pad are shown at the left of the figure. Peak wind gusts experienced during descent onto the pad are shown at the right. These data were obtained from the model of Ref. 4 as derived from scale-model wind tunnel tests of this class ship described by Garnett (Ref. 6). When the aircraft enters the wake of the superstructure within a few hundred feet of the ship, a wind gradient is encountered for the example shown that consists of a wind deficit of approximately 6 knots. This change in the steady wind does not present a serious problem in moving up to and establishing a hover position with respect to the ship. At higher altitudes, wind variations induced by the ship would be even less. The major difficulties are encountered during descent onto the landing pad. For this example, the wind decays to essentially a calm condition at the deck, meaning that during the descent of approximately 50 ft, the pilot must correct for a relative velocity of 20 knots with respect to the ship to hold position and avoid moving into contact with its aft structure. Turbulence in the wake increases to a significant extent during descent, compounding the attitude and position control process. While these conditions are among the most extreme encountered in V/STOL operations, they do represent situations which must be taken into consideration. Along with details of the aircraft's design, operational procedures must be developed to provide options for defining an aircraft's controls to deal with this situation.

Visibility in adverse weather is another factor which will influence the manner in which the aircraft is maneuvered and controlled. Figure 7 from Hoh and Ashkenas (Ref. 7) condenses the definition of these conditions and their implications for design and operation. In fully visual flight (visual meteorological conditions - VMC) visual cues for attitude and translational control are easily obtained and no constraints are imposed on the aircraft or its operation. As visual information degrades to partial instrument meteorological conditions (partial IMC), cues for attitude control begin to degrade and translational rate information becomes marginal, and eventually only intermittent. Position cues may be only marginal for outside visual cues (OVC) Level 4. At the extreme is full IMC where all information for control of the aircraft must be presented to the pilot in the cockpit. For aircraft designed to operate in poor visibility, it is implicit that the control system provide stability to offset the lack of visual information. Otherwise, as will be noted later in the paper, additional control authority may be required for the pilot to provide the stabilization function. Maneuver implications include restricting operations to more docile procedures, or, if full maneuver capability is to be retained, providing the necessary control stabilization and artificial display of information to support more aggressive maneuvers.

2.2 Operational Maneuvers

Given the operational environment discussed in the foregoing paragraphs, the maneuvers peculiar to the V/STOL or powered-lift portion of the aircraft's operation are concerned with takeoff, transition, approach, and landing. Within each phase are particular maneuvers that may have a specific impact on airframe, propulsion, or control system design. In the takeoff, primary concern is devoted to clearing the ground in the presence of ground-induced disturbances, avoiding obstacles near the launch area, and initiating the accelerating transition to cruise flight. Figure 8 presents examples of vertical and short takeoff maneuvers for the AV-8 Harrier described by Lacey (Ref. 8) and in Ref. 9. Sufficient performance and control authority must be available to accelerate vertically near the ground, to suppress the effects of steady winds, turbulence and ground induced disturbances arising from aerodynamic ground effects or from hot-gas-flow ingestion into the propulsion system and to assure aircraft stability at low speed. It is apparent from the examples that control is exercised in relatively large discrete steps for attitude, thrust, and thrust vector angle (nozzle). It can also be stated that in most instances precise control of attitude, heading, and vertical velocity is not demanded to the extent that is associated with the approach and landing.

For the transition to cruise or from cruise to powered-lift flight, it is important to ensure a sufficient performance envelope for maneuvering with satisfactory angle of attack or stall margin. This performance envelope must provide the ability to accelerate or decelerate in level flight, and to climb or descend at constant airspeed, or an appropriate combination of both. One means of presenting this performance envelope is shown in Fig. 9 for the X-22A aircraft (Ref. 10) in terms of duct angle tilt for a given airspeed. The range of duct angles for a given airspeed, or the range of airspeeds at a given duct angle, is a measure of the ability of the aircraft to maneuver through transition. Each range implies a reserve of thrust vector, attitude, and thrust control to generate accelerations for changing airspeeds or for changing flightpath angle. An alternate presentation of this envelope would illustrate the variation in flightpath angle and airspeed against parameters of thrust vector magnitude and angle. The X-22A has an ample transition corridor and corresponding operational flexibility as a consequence of the ability to climb and accelerate and to descend and decelerate within this envelope. A much narrower corridor would restrict the flightpath and speed profiles that could be flown, or even the ability to halt and reverse the process once initiated. Control authority in addition to that for flightpath and airspeed must be sufficient to stabilize the aircraft. Operations tend to be carried out in discrete steps as illustrated for the example from a Harrier at the right of the figure, and, in general, nonprecision control of attitude and heading, as well as airspeed and altitude, is all that is demanded.

The landing approach is concerned with the portion of the flight envelope that encompasses mid-transition to hover. Here, it is important to ensure sufficient capability for steep descents and for ability to decelerate to hover with some margin for climb and descent at low speed. Figure 10 shows a representative approach envelope with parameters of thrust magnitude and vector angle as suggested in the previous paragraph. Constraints may be imposed by aerodynamic lift, flightpath control authority about the nominal approach condition, and maximum allowable descent rates during the approach and near the ground. Within these constraints, it should be possible to manipulate the thrust vector to perform a decelerating descent to hover. Under these circumstances, it should also be possible to make large changes in aircraft attitude and heading rapidly and precisely, as well as flightpath and airspeed. The time history at the right of the figure shows an example of a decelerating approach executed by the Do-31 (Ref. 11). Note the frequent and rapid adjustments of the controls required to maintain precise approach path and speed control in the presence of winds and turbulence encountered during the approach.

For the hover and landing, the aircraft must have essentially the same height-and speed-control capability as for takeoff to successfully accomplish the landing in the presence of ground effect or to abort or wave-off and accelerate to conventional flight. The precision of control for attitude, heading, and horizontal and vertical velocities is greatest in this phase of flight, and it is important to be able to initiate, arrest, and stabilize all these motions rapidly to achieve acceptable hover position control. Control authority must also be sufficient to counter disturbances from air wakes, hot gas reingestion, and ground effect. Another example from a Do-31 landing is included in Fig. 11 to demonstrate the magnitude of control used and the activity of controls during the final approach to hover and at the landing. Note the abrupt rise in engine inlet temperature that indicates the encounter with the engine exhaust flow near the ground. In this case, maximum thrust was not sufficient to arrest the rate of descent once the aircraft was in this environment.

One aspect of maneuvering flight that is not associated with V/STOL flight, but which deserves mention in this discussion, is the use of V/STOL controls for air combat. While specific performance characteristics cannot be discussed in this forum, some of the general characteristics that are sought in good combat aircraft are available in V/STOL aircraft and prove to be beneficial in combat encounters. Hooper (Ref. 12) noted the importance of being able to rapidly achieve large changes in normal and axial acceleration within a performance envelope such as that shown in Fig. 12. The particular example might be associated with a high-performance aircraft equipped with a speed brake. This acceleration envelope in turn determines the specific excess power, turn rate at a specific flight condition, and the ability to rapidly change flight conditions. Turn rate associated with normal acceleration capability over a range of flight conditions is presented at the right of the figure. The utility of features related to a V/STOL aircraft, such as thrust vectoring, lies in the expansion of this acceleration envelope, which could substantially enhance acceleration and deceleration, and, to a lesser extent, increase maximum normal acceleration and thereby improve turn performance. It should also be noted that the attitude changes required with any of these maneuvers, or with weapon pointing, must be executed rapidly and precisely.

Based on this review of the operational environment and the associated maneuver demands for V/STOL aircraft, the requirements on control authority to achieve this maneuver capability may be discussed.

3. CONTROL AUTHORITY REQUIREMENTS

It is well recognized (e.g., Refs. 2 and 3) that the total control authority of a V/STOL aircraft must be sufficient to trim the aircraft at a stabilized flight condition, to suppress external disturbances imposed on the aircraft, and to provide for maneuvering the aircraft as dictated by the mission and the particular phases of flight. Each of these demands on control authority are important to the designer and must be dealt with in the course of an aircraft's configuration definition and refinement. Control necessary to trim throughout the flight envelope is associated with specific details of a particular configuration and must be considered on an individual basis. The appropriate generalization to be made concerning trim control is that considerable attention should be given in the design process to minimize this requirement. Control authority frequently comes at considerable cost in propulsion system and airframe weight and overall aircraft performance, and the greatest fraction possible should be available for executing maneuvers associated with the mission tasks and for operating in the mission environment. Examples of pitch and roll trim control are shown in Fig. 13 and are representative of jet V/STOL designs. In these cases, trim requirements absorbed so much of the total control available that the control remaining was only marginally adequate for longitudinal path and speed control, lateral maneuvers, and for counteracting vertical and lateral wind disturbances. More recent designs of this class of aircraft, including the advanced Harriers such as the AV-8B and GR MK 5, have substantially reduced these trim requirements, and their operational flexibility and acceptability to pilots have improved accordingly.

Control utilization for suppressing external disturbances that is peculiar to V/STOL aircraft is associated with wind gradients and turbulence in the wake of obstacles, with forces and moments imposed near the ground, and with thrust variations due to hot gas reingestion. Figure 13 illustrates the increase in control activity for the Harrier as it approaches and lands vertically on a CV- class carrier with approximately 40 knots of wind over the deck (Ref. 13). Large control inputs were used to maintain tight control of roll attitude during the hover and landing. Examples of ground effect, including normal force and rolling moments are also shown (Ref. 9). A small initial suck-down, followed by a substantial and abrupt buoyancy, characterizes the normal force. Although the buoyancy is favorable in terms of thrust required to arrest sink rate, the variation in sink rate associated with the force perturbation must still be compensated. In the roll axis, the moment disturbance is abrupt and unstable. If this moment is not counteracted, objectionable roll attitudes and excessive lateral drift may develop during landing.

Control authority reserved for maneuvers is the primary subject of this section. For V/STOL operations, it has been possible to associate these manuever demands with tasks the pilot must perform in the hover and in the transition flight phases. For each phase, the force and moment authority to develop rotational and translational accelerations must be defined consistent with the individual maneuver requirements. Types of maneuvers that dictate control authority are large and rapid attitude and translational velocity changes. An example for hover is provided in Fig. 13 in the form of a quick stop that is required to arrest an increasing drift in speed that has developed inadvertently due to a mistrim condition or an external disturbance. Although the control mistrim may have been small, the buildup in speed that occurs over a period of time requires considerably greater control when the pulot needs to stop quickly. This capability is important for operation in confined space and can be a major factor in determining control utilization. During transition, the width of the operational corridor and the related flightpath acceleration capability is of primary concern. For air combat, the dominant factors involve the ability to produce normal accelerations to turn the aircraft rapidly, axial accelerations to quickly change flight condition and speed relative to an opponent, and rotational accelerations to enable rapid and precise pointing of the aircraft. In the subsections to follow, each of the three flight phases, with their appropriate manoeuvre control authority will be considered.

3.1 Hover

The preponderance of criteria and requirements for control authority in hover is contained in the AGARD V/STOL Handling Criteria (Ref. 2) and in the U.S. Military Flying Qualities Specification for V/STOL aircraft (Ref. 3). The information in these two documents was obtained from a variety of flight tests of fixed-wing and rotary-wing V/STOL aircraft and from ground-based simulator tests of specific aircraft models and of generic V/STOL control characteristics. Much of the data were obtained under fully visual flight conditions and in relatively calm air. Ground effects and hot gas reingestion are peculiar to each configuration. None of the experience in Refs. 2 and 3 includes shipboard operation; hence the influence of air wake and ship motion environment are not reflected in the data or the criteria derived from them. In the case of Ref. 2, the stated control authority criteria are defined separately for maneuver and stabilization in the presence of turbulence. Ref. 3 requirements for control power include demands for maneuvering and stabilization in gusty air.

In the material to follow, each control axis (pitch, roll, yaw, and heave) is addressed individually, followed by a summary of the combined authority requirements for all axes and implications for total installed propulsion system thrust necessary to meet the combined control demand. Based on the categorization of maneuvers in the preceding section, the control utilization and requirements which are about to be described are determined by the following control tasks. For pitch and roll control, the primary concern lies with precision hover positioning and with the execution of longitudinal and lateral quick-stop maneuvers. Any control cross-coupling resulting from maneuvers about other axes must also be accommodated. Yaw control is used to make heading changes, to hold heading during lateral translation, and to reduced undesired sideslip. Propulsive thrust, deflected vertically, is used for height control to maintain vertical clearance and to control rate of descent during the landing. While some of these maneuvers can be described analytically, and control authority can be derived from the analysis, the overall task of the pilot in controlling the aircraft in the hover cannot be reduced to a simple analytical expression. Consequently, the criteria and requirements that follow are based on pilots' assessments of control demands while performing hover control tasks in the framework of a complete operational situation. The pilots' evaluations of control capability in hover account for the precision of control judged to be acceptable for the specific task and for the effort the pilot must expend in terms of attention, mental anticipation, and physical effort that must be devoted to compensate for deficiencies in the aircraft's inherent response to the pilots' control commands. The pilots' evaluations are quantified in terms of the Cooper-Harper rating scale (Ref. 14), and are ultimately interpreted as levels of flying qualities that may be characterized as follows:

Level 1: Flying qualities clearly adequate for the mission flight phase.

Level 2: Flying qualities adequate to accomplish the mission flight but with some increase in pilot workload of degradation in mission effectiveness, or both.

Level 3: Flying qualities such that the aircraft can be controlled safely, but with excessive pilot workload or inadequate mission effectiveness, or both.

These levels have direct correspondence to the major ranges of flying qualities quantified in the Cooper-Harper scale, namely: Satisfactory - Level 1; Adequate - Level 2; Inadequate - Level 3. With satisfactory flying qualities, no improvement in the aircraft's characteristics is necessary. With adequate flying qualities improvement in the aircraft's characteristics is warranted. When flying qualities are inadequate, improvement is required.

Pitch control authority for maneuvering in hover is presented in Fig. 14. The table included with the figure summarizes the AGARD criteria of Ref. 2 and the military (MIL) specifications of Ref. 3. The AGARD criteria are presented alternately in terms of maximum angular acceleration initiated from trimmed flight, or in terms of pitch attitude achieved in 1 sec following an abrupt control input. MIL requirements are stated solely as pitch attitude in 1 sec. An example time history of pitch rate and attitude response to an abrupt (0.3-sec) ramp-control input is provided to illustrate the interpretation of the maximum angular acceleration and attitude change in 1 sec. The attitude change in 1 sec accounts both for the angular acceleration produced by the control and the restoring moment proportional to angular rate that opposes the control moment. AGARD criteria are provided for only Level 1 (fully satisfactory) flying qualities. The lower end of the AGARD criteria apply to configurations which permit longitudinal translation to be accomplished through thrust deflection, while the upper end of the range applies to translation assumed to be performed using pitch rotation. The alternate criteria are self-consistent if the aircraft responds to the longitudinal control as a rate command as indicated in the time history, with a first-order time constant of approximately 0.6 sec. Since the MIL-F-83300 values include some provision for gust disturbances, they are somewhat more lenient than those of AGARD which only account for maneuvering.

Characteristics of several fixed-wing jet V/STOL aircraft are presented at the right of Fig. 14, in terms of the alternate criteria. They include the prototype and current operational versions of the Harrier (Ref. 2 and 8), the VAK-191B (Ref. 15), the X-14A and B (Ref. 16 and 17), and the XV-5A (Ref. 2). These values represent maximum available control authority and do not have trim control extracted. With the exception of the AV-8A nose-down control, all the aircraft substantially exceed both requirements. The AV-8A nose-down capability is lower than the rest because it is determined for the case of maximum bleed in all axes, which reduces the maximum reaction control authority in the individual axes. Various values shown for the X-14A and B represent ranges of control authority that have been evaluated with that aircraft in its variable stability mode. All of these aircraft were considered to have marginal Level 1 or better control power in hover. The fact that all seem to have an excess is attributable to the requirement to trim under various hover and low-speed translational flight conditions and for various loadings. Thus this magnitude of control authority is not always available for maneuvering. With the exception of the AV-8A under maximum bleed, all the aircraft have total control authorities that agreed with the upper-level recommended in Ref. 2 to accommodate trim, counteract gust upsets, and to maneuver.. While it would be desirable to more clearly define the individual maneuver and turbulence control demands, credible experimental data are just now being acquired from ground-based simulation experiments and, potentially, from Harrier flight experience. In the absence of more definitive criteria, the recommendations of Refs. 2 and 3 stand as the best guides for maneuver control authority.

With the exception of the VAK-191B, all the example aircraft in Fig. 14 had pitch-control systems of the rate-command type. Some experimental evidence from ground-based simulation experiments suggests that maneuver and turbulence-suppression control authority may be reduced if attitude command and stabilization is provided by the flight control system. In Fig. 15, the influence of attitude stabilization on turbulence suppression is noted, both in terms of control utilization and attitude variations. Specifically, these are analytical predictions of the root-mean-square control activity and attitude variations in proportion to the rms gust disturbance magnitude for a range of attitude retention or stabilization control bandwidths. The gust environment represented in this analysis is a random horizontal component with frequency content up to 0.1 rad/sec, which is a reasonable approximation for this component of atmospheric turbulence. Attitude stabilization bandwidths above 1.0 rad/sec dramatically reduce attitude variations and also reduce to some extent the amount of control used to counter the gust upsets. At the right of the figure, the effect of attitude command systems on flying qualities level for aggressive quick-stop maneuvers is shown. For Level 1 flying qualities, the amount of control authority, expressed in terms of maximum angular acceleration, is approximately half that for the rate-command system. This reduction in control required is not so dramatic for Level 2 flying qualities, but it is still significant. These results were obtained from moving-base simulator experiments reported by Greif et al. (Ref. 18) and apply to optimized dynamic characteristics for each of the control systems. The piloting task included aggressive quick-stop maneuvers which produced a higher level of control demand than for the precision control requirements of Refs. 2 and 3. While the absolute magnitude of control for a given level of flying qualities to accomplish the task exceeds the AGARD criteria and the MIL specification of Refs. 2 and 3, the relative control demands for rate and attitude command systems may be correct. Current simulation and prospective future flight experiments are expected to provide information to verify this supposition.

Roll control authority in hover is the subject of Fig. 16. The table provides the AGARD criteria (Ref. 2) and the MIL specification (Ref. 3) results in the same form as for the pitch axis. Again, since the MIL specification values provide for some gust suppression, they are also more lenient than the AGARD criteria. At the right of the figure, characteristics of the same aircraft noted in the discussion of pitch control are presented. In all cases, they substantially exceed the Level 1 criteria, primarily because of the provision for countering rolling moment due to sideslip in low-speed translational flight, or, in the case of the X-14, for variable stability research purposes. With the exception of the lowest control power case for the X-14A, all these aircraft have Level 1 flying qualities for roll control in hover. The X-14A with 0.8 rad/sec^2 angular acceleration was rated to have only marginal Level 2 flying qualities for precision hover. All the other aircraft have control authorities that fall within the range of angular acceleration (0.8 to 2.0 rad/sec^2) that is suggested by the AGARD criteria for trim, upset, and maneuvering. Until more definitive experimental results are available, the criteria for roll control presented in Refs. 2 and 3 stand as the best guides for control authority in hover.

As in the case of pitch control, some prospect for reducing control authority requirements may be provided by attitude stabilization (Fig. 17). In Ref. 11, it was noted that the Do-31, which incorporated pitch and roll attitude stabilization, was considered to have satisfactory roll maneuvering capability in hover using a control power of 0.4 rad/sec^2.Results from Ref. 18 reveal fractions of attitude to rate command control to achieve Level 1 flying qualities that are similar to, results obtained for the pitch axis. These data also show the effect of turbulence magnitude on the level of flying qualities , and indicate that in comparison to rate command systems, attitude command systems provide the same level of flying qualities at approximately twice the level of gust disturbance. Rolling moments induced by turbulence that are one-third of the total roll control authority of the aircraft can be encountered while retaining Level 1 flying qualities. Although the absolute value of these roll control requirements are subject to further experimental verification, the influence of attitude control in reducing the total roll control demand is likely to be valid for maneuvering in hover and for suppressing the influence of turbulence.

Criteria for yaw control in hover are given in Fig. 18 for both the AGARD and the MIL specification documents (Refs. 2 and 3). In this case, the AGARD criteria are given in terms of the maximum angular acceleration or the time to achieve a 15° change in heading angle. The MIL specification, as before, refers to the attitude (heading) change achieved in 1 sec. The three criteria are reasonably self-consistent, assuming yaw damping that produces yaw rate time constants of 0.5 to 1.0 sec. Characteristics for the same example aircraft are shown at the right of the figure. With exception of the AV-8A under maximum bleed conditions, all these aircraft exceed Level 1 values for heading change in 1 sec and fall within the satisfactory range of angular acceleration capability suggested by AGARD. The two points for the X-14A represent the extremes of yaw control characteristics evaluated with the variable stability system. The X-14A (at its highest control power) and the AV-8A (single-axis bleed) are considered by pilots to have satisfactory yaw control characteristics in hover. The X-14A at its lowest control power was rated by pilots to be marginally adequate to inadequate for yaw control in hover; however, this assessment may have been due to a particularly low level of yaw damping for this configuration. With the damping increased to an acceptable level, this same control authority was felt to be adequate (Level 2) by the pilots. Most interesting is the fact that the VAK-191B, with its apparently quick response, was considered to have somewhat sluggish yaw control. This impression is in contrast to a more widely held view, expressed by Lacey (Ref. 8) and Hutchins (Ref. 19), among others, that the AGARD and MIL specification yaw control requirements are more stringent than necessary. It is more likely that the VAK-191B experience reflects a low control sensitivity rather than a deficiency in total control authority. When it is necessary to establish priority for control authority among the three axes, the requirement for yaw acceleration capability will ordinarily be less than for roll and pitch. As a final observation, all these values, with exception of the AV-8A at maximum bleed, fall within the range noted by AGARD to account for trim, gusts, and maneuvering.

Control utilization in heave for height control and stabilization in hover is presented in Fig. 19. For this control axis, both AGARD and the MIL specification cite criteria for minimum thrust-to-weight ratio. In addition, AGARD recommends a minimum steady climb rate, and both AGARD and the MIL specification note the same minimum incremental normal acceleration (though only the MIL value is shown in the table). The heave response characteristics shown in the table are not independent of other heave axis characteristics. Both AGARD and the MIL specification note a dependence of thrust/weight on the level of heave damping inherent in the airframe. This interaction is apparent in the boundary for satisfactory (Level 1) flying qualities at the right of the figure. The lower thrust/weight is considered satisfactory only for sufficient damping in the vertical axis. This trade-off is similar to the variation in control authority for the pitch and roll axes for rate and attitude command systems in the sense that increased damping, like attitude command, improves stability for that control axis. However, it is unlikely that little or no heave damping can be tolerated, no matter how large the thrust/weight. As Hoh and Ashkenas suggest (Ref. 20), a minimum tolerable heave damping on the order of -0.3 sec^{-1} will likely be imposed for height control. These implications on the dynamics of height control will be covered in a later section of this paper.

No aircraft configurations were included on Fig. 19 because of the wide variation in thrust/weight for a given aircraft, depending on it's loading condition. For the aircraft listed previously in the paper, a range of thrust/weight from 1.0 to 1.2, and heave damping from nearly zero to -0.3 sec^{-1} was covered. In no case could Level 1 flying qualities be obtained for a precision hover if thrust/weight was less than 1.05. According to Ref. 15, the VAK-191B was considered to have Level 2 flying qualities in hover for thrust/weight of 1.05. In cases in which these aircraft were hovered in calm air, heave damping less than -0.3 sec^{-1} could be tolerated while retaining satisfactory flying qualities. However, it should be emphasized that no significant ground effects or hot gas reingestion were encountered in these cases. The criteria are meant to provide height control capability in excess of heave forces imposed by ground effect of reingestion. Holzhauser (Ref. 11) comments that the Do-31 had unacceptable height control approaching the ground because of reingestion, even though its lift engines provided a hover height control reserve of 0.1 g. For nonprecision maneuvers such as takeoff, it may be adequate for incremental normal accelerations in excess of ground effect to be less than 0.05 g as suggested in Ref. 8. However, for tasks that require precise control, which are performed during a sustained hover near the ground, minimum thrust/weight of 1.05, and incremental normal acceleration of 0.1 g over that necessary to counter ground effects and reingestion of hot gasses is reasonable.

As the MIL specification (Ref. 3) states, the aircraft's control system must be capable of trimming the aircraft in a steady hover in the presence of a wind from the most critical direction, and hold sufficient control in reserve to meet the pitch, roll, yaw, and thrust control demands simultaneously. The wind magnitude most frequently cited for this requirement is 35 knots. This combined requirement for trim and maneuver is assumed to account for stabilization in the presence of gusts and does not require an additional control increment to be added to counteract gust upsets. Since the entire control capability in hover is derived from the propulsion system, either through direct use of thrust or through bleed air from the compressor, this combined control requirement is of serious concern to the designer. An example of the impact on a Level 1 flying qualities requirement for a conceptual design of a four-poster lift-cruise fan aircraft is cited by Shaw and Craig et al. in Ref. 21. The individual contributions to the aircraft's installed thrust/weight are reproduced from their paper at the right of Fig. 20. The combined requirement for trim and maneuver control for attitude and height is over 30% of thrust in excess of weight. To meet this requirement for vertical takeoff would seriously penalize the aircraft's range/payload performance. The thrust necessary to meet Level 2 flying qualities is not reduced substantially. Not all designs present a concern of such magnitude; however, any thrust held in reserve for control often reduce the aircraft's mission effectiveness, and, if excessive, could prevent it from proceeding beyond the design stage. However, the reserve thrust associated with the Level 1 requirement is available for meeting unforseen operational situations, particularly in adverse weather aboard ship, and may permit a V/STOL aircraft to operate routinely in these conditions for the first time.

Other options may be considered as a means for alleviating this substantial demand on the propulsion system for control. Short takeoff will unlikely impose a stringent demand for control reserve as does sustained hover in ground effect. If heavyweight takeoffs are performed with some ground roll, the vertical takeoff demand must no longer be met at those weights. Meeting the vertical landing requirement will be substantially easier on the propulsion design. Another option is to prioritize the axes for control demand and meet their individual needs accordingly. Hutchins comments (Ref. 19), and it is generally appreciated, that the yaw axis is less critical for control than roll or pitch, and may be treated accordingly. Roll is considered to have first priority, followed by pitch. The Harrier is a good example of a design that has successfully adopted the approach of shared reaction control demand. In that aircraft, an individual control axis has full authority, available when the aircraft is operating below maximum thrust and no other controls are activated. When the aircraft is at maximum thrust and more than one control is demanded, the demand is shared, with the least proportional reduction applied to roll, then to pitch and yaw in that order. Figure 21, taken from Fozard's case study of the Harrier design (Ref. 22), illustrates the time that compressor bleed flow exceeds a fraction of the total available. These characteristics were used to establish a time mean bleed for all three axes which would be provided without any reduction in gross thrust. For bleed demand exceeding this level, maximum thrust would be reduced rapidly as indicated at the right of the figure. In the case of maximum bleed, and for the normal lift dry condition, this penalty would be considerable. In fact, as momentary demands approach this level, transient disturbances would be introduced to other axes as their control was momentarily reduced. However, for operation at the extreme of the control envelope, this design approach has proven to allow the essential control demands to be met without unduly compromising control in other axes. This points out the need to reduce trim requirements, including those for crosswinds, to a minimum during the design phase.

3.2 Transition

Given the nature of maneuvers associated with transition control tasks in Section 2, the AGARD criteria and MIL specification attempt to ensure sufficient control margins as the aircraft accelerates or decelerates between wing-borne and fully propulsion-sustained flight, and to accommodate those maneuvers associated with precision flight at low airspeed. With regard to the latter objective, the AGARD criteria deal primarily with STOL operations and are based on a substantial body of data on powered-lift STOL operations contained in the report by Innis, Holzhauser, and Quigley on STOL aircraft airworthiness considerations (Ref. 23). Pitch axis concerns are related to the need to control either angle of attack, airspeed, or flightpath, and to counteract cross-coupling from thrust to thrust vector angle control activity. Roll control demands arise from the precise lateral flightpath control associated with a precision approach, from yaw to roll coupling during directional maneuvering, and from the need to counteract asymmetric thrust transients. Yaw control is required for de-crab maneuveres, to counteract roll-yaw cross-coupling during lateral maneuvers, and also to suppress asymmetric thrust transients. Flightpath control, obtained from whatever source is identified as the primary flightpath controller (thrust or thrust deflection, or even pitch control), is related to either precision or nonprecision approach and to the need for adequate climb and descent authority and normal acceleration to complete or abort the approach and to execute the landing flare, if required. Longitudinal (axial) acceleration, along with flightpath authority, defines the transition corridor and determines how quickly the aircraft can transit from powered-lift to wing-borne flight and how readily the transition can be arrested or reversed. Criteria for each of these controls will be covered in the following discussion.

AGARD criteria for pitch control during transition are of the same form as used for hover. The values shown in Fig. 22 for attitude change in 1 sec are identical to those for hover whereas the angular acceleration capability is slightly less. They are considered sufficient to accomplish speed or angle-of-attack control during takeoff and approach and to rotate the aircraft for takeoff and landing flare. U.S. Air Force STOL transport flying qualities requirements (Ref. 24) are consistent with the attitude change in 1 sec. The MIL specification (Ref. 3) takes the approach of requiring a 50% control margin in excess of trim through the transition envelope. This is a more general requirement, and, though somewhat arbitrary, has support among the designers. Examples of pitch control used for trim during transition for the AV-8A (Ref. 8) and VAK-191B (Ref. 25) are presented at the right of Fig. 22. At the high end of the transition range, the AV-8A uses somewhat more than half its longitudinal control for trim. Although the aircraft's control margins are considered to be adequate, they have been observed to be less than desired (Refs. 8 and 13), as would be anticipated given the MIL specification values. The VAK-191B longitudinal trim approaches 50% toward the upper end of its transition; however, its longitudinal control margins are considered to be adequate (Ref. 15). The AV-8B requires substantially less control to trim through transition than its predecessor, and it felt by pilots to have fully satisfactory pitch control margins.

AGARD roll control criteria are also of the same form as for hover. The range of angular acceleration shown in Fig. 23 is somewhat greater than for hover, whereas the attitude change in 1 sec remains the same. AGARD also adopts the MIL specification philosophy and includes a 50% control margin criteria to be applied for sideslips produced by full rudder authority. The MIL specification includes this 50% margin as an alternative, but introduces time to bank to 30^{o} as the primary requirement. The latter is an alternative to attitude change in 1 sec as a metric by which to judge roll maneuver capability. Both metrics account for the amount of control authority and for opposing moments produced by roll damping. The range of values contained in the MIL specification encompass aircraft ranging in size from fighter to heavy transports.

Data for angular acceleration and time to bank for recent STOL transport designs in the medium weight class are indicated at the right of the figure. The NASA/Boeing-deHavilland Augmentor Wing Research Aircraft (Ref. 26), the NASA/Boeing Quiet

Short-Haul Research Aircraft (Ref. 27), and the Breguet-941 (Ref. 28) all were determined to have satisfactory Level 1 roll control power and response. The STOL transport flying qualities requirements of Ref. 25 correspond to the upper range of the MIL specification values. The inset at the right of the figure provides data from the AV-8A (Ref. 9) and the VAK-191B (Ref. 25) to illustrate the control margin during sideslip at two speeds within the transition. At 100 knots, both aircraft have lateral control requirements that are extremely sensitive to sideslip and both are considered to have inadequate control remaining during uncoordinated flight (Refs. 8 and 15). The AV-8B, by contrast, has substantially less effective dihedral during transition and its lateral control margins are twice those of the AV-8A (Ref .9).

Yaw control criteria are of the same form as for hover, and include the 50% control margin as an alternate requirement for the MIL specification. AGARD values shown in Fig. 24 are less than stated for hover, reflecting less of a demand for rapid heading change during a landing decrab than during the hover maneuvering. MIL specification values are the same in both cases. Two examples of yaw response for STOL aircraft are provided at the right of the figure. Both the Breguet-941 (Ref. 28) and the Augmentor Wing Research Aircraft (Ref. 26) meet the AGARD criteria; however, the Breguet-941 would fall somewhat short of the MIL Level 1 requirement. Specific pilot evaluations were not obtained for either aircraft, although no objections have been raised concerning their yaw response.

Flightpath control authority is specified by AGARD in terms of steady climb and descent capability at the selected approach condition and the incremental normal acceleration that can be generated. In Fig. 25, the 6° climb capability was derived by analogy from FAA operational requirements for multiengine transport aircraft, and was intended to permit the approach to be aborted without resort to changing the aircraft's configuration. Descent capability below the intended approach path is specified to permit control authority for flightpath tracking. Recently, the FAA and NASA have developed tentative powered-lift airworthiness criteria (Ref. 29) from extensive moving-base simulation experiments to evaluate a variety of STOL aircraft characteristics. These criteria suggest that enough flightpath control be available to achieve level flight with no configuration change, and to descend to 4° below the nominal approach path. The diagram at the right of the figure illustrates the most recent criteria. The ability to achieve level flight without changing configuration was felt to be sufficient to permit the pilot to discontinue the approach, and that a configuration change would be permissible for initiating the subsequent climb. This proposal imposes less demand on excess thrust than does the AGARD criteria, and it is believed to offer adequate safety for operations. The FAA criteria include a greater descent capability than is suggested by AGARD because of results from the simulation program that indicated the need for 4° incremental descent authority for control to the approach path in moderate turbulence. The AGARD requirement was based on flight data that were obtained under essentially calm air conditions. These proposals await further substantiation from flight experience. It should be noted that the descent condition should not violate safe angle-of-attack or airspeed margins described in Ref. 29.

Longitudinal acceleration capability during transition is specified in Fig. 26. Both the AGARD and MIL specification cite the need to accelerate and decelerate rapidly and continuously through transition, and to easily reverse the direction of the transition. AGARD suggests 0.5 g to be a desirable capability. This criterion is largely subjective and it is only possible to cite good and bad experiences in support of this conjecture. The example at the right of the figure is the corridor of the XV-15 tilt rotor, and it represents a very generous transition maneuver capability (Ref. 30). The aircraft accelerates and decelerates well within the envelope, and the pilot is not required to observe a precise conversion schedule. The various models of the Harrier also provide excellent acceleration authority during transition. Capability exceeding 0.5 g has been achieved for these aircraft. The X-22A, whose envelope was given as an example in Fig. 9 also has good acceleration and deceleration capability. The VAK-191B could accelerate at about 0.5 g during the low-speed end of its envelope; however, this capability diminished to nil at higher transition speeds and was considered objectional to the pilot (Ref. 15). Deceleration authority was of no concern. The XV-5A had a limited acceleration capability in transition due to limited thrust, a complex angle-of-attack schedule, and a slow thrust deflection rate (Refs. 1 and 2). Accelerations of 0.13 g were observed during operational experience. Based on these examples, and the body of data on which the AGARD and MIL specification rest, it is possible to say that 0.5 g acceleration and deceleration capability will assure good transition control authority. If this authority is as low as 0.1 g, it will clearly be inadequate. Where the capability to assure adequate acceleration authority lies must be determined more definitively.

3.3 Combat Maneuvering

It is not the intent of this section to discuss requirements for combat maneuvering of V/STOL aircraft, but rather to note some of the favorable contributions that features of a V/STOL configuration may provide in this regard. Quantitative results are not available in the open literature; however, selected references cite advantages of thrust vectoring in qualitative terms that relate to deceleration and reacceleration, turn rate, weapons pointing, and controllability at low airspeed (Refs. 12, 31, and 32). More definitive information is available in the classified literature. Hooper (Ref. 12) notes the approximate magnitude of the expansion of the acceleration capability due to thrust vectoring. In his acceleration vector envelope, which is reproduced at the left of Fig. 27, a great increase in deceleration potential is indicated, and, given a basic 8 g airframe, approximately a 15% increase in normal acceleration is realized. This capability converts to maneuver performance in the proportions shown at the right of the figure. Full thrust vectoring produces modest fractional increments in turn rate in the combat flight envelope and substantial reductions in time to decelerate or to force an overshoot by an opponent. This capability is available to the pilot essentially as fast as the cockpit control can be manipulated. No time delays of the order required to change thrust or change the aircraft's attitude are required. The use of the deceleration capability is not without its penalties, since it implies a reduction in the aircraft's energy state. It is a capability to be used with discretion, depending on the adversary or adversaries' relative aspect and energy, and is not to be used indiscriminately. Nevertheless, it is an option that may be inherent in some V/STOL aircraft that may be used to advantage against a conventionally equipped opponent.

Another aspect of V/STOL design that may be of value is the ability of some concepts to use the thrust vector to generate moments for rotation of the aircraft to attitudes that could not be sustained by purely aerodynamic controls. Figure 28 illustrates this feature qualitatively for either pitch or yaw control in relation to angle of attack. Trends of the aerodynamic moments with increasing angle of attack as shown in the figure are typical of advanced fighter designs. The proportion of thrust vector moment to that of the aerodynamic control at low angle-of-attack is also reasonably well established. The advantage in ability to rapidly rotate the aircraft in pitch and yaw over a wide range of attitudes of the thrust vectoring VSTOL aircraft over a conventional adversary is clear. Although the contribution of reaction controls to moment generation are not shown for comparison, they have been found to provide similar benefits at lower airspeeds (Ref. 33).

4. V/STOL CONTROL ARRANGEMENTS

With the background of requirements for control forces and moments to achieve maneuver capability that has been discussed earlier in the paper, this section will provide examples of the approaches to control system design for an existing V/STOL aircraft and for several conceptual V/STOL configurations. To focus the discussion, these aircraft will be associated with one of two groups: fighter-attack or subsonic multimission configurations. Although this grouping is somewhat arbitrary, it recognizes that fighter-attack aircraft obtain most, if not all, of their control moments through bleed reaction controls, and that the multimission configurations achieve most of their moment control through redistribution of thrust among the various force generators. The grouping is not intended to infer superior capability for either approach to control design. A general description of these configurations is presented in Nelms' paper in this lecture series (Ref. 34).

4.1 Fighter-Attack Configuration

It is appropriate that the first example deals with the only operational jet V/STOL fighter-attack aircraft, the AV-8 and GR MK series Harriers, originally designed by Hawker Aircraft and most recently modified in design and produced by British Aerospace and McDonnell-Douglas. This aircraft, shown in Fig. 29, relies on high-pressure compressor bleed for reaction controls as well as conventional stabilator (tailplane), ailerons, and rudder for pitch, roll, and yaw moment generation. Bleed flow for the reaction controls is fully selected when the Pegasus engine nozzles are deflected beyond 20°. The reaction controls, along with thrust modulation and thrust deflection, produce control required for hovering flight. During transition, both reaction and aerodynamic controls are effective. In conventional flight, with the Pegasus nozzles undeflected, bleed flow to the reaction controls is shut off and pitch, roll, and yaw control is provided only by the aerodynamic surfaces (Refs. 9 and 22).

The reaction control system uses variable shutter valves located at the extremities of the airframe and which are supplied bleed air on demand. Pitch control is produced through downward exhausting valves in the nose and tail extension. Roll control is provided by valves in the wing tips that thrust either up or down. Yaw control is derived from a single valve in the tail extension. Bleed flow demand is scheduled such that any single axis can achieve its full bleed authority, and that combinations of axes receive proportionally less than their full capacity based on a priority of roll/pitch/yaw. Reaction control does not begin to reduce maximum available thrust from the engine until the level of bleed exceeds 50% of full authority. When water injection is selected, or short lift ratings are used, maximum rated thrust is sustained at higher bleed levels.

Height control in hover is obtained by modulating engine thrust. Longitudinal translation can be performed either by rotating the Pegasus nozzles fore or aft of the hover setting, or by rotating the aircraft in pitch. During transition, flightpath and longitudinal acceleration are controlled by a combination of thrust modulation and deflection. In forward flight, the aerodynamic controls are used conventionally to maneuver the aircraft. Thrust vectoring may be employed to augment turn capability, generate rapid deceleration and reacceleration, and to assist the stabilator in rotating the fuselage in pitch. In its later designs, the Harrier's longitudinal and lateral control margins during transition have been improved considerably. Both longitudinal trim and effective dihedral have been reduced to permit more of the respective controls to be available for maneuvering.

A conceptual design of a single-engine supersonic, V/STOL fighter/attack aircraft of the deflected-thrust class like the Harrier is reviewed next. This configuration is shown in Fig. 30, and, similar to the Harrier, it incorporates a combination of bleed reaction and aerodynamic controls. Reaction control valves are placed in the same locations as for the Harrier and, with exception of the rear pitch valve, the valves exhaust bleed air in a similar manner. The rear pitch valve exhausts up as well as down. Aerodynamic surfaces include canards, trailing edge flaps, ailerons, and a rudder. Two additional means of control are provided during hover and transition to relieve pitch trim demands on the reaction control system. Differential thrust modulation between the front fan stream burning nozzles and the aft core flow nozzles provides pitch trim in hover. During transition, differential deflection of the front and rear nozzles affords similar trim capability. Engine sizing allows approximately 10% of thrust for control and 5% for ground effect and reingestion during heavy-weight vertical takeoff. The control allowance is increased 4.8% for landing. Reaction controls were sized to meet maximum simultaneous control demands at the vertical takeoff weight and provided the following angular acceleration for each axis: pitch = +0.33, -0.21 rad/sec^2; roll = 0.32 rad/sec^2; yaw = 0.21 rad/sec^2. Maximum single axis capabilities that result from this design are: pitch = +0.7, -0.56 rad/sec^2; roll = 1.35 rad/sec^2; yaw = 0.44 rad/sec^2. This configuration is described in more detail in Ref. 35.

Another supersonic fighter concept that uses a wing-root chordwise ejector for V/STOL capability is shown in Fig. 31. In hover, all moment control is derived from reaction controls arrayed at the wing tips, under the cockpit, and in the tail. The wing tip and cockpit control valves exhaust downward only for pitch and roll control. The tail valves exhaust laterally for yaw control. These controls were sized in accord with the AGARD criteria of Ref. 2 and the MIL specification (Ref. 3). In conventional flight, elevons are used for pitch and roll control and a rudder is used for yaw. While in hover, engine thrust modulation provides height control and attitude rotations are used to translate the aircraft horizontally. During transition, flightpath and longitudinal acceleration are controlled through a combination of thrust modulation, deflection of the core flow, and diversion of fan air from the ejector to the aft nozzle. Engine sizing allows approximately 6% thrust margin at the maximum vertical takeoff weight. A more complete discussion of this concept is provided in Ref. 36.

The other fighter concept to be discussed in this section is based on the tandem-fan propulsion arrangement described in Ref. 37 and shown in Fig. 32. During hover, this concept produces pitch control by differential modulation of thrust between the forward fan and rear fan and core exhaust using variable inlet guide vanes at the fore and aft fans. Yaw control is produced by differential deflection of the exit flaps at the front nozzle and the deflector vanes in the aft nozzle. Height control is achieved through thrust modulation. A demand-bleed reaction-control system feeds valves at the wing tips which exhaust up and down for roll control. In conventional flight, pitch control is produced by a blend of canard and elevons, and a blend of elevons, fore and aft ventral fins, and the vertical fin may be used to generate roll and yaw moments as well as side forces. During transition, thrust modulation and thrust deflection through the forward fan and the aft core and fan exits provide control of flightpath and longitudinal acceleration. At the preliminary design stage, single-axis control powers in hover are marginally satisfactory by MIL specification standards. The thrust margin for maximum vertical takeoff weights is 17%.

Other single-engine fighter concepts noted in Nelms' paper (Ref. 34) may employ different propulsion system arrangements than have been discussed here. The remote augmented lift system shown in Fig. 33 is one that may afford some of the longitudinal control flexibility in hover that was shown for the deflected thrust with fan stream burning and the tandem fan. However, other characteristics of aircraft designs associated with this propulsion system are likely to include those of bleed reaction control discussed previously. They will not be dwelt upon further at this point.

4.2 Subsonic Multimission Configurations

During the U.S. Navy Type A V/STOL concept definition phase, several lift/cruise fan designs were presented for consideration. An example of one of these configurations is provided in Fig. 34. Both gas-coupled and shaft-coupled versions of twin-engine, three-fan aircraft were defined that made use of differential and vectored thrust from each of the fans to produce pitch, roll, and yaw control moments in hover. Symmetric deflection of the fan thrust fore and aft or to either side could be used to generate longitudinal and lateral forces for horizontal translation. Collective control of thrust provided height control. Either variable fan pitch or variable-inlet guide vanes were used to permit rapid modulation of thrust for these control purposes. For transition, the combination of thrust modulation and deflection from all of the fans was used for climb, descent, and acceleration. Control authorities for V/STOL operations were designed to the AGARD and MIL specifications. A description of a typical control design for this configuration is given in Ref. 38.

Another of the lift/cruise fan designs that has attracted considerable attention recently is the twin-tilt-nacelle aircraft. Its control arrangement is presented in Fig. 35 and is distinguished by a set of control vanes located in the engine exhaust flow. These vanes are used to produce pitch, roll, and yaw moments as illustrated in the figure. In generating pitch and roll moments, the vanes also produce forces that would translate the aircraft in the opposite direction intended by the pitch or roll rotation. To compensate for this undesirable characteristic, nacelle tilt and differential thrust modulation with variable-inlet guide vanes act to permit independent control of these forces and moments. Wind tunnel tests (Ref. 39) indicate that the vanes have sufficient effectiveness for trim and maneuvering during hover and transition. Ground-based simulations are being conducted to refine the control design and to confirm the effectiveness of the pitch and roll control blending described above (Ref. 40).

5. BASIC AIRCRAFT STABILITY AND CONTROL

With an understanding of the control authority necessary to accomplish maneuvers associated with V/STOL operations, attention can be given to the influence of basic aircraft stability and control on the pilot's ability to perform specific flight tasks. The low inherent static and dynamic stability at low airspeed, control cross-coupling, and sensitivity to disturbances are all significant influences on the precision of control that the pilot can achieve and the effort that must be devoted to control undesired responses due to poor stability, unwanted coupling, and external disturbances. These characteristics are reviewed in this section as are specific control requirements for height and translational velocity control in hover, and flightpath and airspeed control in transition. Before these characteristics are discussed, it is useful to review the contribution of lift and drag to aircraft controllability at low airspeed. The influence of lift and drag on performance is primary; however, it is also important to appreciate their significance to stability and control at low speed.

5.1 Influence of Lift and Drag on Low-Speed Control

The relationship of steady-state flightpath and airspeed to the lift-drag polar of an aircraft is well understood. Figure 36 provides an illustration of the mapping of a polar for a representative jet V/STOL aircraft into the flightpath-airspeed plane that is appropriate for operationally assessing performance and control. The polars are functions of angle of attack and the equivalent jet velocity ratio for a thrust vector deflection of 55^{o}. Flightpath-airspeed curves at the right of the figure are shown for a representative range of thrust settings and have lines of constant-pitch attitude superimposed. From the path-speed plot, it is possible to determine some of the factors of importance to precision control during the low-speed transition. For example, once the operating flight condition is located, the local gradients of flightpath and airspeed for variations in thrust and attitude control will determine the appropriate control technique that the pilot must use and will establish the steady-state control coupling at this condition. The variation of flightpath angle with airspeed at constant rpm is an indication of whether the aircraft is operating on the front or backside of the drag curve (or thrust or power required curve). Negative gradients represent frontside and positive gradients denote backside conditions. This characteristic has a bearing on whether thrust (rpm) or attitude will be the primary flightpath control. Typically, thrust is used as the primary path control for backside operations whereas attitude is frequently used to control flightpath on the frontside. The delineation between these regions occurs at the peak of the path-speed curve; however, the transition between control techniques is also dependent to a great extent on dynamic response characteristics of the two controls. Gradients of flightpath and airspeed with their respective controls establishes control sensitivity. Cross-coupling is represented by the gradient of either path or speed with the opposite controller. For example, the variation of speed with thrust at constant attitude defines speed cross-coupling when thrust is the primary flightpath control. The cross-coupling illustrated in the figure is conventional and is not objectionable to pilots. Coupling of the opposite sense (speed decrease for an increase in thrust) is of concern for low speed operations and generally leads to poor flying qualities (Refs. 24, 41, and 42).

Influences of lift and drag on flightpath and airspeed dynamic response are indicated in Fig. 37. Characteristics of interest are the initial flightpath time response, the relationship of steady-state to short-term path response to thrust, and the variation of airspeed with flightpath response to thrust. Initial flightpath response is related to the control sensitivity of normal acceleration to thrust and the heave damping that is determined by the incremental normal acceleration due to change in angle of attack. Relation of long-term to short-term flightpath response is defined by flightpath overshoot ratio. As the diagram at the right of the figure indicates, this overshoot is aggravated by deflection of the thrust vector beyond angles of $70\text{-}75^{o}$. A summary of flight and simulation data in Ref. 42 suggests that overshoot ratios should not exceed 2.5 to maintain at least adequate flying qualities (Level 2) for performing a precision instrument approach. Coupling of speed with flightpath response is also sensitive to thrust deflection angle, and changes from a conventional (favorable) to an adverse sense when thrust deflection exceeds the ratio expressed in the relationship at the bottom of the figure. This ratio is a function of lift curve slope, speed, wing loading, and induced drag. The thrust deflection angle for the approach can be chosen considering these interrelationships to minimize coupling of speed to flightpath.

In hover, the influence of lift-drag aerodynamics on controllability becomes more subdued for a high-density V/STOL configuration; these aerodynamics are also influenced to a great extent by propulsion-induced flows. Although it is possible to see some effect on the dynamics of translational motions attributed to aerodynamic forces, the time constants of the translational aerodynamic damping in the respective axes are generally too long to be acceptable for control of height or horizontal position. Illustrations of these dynamic response relationships to the thrust and attitude controls in Fig. 38 indicate the disparity in time between the propulsion and attitude response and the translational motions they are intended to command.

From these few examples, it is possible to appreciate the effect that propulsion-induced aerodynamics, or the lack thereof, have on V/STOL control. They are an indication of the extent to which the aircraft's flying qualities are determined by performance design for V/STOL operation.

5.2 Stability at Hover and Low Speed

To consider stability of the aircraft in hover, it is helpful to review an example of the hover equations of motion and some typical control response relationships that may be derived from them. An example is presented in Fig. 39 for the longitudinal motions of the aircraft. These are in the form of linear differential equations for the axial, vertical, and pitch rotational degrees of freedom and assume small perturbation motions that are decoupled from the lateral and directional motions by virtue of symmetry and uncoupled aerodynamics. Aerodynamic and propulsion-induced forces and moments are included that provide translational and angular velocity damping and pitching moment due to longitudinal translational velocity. Control inputs from thrust and pitch controls provide vertical force and pitching moment and are decoupled from the rest of the axes. In fact, vertical response is entirely decoupled from the pitch and axial motion of the aircraft in this example.

These equations yield characteristic roots that consist of a third-order set that represents the coupled pitch and axial velocity motions, and an uncoupled aperiodic mode that describes the vertical velocity response.

The third-order set typically factors into an aperiodic root and a complex pair, of roots, the latter of which may or may not be stable. The two aperiodic roots generally are stable, although they may have long time constants as a consequence of low axial and vertical velocity damping. Control response relationships are shown at the bottom left of the figure. When appropriate cancelling of numerator and denominator factors is done, it may be seen that height control is second order, pitch attitude control is third order and axial position control is fourth order.

The significance of the order of response to the controls may be more evident if the simplified example at the right of the figure, which neglects aerodynamics entirely, is considered. When the pilot's pitch control applies a pure moment as shown here, the eventual pitch attitude change occurs solely as a result of two integrations of the control input. The axial degree of freedom is still coupled to pitch and, similarly, in the absence of aerodynamic forces, change in axial position is a result of two integrations of the change in pitch attitude. Hence, the fourth-order relationship of the pitch control to axial position means that the pilot must control the intended response of the aircraft through four integrations. In addition, height control must be accomplished through two integrations of the thrust controller. Even if the simplifying assumption is not taken and aerodynamic contributions are included, the resulting stabilizing forces and moments are generally so weak in hover that the pilot observes the control response to be the same as if the aerodynamic effects were neglected.

The significance of control through an integration is that the pilot must anticipate the time to apply and remove the control input to achieve the intended response. A considerable body of literature has shown that a human controller can easily operate through one integration; the response to control application appears as a rate of motion which may be stopped at the desired value when the control input is removed. Little mental or physical effort is required to accomplish this control task. For each subsequent integration, the control effort increases substantially. Figure 40, inspired by a similar example from Ref. 43, provides an example of the control activity the pilot must expend to accomplish a change in position with control characteristics typical of early V/STOL aircraft. Eight control inputs and reversals are required to initiate and establish the change in aircraft position for the situation in which the pilot's control commands pitch angular acceleration. If the control commanded pitch rate instead, the number of control applications and reversals would be halved. For an attitude command, only two inputs and reversals would be required. If the pilot were provided the luxury of translational rate command (returning to the simple rate command example), a single input and reversal would accomplish the task. Hopefully, this example provides an indication of the difficulty a pilot encounters in controlling and stabilizing a hovering aircraft. It should also illustrate the reduction in effort the pilot expends for this control task for some of the higher levels of control augmentation such as attitude and translational rate control. That subject will be covered in more detail in a later section of the paper.

The conclusion should not be drawn that it is impossible to hover an aircraft that has little or no inherent aerodynamic stability or damping. As noted in Ref. 1, numerous aircraft were flown with only inherent rate damping. As shown at the left of Fig. 41, the MIL specification (Ref. 3) allows a slight dynamic instability at low frequency for Level 1 flying qualities in visual flight conditions and accepts exponential divergences of time to double amplitude greater than 12 sec for Level 2 VFR. For instrument operations, Level 2 requirements are equivalent to Level 1 for VFR. It is possible for a well trained pilot to hover an unstable aircraft when full visual and motion cues are available, although considerable effort may be expended in the process. However, as visual cues degrade and when external disturbances are imposed on the aircraft, the benefits of good stability and control response are appreciated. Many of the results on which this specification is based were obtained in fully visual flight in calm air and with a great deal of freedom to maneuver the aircraft. They do not reflect the more challenging operational requirements imposed by a shipboard environment.

Basic static and dynamic stability that may characterize a number of fixed-wing V/STOL configurations is illustrated at the right of Fig. 41. The aircraft's characteristic roots are stable when axial and angular velocity damping are positive and pitching moments due to forward speed (an inlet momentum contribution) are neglected. Increasingly positive pitching moment with forward speed destabilizes the aircraft and may eventually lead to a low-frequency oscillatory instability of the type restricted by the MIL specification at the left of the figure. As Ref. 8 indicates, the AV-8A dynamic stability at low airspeed does not meet Level 2 flying qualities requirements of the MIL specification because of a rapid pitch divergence. While these characteristics were considered to be adequate for visual flight, they are inadequate for operation in poor visibility at low speed or for operation aboard ship in strong winds and heavy seas (Refs. 13 and 44). Because of low dynamic pressures and the dominance of propulsion-induced flows at low speed, it is unlikely that the basic airframe can be endowed with sufficient inherent stability to provide precision flying qualities in hover and low speed. In most cases, the stability augmentation system must be used to achieve the desired stability for precise control in this portion of the flight envelope.

5.3 Cross-Coupling

Coupling of response to the pilot's controls that produces undesired motion of the aircraft is detrimental to flying qualities for precision tasks. Coupling of this nature may occur as a consequence of aerodynamic characteristics, control effector arrangement, propulsion system geometry, or gyroscopic effects. An example of aerodynamic influence on the coupling of flightpath and airspeed response was cited previously in this section. Other examples are shown in Fig. 42 for hover and transition, and are taken from simulation time histories of the AV-8A with its basic stability augmentation system operating. At the left of the figure, the response to a step increment in rpm in hover shows the coupling into the pitch axis that arises from pitching moments due to thrust. The same sort of influence can be seen in the response to a step change in nozzle during transition. While this control input had the intended effect on airspeed response, both pitch attitude and flightpath angle were also changed to a substantial extent. At the right of the figure, the familiar coupling of roll to yaw that requires a large portion of the lateral control to hold bank angle for a steady heading during moderate sideslips is noted. These are three frequently encountered examples of cross-coupling that force the pilot to direct attention away from the primary control task to counter unintended responses in other axes. When they are of sufficient magnitude, such as the roll-yaw example, they degrade flying qualities and may leave the aircraft unacceptable for operation other than day, VFR, calm air conditions. Except for coupling due to lateral control yawing moments, the AGARD and MIL criteria are not particularly definitive on this subject. Suffice to say, the designer should attempt to minimize undesired coupling in the basic configuration. When that is not possible, control augmentation must be used to achieve satisfactory characteristics.

5.4 External Disturbances

External disturbances imposed by winds and turbulent air wakes, ground effect, and ingestion of hot propulsion gases are another source of unwanted response that affect precision control tasks. The example provided in Section 3 of control response in the turbulent wake behind a ship's superstructure represents a situation in which it is difficult to maintain the desired hover control precision. For precision approaches at slow speed, wind gradients may be a cause of large and rapid excursions in flightpath (Refs. 42 and 45). Figure 43 presents the results of a simple analysis to compare the flightpath and speed response of conventional and powered-lift STOL aircraft when encountering wind shear. For this example, pitch attitude is assumed to be constant. As indicated in the equation at the top of the figure (from Ref. 42), flightpath response is composed of an increment required to counter the inertial acceleration due to the shear and an increment associated with the change in lift-drag ratio with the variation in airspeed. For a typical STOL aircraft that operates on the backside of the drag curve, the magnitude of the flightpath perturbation for a given wind gradient is two-thirds larger than for its conventional counterpart. Furthermore, the disturbance is fully developed for the STOL aircraft in half the time associated with the CTOL aircraft. The comparison is intended to emphasize the concern for low speed operation in these wind environments under circumstances in which the pilot may have insufficient information concerning the aircraft's situation during the approach, or may be distracted by secondary tasks that prevent prompt control action to counter this disturbance. There are few choices in the basic airframe design for reducing any of these disturbances imposed by air wakes, gusts, and wind shears. If the control augmentation system is incapable of suppressing these disturbances, operational restrictions must be based on the severity of the environment.

Forces and moments imposed on the airframe by propulsion-induced flows in proximity to the ground create considerable difficulty for control in hover during landing. The report by Henderson, Clark, and Walters (Ref. 46) provides a concise description of the contributions to these disturbances, including configuration influences on suck-down or buoyancy and on destabilizing pitch and roll moments. The arrangement of the jet exhausts and the contouring of the lower surface of the airframe are particularly important. Because of the influence of height above the deck, jet velocity, and pitching and rolling motions of the aircraft relative to the landing pad, it is possible for the pilot's control application to couple with the upsetting forces and moments and to seriously degrade controllability. For this reason, it is important for the designer to give consideration in the definition of features of the configuration that help to minimize unfavorable interactions.

5.5 Hover Control

After reviewing the character of stability of motion in hover and low speed and the nature of uncommanded motions of the aircraft, the features of the primary, or intended, response to the pilot's controls may now be considered. The example time response of thrust and vertical velocity to the pilot's power lever is repeated from Fig. 38 at the right of Fig. 44. This response is characterized by the initial lag in thrust response to the power lever input, and by the time lag in vertical velocity response to thrust. Thrust response lag is inherent in the acceleration and dynamic response of the fan and core flow of the propulsion system and its associated force generators. For a powered-lift aircraft, basic design philosophy dictates that dynamic response of forces and moments produced by the propulsion unit meet the same requirements as primary flight control. For height control, the MIL specification (Ref. 3) indicates that the force producer respond with an effective first-order time constant of 0.3 sec to achieve Level 1 flying qualities. This requirement, and that for Level 2, is shown at the left of the figure. AGARD criteria suggest that this time constant should be less than 0.5 sec. The subsequent vertical velocity time constant of the airframe is dominated by vertical velocity damping. An approximate representation of this damping shows the influence of the normal force coefficient, the dynamic pressure of the local flow, and the aircraft loading condition. A crude approximation of this term would indicate that it is inversely proportional to the square root of disk loading. For compact aircraft such as jet fighters, this level of damping converts to time constants of 10-30 sec. Recall from Fig. 19 that levels of damping of -0.3 sec^{-1} or greater were recommended. That level converts to time constants of approximately 3 sec or less as is shown in Fig. 44. The lines of time to reach 50% of the maximum vertical velocity that are superimposed on the plot at the left show that the combination of the thrust and vertical velocity time constant criteria yield vertical velocity rise times between 2.5 and 3 sec. These values are in reasonable agreement with the 3-sec rise time recommended by the powered-lift STOL airworthiness criteria (Ref. 29) as minimally acceptable for precision instrument approach path control. It would appear unlikely that this criteria could be met by most fixed-wing V/STOL aircraft considering their high disk loadings. Thus, this class of aircraft must rely on height control augmentation to achieve acceptable response for precision height control. Additional criteria for thrust time response for height control of aircraft with lift-cruise propulsion systems are given in Ref. 47.

Translational velocity control for hover positioning may be accomplished either through control of aircraft attitude, as discussed at length at the beginning of this section, or may be performed by deflecting the thrust vector about the vertical. Given the lack of stability of the basic airframe for hover control, this is a difficult task when it is performed using attitude control. Even if some level of stability is provided by an attitude rate or attitude command control, the low axial velocity damping means that translational velocity time constants will be long and that the pilot will have difficulty in establishing steady translational rates. This response characteristic is seen at the left of Fig. 45. If the translation is to be performed by thrust vector control, the response is still governed by the axial velocity damping and associated time constant. The advantage of this mode of control is that the dynamics of attitude control are circumvented. However, any pitching moment changes associated with thrust vector angle will disturb the aircraft's attitude and cause the pilot to devote some attention to attitude control. Requirements for translational velocity control do not exist in either the AGARD criteria or the MIL specification. Tentative criteria have recently been developed for this mode of control and will be reviewed in a following section on control augmentation.

5.6 Transition Control

The major concerns for control during transition relate to changing the aircraft configuration and the precision control of flightpath and airspeed within this flight regime. The issue of flightpath and longitudinal acceleration control authority during transition, covered previously in this paper, determines the ability to achieve a range of operating conditions or to transit this part of the flight envelope. The acceptability of control during transition is dependent, in part, on the number of controls the pilot must manipulate and the difficulty of procedures required to change the aircraft control configuration from one that is appropriate for wing-borne flight to one that is suitable for the powered-lift regime (Ref. 48). The transition envelope at the left of Fig. 46 illustrates the selection of thrust setting and thrust vector angle to establish a descending approach condition. To perform this control task for the Harrier, the pilot uses the throttle and nozzle control levers on the throttle quadrant shown in Fig. 47. The manipulation of two controls to accomplish this configuration selection is acceptable so long as the transition profile is not demanding. If the profile is complicated, such as a continuous deceleration on a precise flightpath under instrument conditions, then the continuous and precise manipulation of these two controllers could become an objectionable task for the pilot. If, as for some designs, the pilot has redundant controls for flaps, thrust vector angle, lift and cruise engine thrust, the complexity of the control task becomes insurmountable for all except the most simple transition profiles. Thus a tradeoff is made between operational demands and control complexity.

As shown in Fig. 46, the control of flightpath and airspeed for the example shown is partioned for thrust and pitch attitude. With attitude held constant, flightpath responds to thrust with the characteristics described in Fig. 37. When thrust is fixed, airspeed control with attitude is accomplished as shown at the right of Fig. 46. For airspeed control, the steady speed change per degree of attitude is the significant feature. Flightpath will also respond to the attitude change with a short-term response determined by the aircraft's normal acceleration sensitivity to angle of attack. The long-term response as shown is indicative of operation on the backside of the drag curve, and the reversal between short-term and steady-state response is a primary reason pitch attitude is not used to control flightpath under these conditions. As discussed in Section 5.1, these flightpath and airspeed control characteristics are established primarily by the propulsion-induced flow effects on lift and drag in low-speed flight. Assuming that there is little flexibility for altering the lift and drag of the basic configuration for control purposes, it remains to use the control system to modulate lift and drag so as to produce response consistent with good flying qualities.

6. STABILITY AND CONTROL AUGMENTATION SYSTEMS

As noted throughout the previous section, deficiencies in the low-speed flying qualities of V/STOL aircraft require the use of the flight-control system to improve the precision of control, reduce the effort the pilot must devote to control of the aircraft during hover and transition, and desensitize the aircraft to external disturbances. Over the past 15 to 20 years, several experimental V/STOL aircraft have used stability and control augmentation systems of varying degrees of complexity and have demonstrated their benefits in flight. The Harrier prototype P-1127 started with a simple rate-damping system which was eliminated from the Kestrel development prototype. However, the poor flying qualities of the Kestrel for precision instrument flight and for operations aboard ship led to the installation of an improved system in the first operational versions of the aircraft (GR MK 1 and AV-8A). Substantial improvements to that system have been incorporated in the Sea Harrier and the AV-8B (Refs. 9 and 22). The AGARD advisory report on displays for approach and landing of V/STOL aircraft (Ref 49) summarized the anticipated requirements for stability and control augmentation and the necessity for an integrated control and cockpit display design approach for aircraft of this class to operate in adverse weather. Figure 48, taken from Ref. 49, illustrates the importance of the interaction of augmented controls and displays with the aircraft's flying qualities for precision instrument flight tasks. Since that report was published in 1972, several research programs have been conducted that have helped to quantify the contribution of control augmentation and displays to flying qualities for these precision operations. This section provides a review of this research and the operational experience obtained over that period.

6.1 Conventional Stability Augmentation

To alleviate some of the deficiencies in flying qualities of the basic aircraft, stability augmentation concepts have been adapted from conventional military fighter aircraft. Pitch, roll, and yaw rate dampers have been used for this purpose, and turn coordination logic has also been included in the yaw axis control. Control-force-feel systems have been used to produce effective "control free" stability at low speed and in transonic flight.

A simple illustration of the characteristics of a rate-damping stability augmentor is provided in Fig. 49. The example shown is for a roll damper that in concept consists of feedback of roll rate from a rate gyro, and feed forward of control position or force from an appropriate control sensor. Although an actual system would incorporate additional filters and gain scheduling, the diagram at the top left of the figure captures the essential design features of the system. The roll equation of motion derived from this simplified diagram is shown below. Any angular rate damping or control sensitivity inherent in the airframe would be included in the appropriate constants in this equation. A time history of roll rate response to a step control input shows that the initial response is proportional to control sensitivity, the response time constant is inversely proportional to the inherent and artificially supplied damping, and the steady- state response depends on the ratio of control sensitivity to damping constants. These characteristics are sufficient to define design criteria for a rate damping augmentation system, and both the AGARD criteria and MIL specifications (Refs. 2 and 3) are shown as examples at the right of the figure. AGARD notes the desired damping and control sensitivity, and the MIL value is expressed in terms of bank angle achieved in 1 sec in response to an abrupt 1-in. step input. With the exception of the X-14A example at the lowest value of damping, all the other aircraft were evaluated to have Level 1 flying qualities for visual flight operations. The lowest damping evaluated for the X-14A was considered to be only marginally adequate even though it does fall within the MIL Level 1 boundary. Thus, a minimum amount of damping, though perhaps not as much as the AGARD criteria suggest, would be appropriate. The recent recommendation of Hoh (Ref. 20) and Clark (Ref. 50) for effective damping of 1.5 sec^{-1} would be about the desired value for Level 1.

For a demanding task such as a precision decelerating approach under instrument conditions, simple rate-damping augmentation will not be sufficient to provide fully satisfactory flying qualities. The diagram at the bottom of Fig. 49 summarizes a range of pilot evaluations from Lebacqz and Aiken's flight experiment on the Calspan X-22A (ref. 10) and the moving-base simulation experiments of Merrick and Gerdes (Ref. 51) and Stapleford, et al. (Ref. 52). These results show that only Level 2 flying qualities can be achieved at best, and that degradation to Level 3 occurs in moderate turbulence. Flight experience with the Do-31 (Ref. 11), the Kestrel (Ref. 44), and the XV-5B (Ref. 53) agrees with these findings. To achieve further improvement in precision approach and hover flying qualities, all these results indicate that some form of attitude stabilization is required.

Another form of stability augmentation that has frequently been applied to V/STOL aircraft is the yaw damper-turn coordinator. The intended benefits of this system were improved dutch roll mode damping during transition, elimination of yaw-roll coupling in the form of adverse sideslip caused by lateral control yawing moments, and yaw rate command and stability in hover. The system concept is shown in the diagram at the right of Fig. 50, and consists of feedback to the directional control (rudder or yaw reaction control valve) of lateral control position, roll and yaw rates, bank angle, and lateral acceleration. Criteria for suppressing sideslip excursions during turn entry are presented in terms of the relative magnitude of sideslip to roll excursions and the phasing of the sideslip transient (Ref. 3). The criteria are more tolerant when sideslip phasing is such that conventional coordination can be performed with the rudder. These criteria are made considerably more stringent in the MIL specification when large roll-yaw coupling exists in the dutch roll mode and are reduced by a factor of 5 below the level shown here. The time history at the bottom of the figure defines the sideslip and bank angle excursions upon which the criteria are based. The effect of the yaw stability augmentation in suppressing the yaw-roll coupling and in damping the dutch roll oscillation is apparent.

This form of yaw axis control augmentation has been very effective in improving lateral-directional flying qualities for precision flight. For demanding hover control tasks, the inclusion of a heading hold feature in combination with the yaw rate command has been investigated extensively (Refs. 10, 51, and 52). This type of system can provide Level 1 flying qualities in the most demanding operational environment in hover; however, the heading hold feature conflicts with the need to minimize sideslip during transitions. Therefore, if heading hold is to be provided in hover, it must be phased out as the aircraft enters the transition. This conversion in control mode is generally accomplished at an airspeed of approximately 30 knots.

It was noted previously that the aircraft's artificial force feel system is used to impart artificial "control free" stability to the aircraft during low-speed flight. Another contribution of this system is to compensate for large trim changes during transition. Most of the stability augmentation systems designed for V/STOL aircraft to date have been of limited control authority. These systems are not capable of providing large trim control requirements; thus to avoid saturating the stability augmenter with these demands, the detent of the force feel system may be repositioned to produce the trim control position desired.

6.2 Advanced Stabilization and Command Augmentation

Investigations of the contribution of advanced stabilization and command augmentation concepts to the improvement of flying qualities for precision hover and transition operations have been carried out over the past 10 years in a number of ground-based and flight research facilities. During this time, the predominant moving-based simulation experiments have been conducted using the three, six-degree-of-freedom simulators at NASA Ames Research Center shown in Fig. 51. The open cab facility at the center of the picture was initially used in Greif's hover control experiments (Ref. 18) and has been employed over the years for similar research on V/STOL control concepts. This simulator has a motion envelope defined by an 18-ft cube, and, within those constraints, it is maneuvered without distortion by motion washout. When flown open cockpit, visual cues have the highest degree of realism.

The Flight Simulator for Advanced Aircraft (FSAA) was used to explore the flying qualities and flight control systems of a variety of V/STOL configurations starting in the early 1970s. Until 1980, it was also the facility from which Merrick's data on advanced control and display concepts for V/STOL shipboard operations (Refs. 51 and 54) were obtained. Stapleford (Ref. 52) and Donley (Ref. 55) investigated criteria for the design of control augmentation systems for operation from small ships in adverse weather in this simulator. It was also used extensively for research on powered-lift STOL transport flying qualities by Franklin and Innis (Ref. 41) and Hoh et al. (Ref. 56) and research on airworthiness criteria by Scott and Hynes (Ref. 29) and Heffley et al. (Ref. 57). The distinguishing features of this simulator are its large lateral motion envelope and a fully enclosed cockpit with a dual-window visual scene produced by a camera-model board system and displayed on side-by-side color television monitors. Complete representation of hover and transition operation is provided by this facility.

The Vertical Motion Simulator (VMS) shown at the right of Fig. 51 has been used since 1981 for all of NASA's V/STOL simulation experiments. It has very large vertical and lateral motion freedom (60x40 ft) and accommodates a cockpit with a four-window, computer-generated visual scene. An example of a scene from the deck of an Amphibious Assault Ship (LHA) is shown at the bottom of the figure. Recent experiments by Farris and Merrick (Ref. 58) on advanced V/STOL controls and evaluations of the flying qualities of the tilt nacelle V/STOL configuration (Ref. 40) were all carried out on the VMS.

Over this same period of time, several flight research programs in the U.S. and U.K. have complemented and extended the ground-based research. The most extensive of the V/STOL flight programs was performed by Lebacqz, Aiken, Radford, and Andrisani with the variable stability X-22A at Calspan through the mid-to-late 1970s (Refs. 10, 59, and 60). This aircraft has the capability to alter its pitch, roll, yaw, and heave response over a wide range of characteristics and thereby to generate data over a range of flying qualities from Level 1 to Level 3. The aircraft also employs a programmable head-up display that is used to provide situation and command information that is compatible with the control concept under evaluation.

The NASA/Army X-14B at NASA Ames was used by Corliss et al. (Ref. 17) as a variable stability facility to evaluate in-flight hover control configurations that had been investigated earlier on NASA's Six-Degree-of-Freedom simulator. The X-14B provided the capability to alter the pitch, roll, and yaw response of the basic aircraft over a broad range of characteristics. Because the aircraft retained its open cockpit design, it was used exclusively for hover control research.

The NASA/Army CH-47B helicopter was involved in control and display research that is relevant to fixed-wing V/STOL control technology. This work was carried out by Kelly, Niessen, and Garren at NASA Langley (Refs. 61 and 62) to assess control and display requirements for manual and automatic instrument decelerating approaches. The aircraft has variable-stability capability in the pitch, roll, yaw, and heave axes, with sufficient control authority to represent a wide range of control configurations. It also provided a head-down electronic display for situation and command information.

A two-seat research version of the T MK 4 Harrier has been used by the staff at RAE-Bedford for V/STOL controls and displays research since the mid-1970s. At various times it has incorporated pitch attitude stabilization and integrated control for the nozzles in hover, along with a programmable head-up display for changing symbology and display formats. Research has been devoted to supporting evolutionary development of control augmentation and head-down displays for Sea Harrier and the recent GR MK5 aircraft.

Powered-lift STOL aircraft flight control research has been conducted at NASA Ames using the Augmentor Wing Research Aircraft. Pitch, roll, yaw, heave, and axial forces and moments could be altered on that aircraft to permit the evaluation of flying qualities and flight control characteristics. Programmable head-down electronic dislays were available to present situation and command information to the pilot. Flying qualities criteria and flight control concept evaluation and design guidelines were developed by Franklin (Refs. 42 and 63) and Hindson (Ref. 64) from these flight experiments.

From this collection of simulators and research aircraft, data have been generated on advanced control augmentation concepts. In the hierarchy of control sophistication, pitch and roll attitude command systems are the simplest of the concepts to be considered. Figure 52 provides an illustration of the characteristics of a roll attitude command system, as an extension of the rate command example of Fig. 49. The additional feature that has been included is the feedback of roll attitude from the vertical gyro. This system is described by the second-order equation of motion at the left of the figure and by the time response at the bottom. Inherent and artificial angular rate damping determine the subsidence of the exponential envelope of the response, and the attitude feedback establishes the speed of the initial response and the period of any apparent oscillatory motion. The steady-state attitude response to a control input depends on the ratio of the control sensitivity to attitude feedback constants. These characteristics are the basis for design criteria proposed in Ref. 3 and by Hoh and Ashkenas (Ref. 20) and Clark (Ref. 50). Level 1 flying qualities criteria from the latter two sources are given by the boundaries on the plot at the right of Fig. 52. Evaluations of the flying qualities of the four aircraft on the plot indicated that the Level 1 attitude control capability was obtained for all in hover. The X-22A and Do-31 were both evaluated during instrument approaches, and attitude stabilization resulted in good attitude control for both aircraft. The overall flying qualities of the Do-31 for a constant-speed approach were not considered to be satisfactory because of poor flightpath control characteristics and the use of raw data displays. The X-22A was given satisfactory ratings for the decelerating approach when a well integrated display was also provided to the pilot. The diagram at the bottom of Fig. 52 presents data collected from the X-22A (Ref. 10) and from simulator experiments (Refs. 51 and 52) that indicate that it is possible to achieve Level 1 flying qualities for the decelerating approach up to moderate levels of turbulence. As turbulence intensity increases further, flying qualities degrade to a marginal Level 2. Recent experience by RAE-Bedford with their research Harrier, and by McDonnell-Douglas/Sperry with the AV-8B prototypes, reaffirm the favorable contribution of attitude command. Again, it should be understood that the ability to achieve the most favorable ratings is dependent upon the proper display of situation and command information to the pilot. A poor choice of display design can negate the improvements in flying qualities for precision instrument operation provided by attitude command systems.

The most complex control augmentation systems to be evaluated to date are those that provide translational velocity command. This class of controls includes horizontal (axial and lateral) and vertical velocity systems. Characteristics of vertical velocity command were covered in the discussion of hover height control dynamics for Fig. 44. Axial and lateral velocity command systems that are reviewed in this section produce translational rates either through changes in body attitude or through deflection of the thrust vector. Figure 53 includes schematic descriptions of the two types of velocity command. The attitude-control-based concept adds an inertial or air-mass-derived velocity feedback to the structure of the attitude command system of Fig. 52. The thrust-vector controller is of the rate command type and uses the velocity feedback in combination with appropriate control gearing of the thrust vector input. The essential response characteristics of either system are described by the first-order equation of motion at the left of the figure. To represent velocity response to attitude in this fashion, it is necessary for the attitude control to be designed based on the attitude command criteria of Fig. 52. The time response shown at the bottom of the figure is characterized by the initial response gradient that is proportional to control sensitivity gain, the time constant that is inversely proportional to the rate feedback, and the steady-state response that is defined by the ratio of the control to the rate feedback gain. Given these essential features that describe the system response, Radford and Andrisani (Ref. 60) and Clark (Ref. 50) have proposed criteria for Level 1 and 2 flying qualities based on flight data from the X-22A. The analyses of Hoh and Ashkenas (Ref. 20) that included data from two major simulation experiments (Refs. 65 and 66) and from helicopter flight tests (Refs. 67 and 68) also are a source of criteria. This body of results is derived from various land-based precision hover tests of these systems. Simulation experiments by Merrick (Refs. 51 and 54) and Stapleford (Ref. 52) for shipboard landings on a DD-963-class vessel are summarized at the left of Fig. 53. These results indicate that it is feasible to achieve Level 1 flying qualities for the most demanding precision V/STOL operations. Marginal Level 1 flying qualities were maintained in conditions equivalent to sea state 4 and in an air wake environment associated with 25 knots of wind over the deck. Subsequent experiments by Donley (Ref. 55) suggest that a hover position hold feature be included in these systems to compensate for imperfect inertial velocity information, considering the precision required for landing on this size ship. RAE-Bedford has had experience with a simple nozzle controller integrated with the throttle lever on their Harrier research aircraft. This device provides an easy means of adjusting both thrust magnitude and deflection in the hover. Although it does not provide increased vertical or axial velocity damping, it has reduced the pilot's effort for hover control. It has been adopted in the design of the Sea Harrier power management system. To conclude this discussion, it should again be emphasized that a poor choice of cockpit display format or information can reduce the potential benefits of the contol augmentation systems.

To accomplish these higher levels of control augmentation on a V/STOL configuration, some degree of integration of the flight and propulsion control systems is required. In its simplest form, this integration could be provided by a servo link to the power and thrust vector control levers. Even in this simple example, the dynamic response characteristics of the fan and core elements and the thrust deflection control must be taken into consideration in the flight control system design. In turn, the propulsion designer must consider the likely force and moment control demands and treat that aspect of the propulsion system as a primary flight control element as regards rates and accuracy of response. To achieve the required dynamic response for forces and moments from some of the advanced V/STOL concepts reviewed in Section 4 and Ref. 34, it will be necessary to conduct a more integrated design of the flight and propulsion control systems than has been done before. Digital control technology makes it feasible to undertake such a design, in which the integration to comparable degree of hydro- and electromechanical systems of current aircraft would have made the task impossible. The flight test of an experimental Dowty-Smiths digital fuel control on a Harrier/Pegasus in the U.K. proved to be a successful first step in this regard. In the U.S., a joint research effort between NASA Ames and Lewis Research Centers has been under way since the late 1970s to investigate flight-propulsion control integration for this class of aircraft. This work has been encouraged by earlier efforts of this type conducted by NASA and the U.S. military for conventional fighter aircraft. Initial activities involved the full envelope, nonlinear dynamic modeling of a subsonic V/STOL transport aircraft, and a turbofan propulsion system that was used for a nonpiloted simulation investigation. Fully automatic transition, approach, and shipboard landings were performed that provided data concerning precision approach and landing performance, propulsion system demands and performance, and dynamic response characteristics of the propulsion and flight control system (Ref. 69). Most recently, this effort has been directed to the detailed dynamic modeling from piloted simulation of the AV-8 Harrier airframe and Pegasus engine combination. Both models have been developed and brought to operational status for piloted evaluations on NASA's Vertical Motion Simulator, as indicated in Fig. 54. A description of the development of the Pegasus dynamic model for use in real-time digital simulation is provided in Ref. 70. This airframe-propulsion model will be used to acquire data for the assessment of gross thrust demands, internal engine state dynamic behavior, and acceleration and bleed flow demands during takeoff, transition, and landing operations. Thus the experimental capability for evaluating an integrated flight-propulsion control design has been established. It use awaits the initiation of such a design effort on the next generation of V/STOL aircraft.

7. OPERATIONAL CAPABILITY

The ultimate operational utility of future military V/STOL aircraft will be determined to a considerable extent by their ability to operate in an adverse weather and shipboard environment that is at least as demanding as that faced by conventional sea- and land-based aircraft today. Considering the experience with V/STOL aircraft stability and control design and operating characteristics that has been summarized in this paper, it can be concluded that shipboard operations of these aircraft in adverse weather will be constrained by their basic or control augmented flying qualities. Clark (Ref. 50) proposed control augmentation and cockpit display requirements for precision hover and low-speed operations based on the quality of outside visual cues. His suggestion reflects Hoh and Ashkenas' interpretation of these requirements from a large collection of simulation and flight data (Ref. 7) and is shown in Fig. 55. The outside visual cue scale was described previously in Fig. 7. For a given set of visibility conditions that can ultimately be tied to ceiling and visual range, the combination of aircraft control and display design characteristics is determined. It is assumed that each of the control and display designs is optimized. To meet fully satisfactory (Level 1) flying qualities requirements, velocity command controls may be required when visibility is degraded to any extent. In accord with the trade-off between control and display sophistication hypothesized in the AGARD Advisory Report (Ref. 49) and substantiated by several simulation and flight experiments, this demand for highly augmented control may be relieved to a certain extent by employing more sophisticated display presentations of position and velocity situation information and appropriate control commands. To restate a point made earlier in this paper and emphasized by Farley in his AGARD presentation on display design (Ref. 71), the display of flight information to the pilot is as crucial to the successful control of the aircraft as is the basic or augmented stability and control of the airframe. Improper design or application of the display will negate good control characteristics painstakingly incorporated in the airframe design.

Harrier operational experience is in accord with Clark's proposed requirement. Current and past Harriers (GR MK 1 and 3 and AV-8A) perform their decelerating transition and vertical landing under visual flight conditions (OVC 1 or 2). Even under these conditions, the pilot's workload is high when precision deceleration and hover is required. The next generation of Harrier will have improved capability by virtue of attitude command controls, and should have Level 1 flying qualities in all but the worst visibility conditions.

With regard to the influence of the shipboard environment on operating capability, experiments on the NASA Ames FSAA are summarized in Fig. 56 to illustrate the variation in flying qualities, and hence operational acceptability, over a range of sea conditions for three control command augmentation systems. These results apply for operation aboard a DD-963-class destroyer, and thus represent possibly the most demanding of precision control tasks. To achieve fully satisfactory flying qualities even in calm seas, velocity command augmentation is necessary. Attitude command systems would provide only adequate flying qualities. In moderate seas, decoupled velocity command systems still offer marginally satisfactory flying qualities, and attitude command systems are only marginally adequate under these conditions. Even in heavy seas, the decoupled velocity controls can be expected to provide adequate controllability. Given the limited field of view of the visual display for this simulator, these operations were conducted with the pilot relying entirely on a head-up display for situation and guidance information for landing. Thus, the results effectively apply to fully instrument visibility conditions, and may be somewhat conservative for partial IMC or VMC situations. Experiments that are under way on more advanced simulation facilities at NASA and those planned for the new large motion simulator at RAE-Bedford will serve to clarify this issue. Flight results from the more modern fleet of Harriers that are about to go into service will also provide invaluable data on this challenging sea-going environment.

8. CONCLUDING REMARKS

This paper has provided a summary of the maneuver requirements for V/STOL operations and the related control authority, stability, and controllability demanded of V/STOL designs to achieve this capability. Characteristics of control augmentation systems that enhance operational capability have been reviewed. Based on the existing body of information, several major uncertainties and issues remain to be resolved.

Control authority requirements have not been established for demanding shipboard operations.

- The philosophy of basing the total control authority on the aggregate demands for trim, stabilization or disturbance suppression, and maneuvering is widely accepted in principle. However, it may not be necessary to sum the individual demands for stabilization against disturbances and for maneuvering. Instead, the most stringent of these two requirements may suffice to account for the other.

- Control authority to counter disturbances is amenable to analysis, whether the disturbance is a consequence of air wakes or turbulence, ground effect or hot gas ingestion. Maneuvers are not so easy to specify and describe analytically because of the complex control tasks associated with V/STOL missions. Thus, maneuver requirements need experimental verification. In particular, since quick stop capability can use substantial control authority, realistic requirements for this type of maneuver must be established.

- AGARD Report 577 and MIL-F-83300 pitch and roll maneuver requirements may be reasonably accurate for hover operations; however, those for yaw control seem high based on flight experience.

- The idea of describing maneuver control demands during transition in terms of control margin is an appealing alternative to specifying an absolute value for authority.

Control authority requirements place significant demands on the propulsion system.

- To relieve demands on the installed thrust of the propulsion system, it is desirable to prioritize the use of bleed air or thrust for multiaxis control demands. The order of priority should provide for roll, pitch, height, and yaw control in that sequence.

- Integration of the flight and propulsion controls may be useful in achieving an acceptable design, particularly if the integrated design permits the use of contingency thrust. The potential improvement in mission payload without the sacrifice of control authority or propulsion system reliability is worth investigating.

- The potential indicated in simulation experiments for reducing the overall maneuver and stabilization control authority through advanced control augmentation concepts that exploit the integration of flight and propulsion controls should also be established.

Significant operational benefits may be achieved with advanced control augmentation systems.

- Current indication is that rate command systems are incapable of providing satisfactory flying qualities for a precision control task aboard ship. However, it is not certain whether velocity command augmentation will be required to reduce the pilot's control effort sufficiently.
- It must be determined whether simulation results are unduly conservative and whether attitude command controls can produce at least marginally satisfactory flying.
- The sensitivity of this selection of control mode to cockpit display format and information content has been firmly established. The benefits of good stability and control augmentation design can be negated by a poor display design.
- The influence of the level of control augmentation on operational capability in adverse weather aboard ship requires flight validation. This includes understanding the effect of the visual, air wake, and ship motion environment on the pilot's assessment of a particular control concept.

Based on these major uncertainties and because of the sensitivity of future V/STOL designs to these issues, it is essential that flight validation be performed for the most significant concerns that, to date, are defined only by ground-based simulation. Further, for advanced V/STOL design concepts that appear most promising and are candidates to be carried to detailed evaluation, simulation assessments of their particular flying qualities and operational capabilities are required.

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Figure 1. Harrier operation at a forward site (Photo courtesy of McDonnell-Douglas Corp.).

Figure 2. H.M.S. Hermes in the South Atlantic, 1982. (From the 25th Sir Charles Kingford Smith Memorial Lecture, University of New South Wales, Sydney, Australia, September, 1983, by J.W. Fozard.)

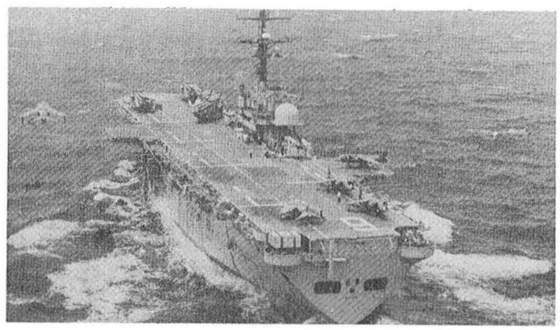
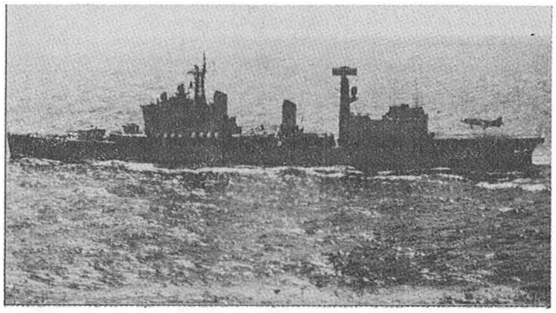
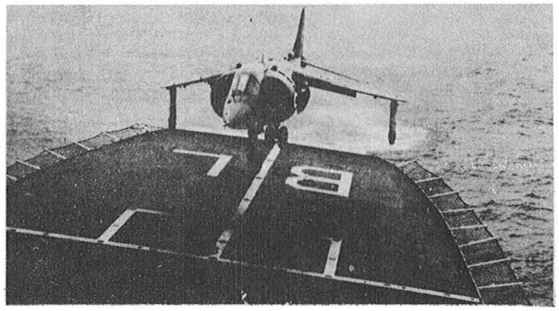


Figure 3. U.S. Marine Corps AV-8As on U.S.S. Guam. (From the 25th Sir Charles Kingford Smith Memorial Lecture, University of New South Wales, Sydney, Australia, September, 1983, by J.W. Fozard.)



a. Vertical takeoff.



b. Vertical landing.

Figure 4. Harrier operations aboard H.M.S. Blake (from Ref. 22).

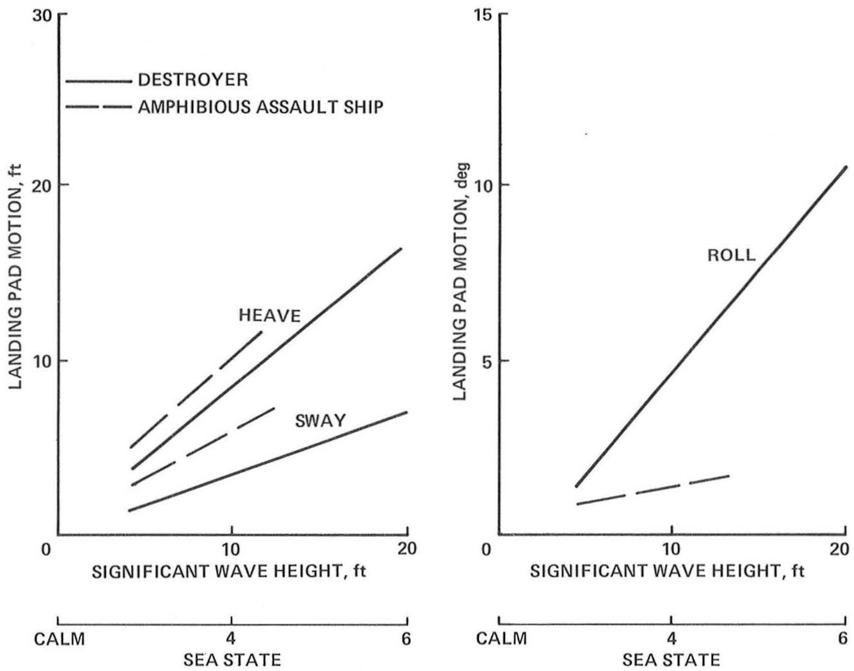


Figure 5. Landing pad motion characteristics for destroyer and amphibious assault ship.

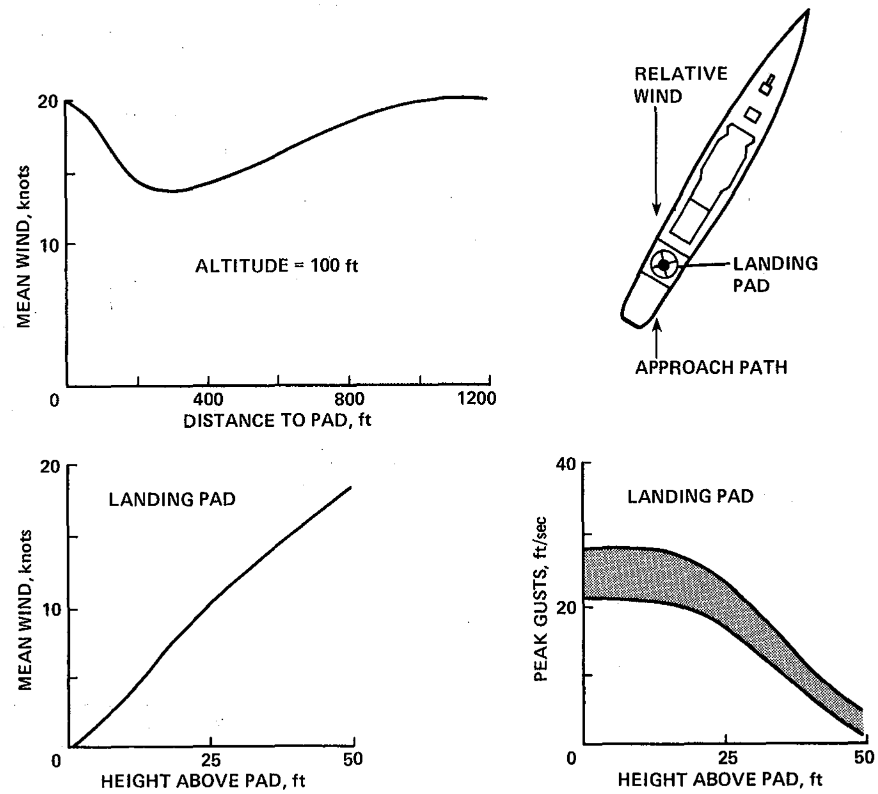
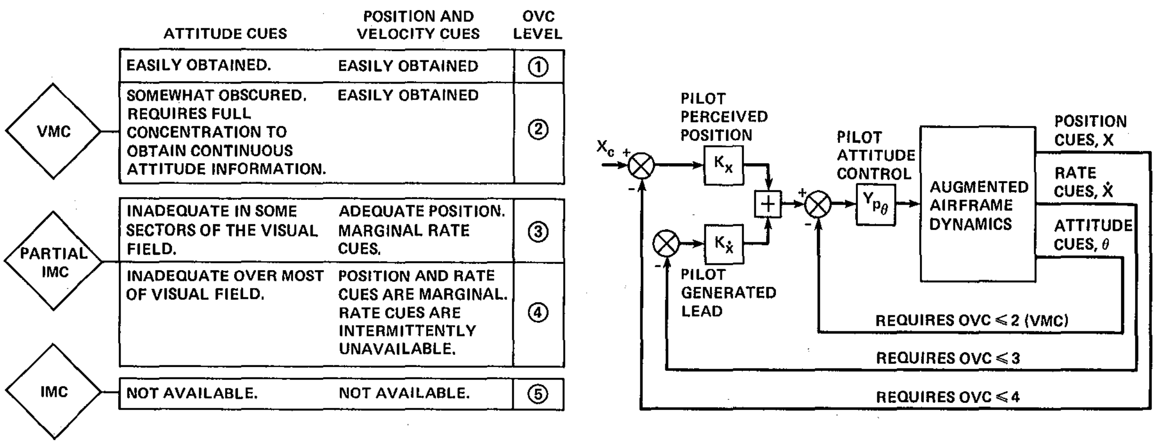


Figure 6. Ship airwake characteristics for DD-963 destroyer.



a. Quantification of outside visual cues.

b. Outside visual cues required for control.

Figure 7. Outside visual cue scale (from Ref. 7).

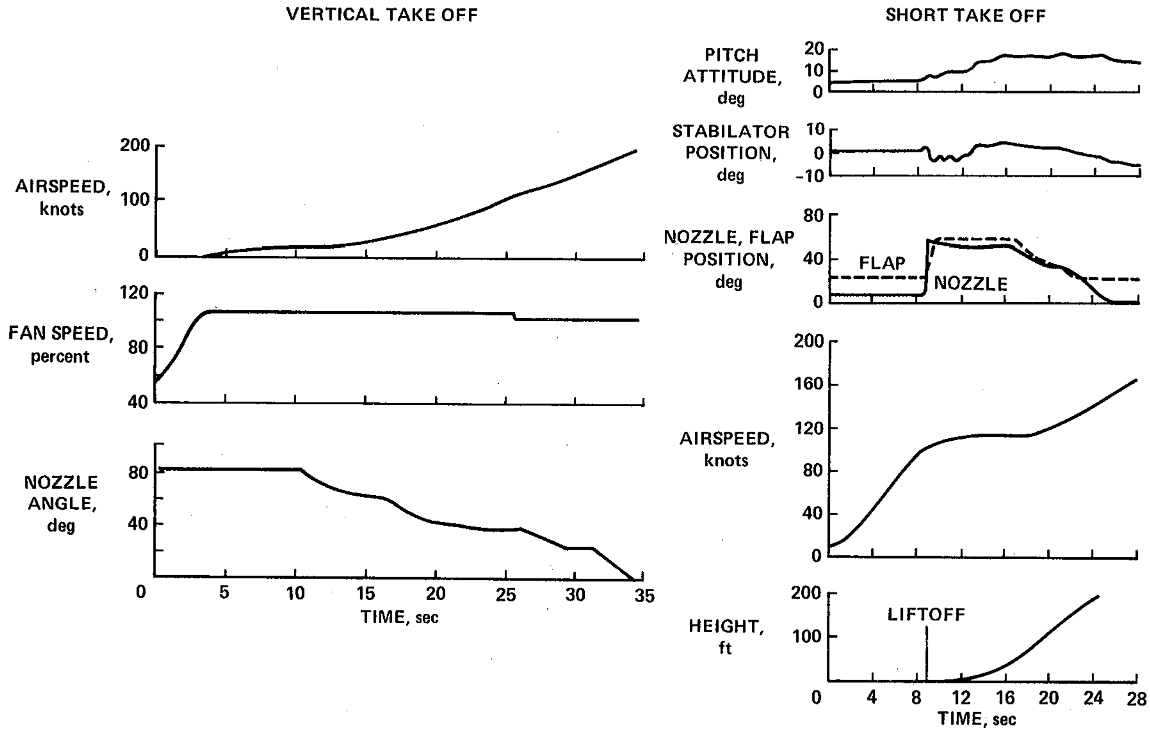


Figure 8. Vertical and short takeoff maneuver.

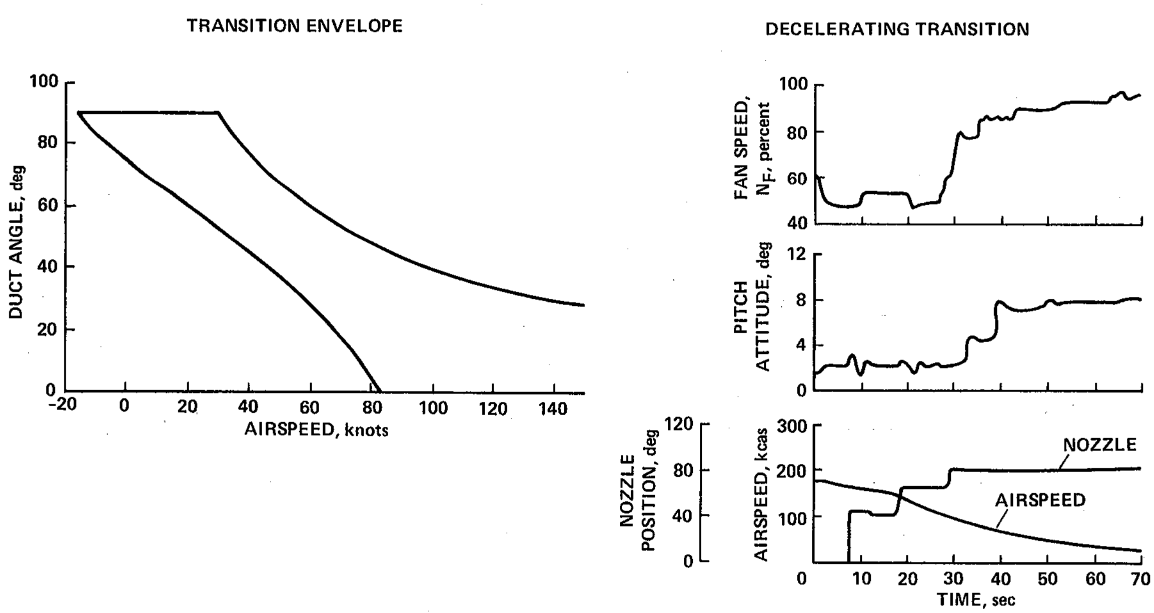


Figure 9. Transition envelope and maneuver.

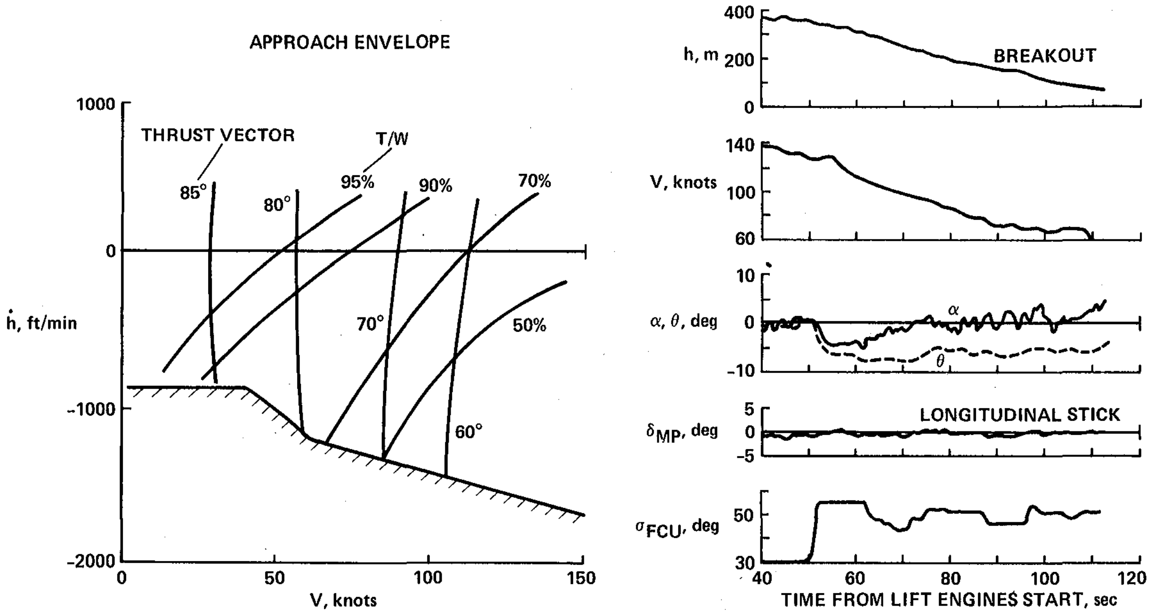


Figure 10. Landing approach envelope and maneuver.

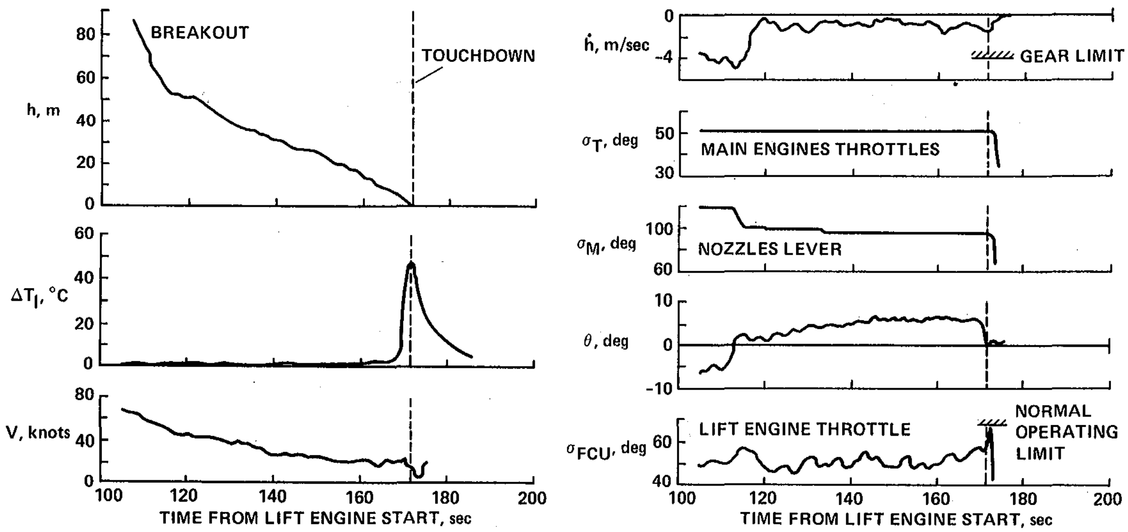


Figure 11. Hover and landing.

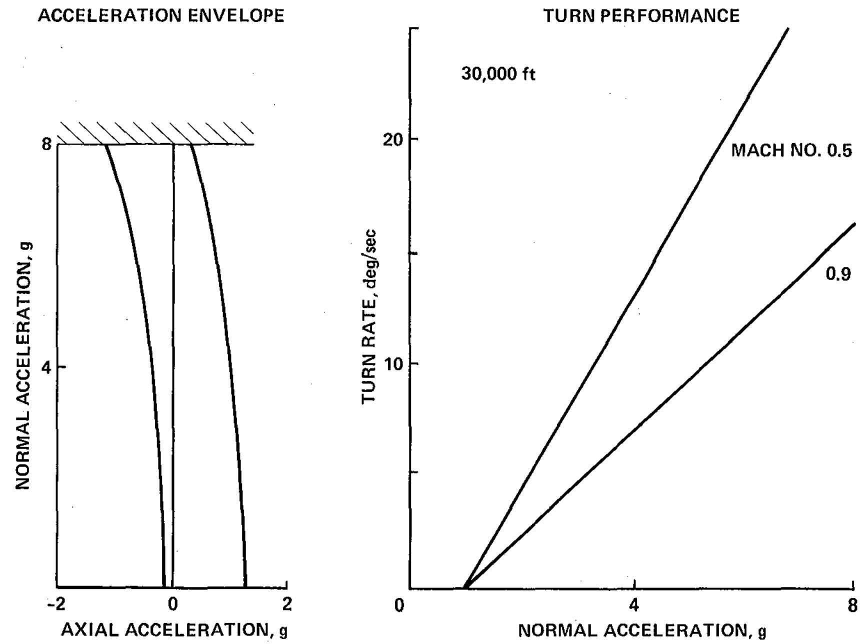


Figure 12. Forward flight maneuver performance.

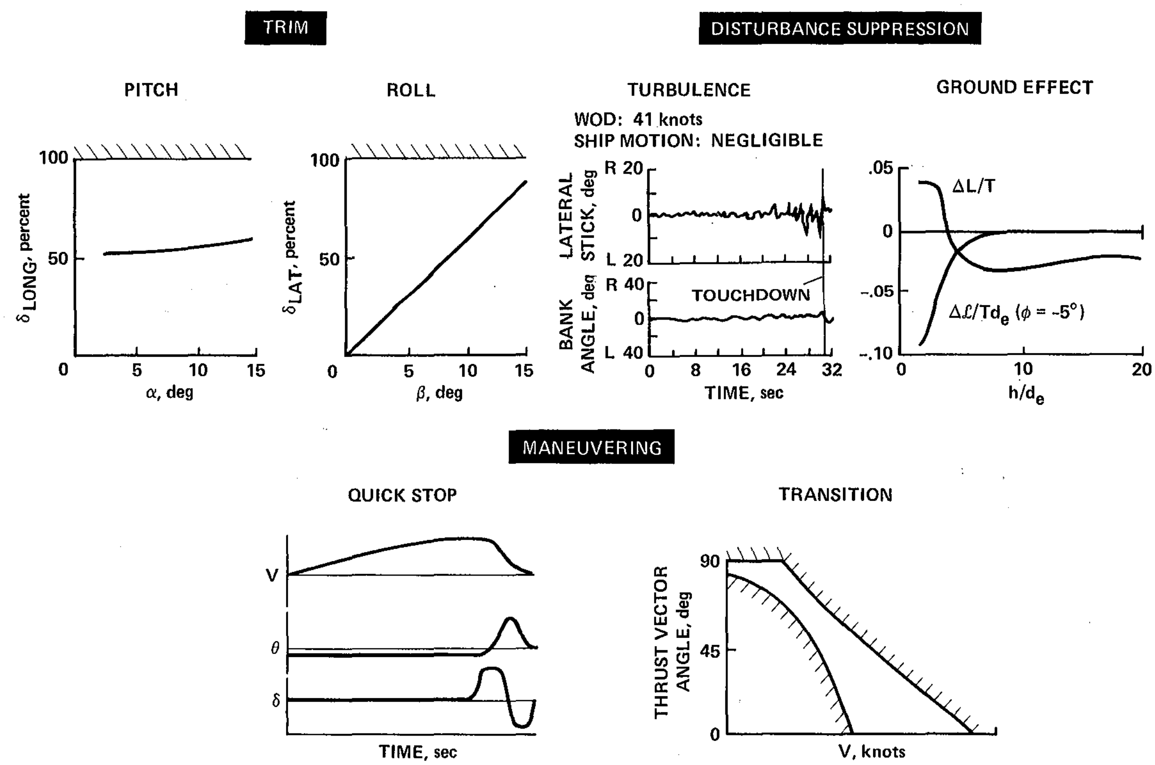
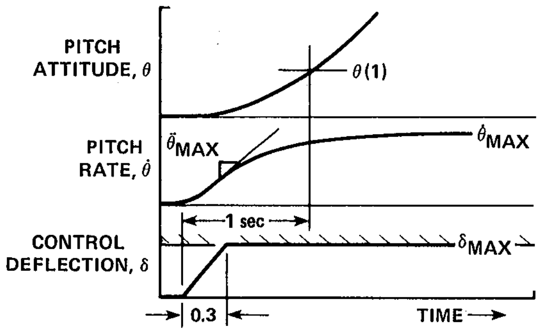


Figure 13. Demands on control authority.

FLYING QUALITIES REQUIREMENT	AGARD 577		MIL-F-83300
	$\ddot{\theta}_{MAX}$, rad/sec^2	$\theta(1)$, deg	$\theta(1)$, deg
LEVEL 1 SATISFACTORY WITHOUT IMPROVEMENT	0.1-0.3	2-4	3
LEVEL 2 ADEQUATE IMPROVEMENT WARRANTED			2



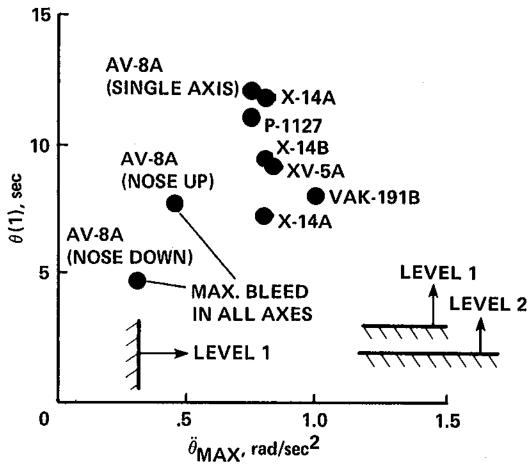


Figure 14. Pitch control authority in hover.

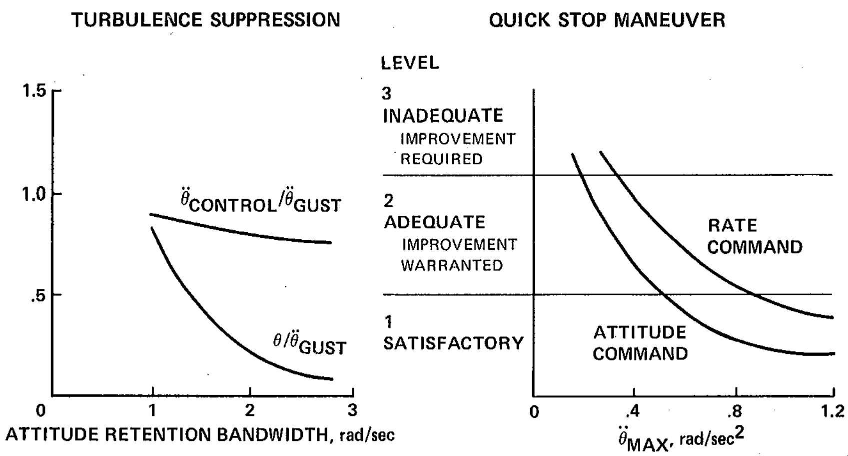


Figure 15. Pitch control utilization in hover.

FLYING QUALITIES REQUIREMENT	AGARD 577		MIL-F-83300 $\phi(1)$, deg
	$\ddot{\phi}_{MAX}$, rad/sec^2	$\phi(1)$, deg	
LEVEL 1 SATISFACTORY WITHOUT IMPROVEMENT	0.2-0.4	2-4	4.0
LEVEL 2 ADEQUATE IMPROVEMENT WARRANTED			2.5

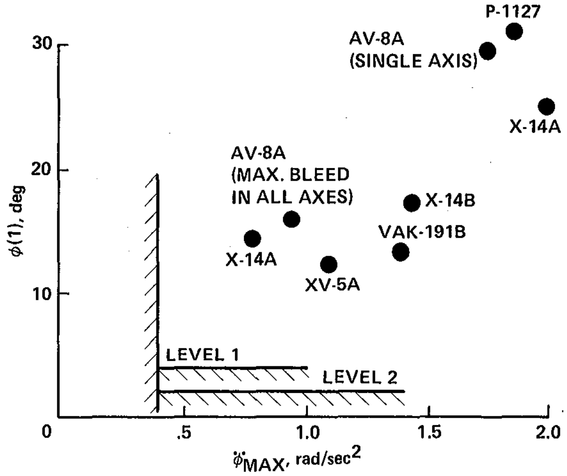


Figure 16. Roll control authority in hover.

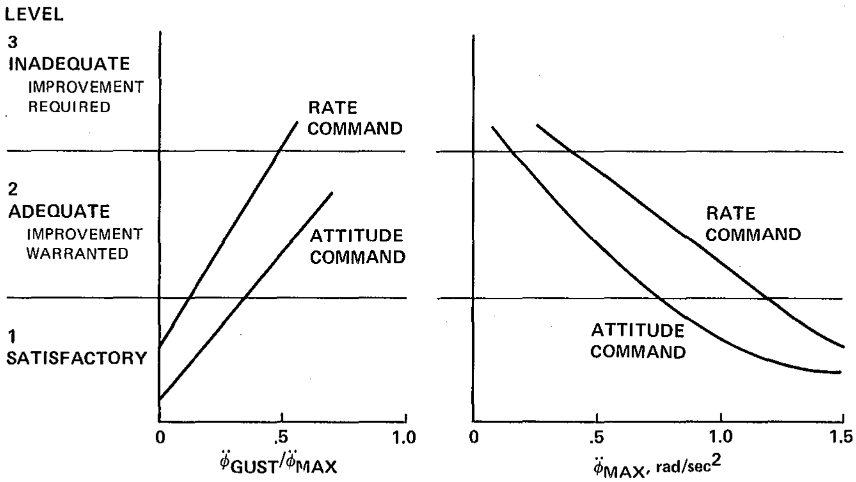


Figure 17. Roll control utilization in hover.

FLYING QUALITIES REQUIREMENT	AGARD 577		MIL-F-83300 $\psi(1)$, deg
	$\ddot{\psi}_{MAX}$, rad/sec^2	$t_{\psi=15°}$, sec	
LEVEL 1 SATISFACTORY WITHOUT IMPROVEMENT	0.1-0.5	1.0-2.5	6
LEVEL 2 ADEQUATE IMPROVEMENT WARRANTED			3

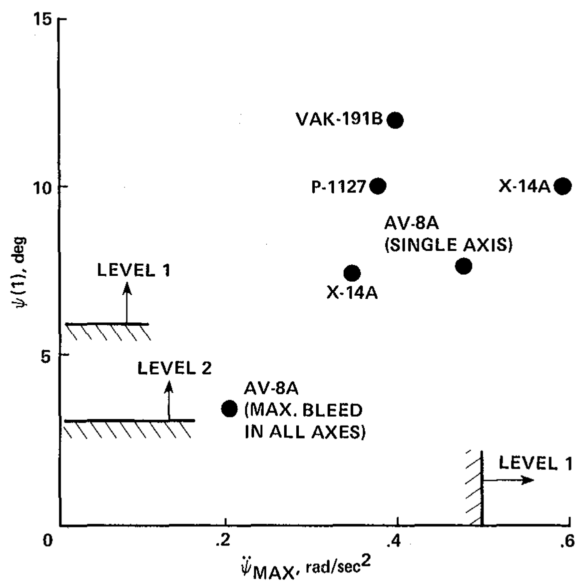


Figure 18. Yaw control authority in hover.

FLYING QUALITIES REQUIREMENT	AGARD 577		MIL-F-83300	
	T/W_{MIN}	$\dot{h}_{MIN}$, ft/sec	T/W_{MIN}	Δg_{MIN}
LEVEL 1 SATISFACTORY WITHOUT IMPROVEMENT	1.03-1.1	600	1.05	0.1
LEVEL 2 ADEQUATE IMPROVEMENT REQUIRED			1.02	0.05

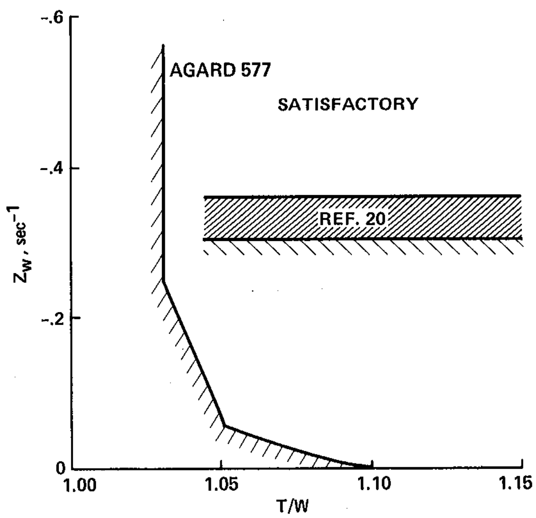


Figure 19. Heave control authority in hover.

FLYING QUALITIES REQUIREMENT	MIL-F-83300				
	PITCH, $\theta(1)$, deg	ROLL, $\phi(1)$, deg	YAW, $\psi(1)$, deg	THRUST, Δg	TRIM WIND, knots
LEVEL 1 SATISFACTORY WITHOUT IMPROVEMENT	3.0	4.0	6.0	0.1	35
LEVEL 2 ADEQUATE IMPROVEMENT WARRANTED	2.0	2.5	3.0	0.05	35

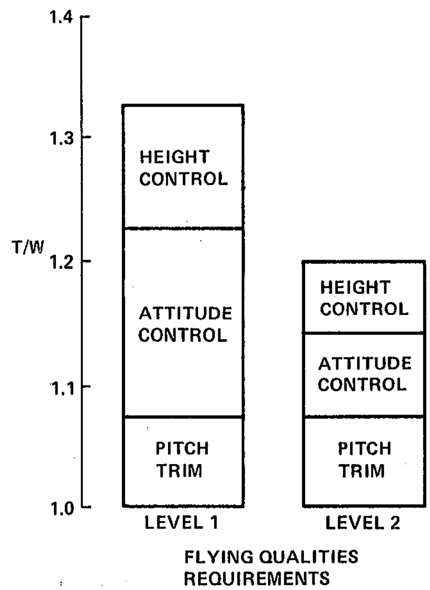


Figure 20. Combined control authority in hover.

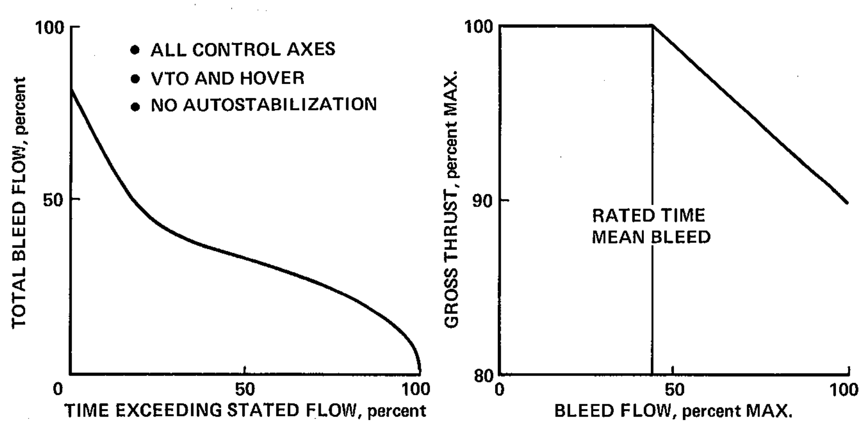


Figure 21. Thrust-bleed tradeoff in hover (from Refs. 9 and 22).

AGARD 577		MIL-F-83300 CONTROL MARGIN IN EXCESS OF TRIM
$\ddot{\theta}_{MAX}$, rad/sec^2	$\theta(1)$, deg	
0.05-0.2	2-4	50% OF MAX.

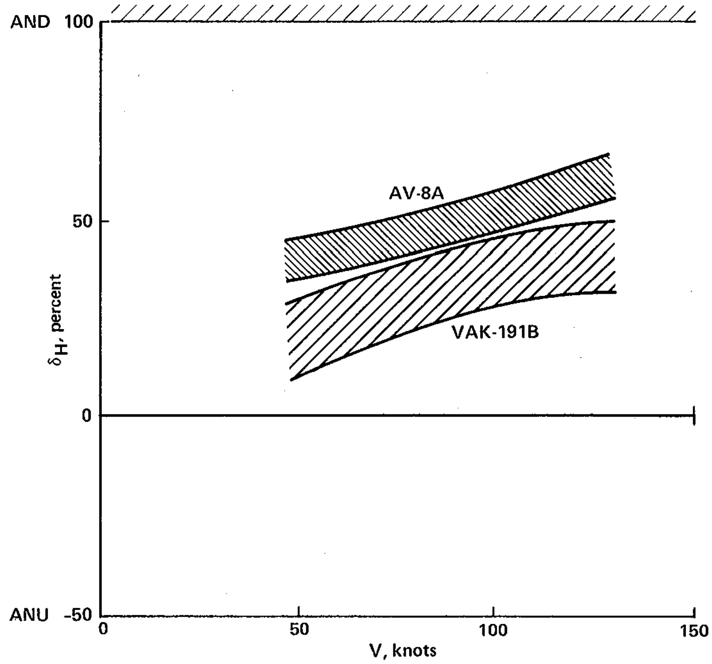


Figure 22. Pitch control authority in transition.

FLYING QUALITIES REQUIREMENT	AGARD 577		MIL-F-83300
	$\ddot{\phi}_{MAX}$†, rad/sec^2	$\phi(1)$, deg	$t_{\phi=30°}$*, sec
LEVEL 1 SATISFACTORY WITHOUT IMPROVEMENT	0.1-0.6	2-4	1.0-2.5
LEVEL 2 ADEQUATE IMPROVEMENT WARRANTED			1.3-3.2

*DEPENDS ON AIRCRAFT CATEGORY RANGING FROM FIGHTER TO HEAVY TRANSPORT. ALTERNATE REQUIREMENT – 50% CONTROL MARGIN.

†50% CONTROL AUTHORITY REMAINING FOR FULL RUDDER AUTHORITY SIDESLIP.

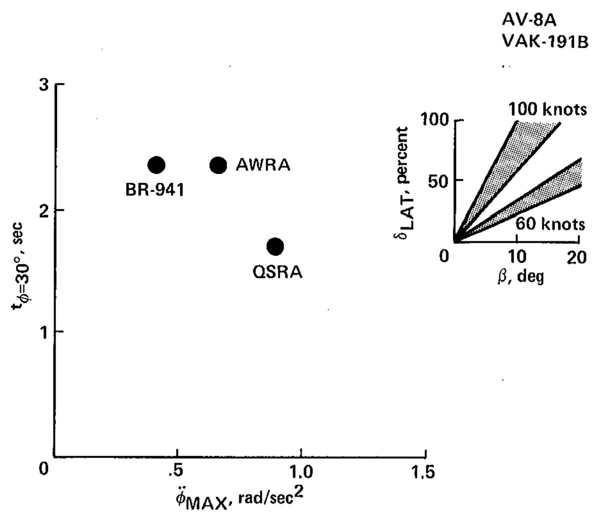


Figure 23. Roll control authority in transition.

FLYING QUALITIES REQUIREMENT	AGARD 577		MIL-F-83300 $\psi(1)$*, deg
	$\ddot{\psi}_{MAX}$, rad/sec^2	$t_{\psi=15°}$, sec	
LEVEL 1 SATISFACTORY WITHOUT IMPROVEMENT	0.15-0.25	2.0	6
LEVEL 2 ADEQUATE IMPROVEMENT WARRANTED			3

*ALTERNATE REQUIREMENT 50% CONTROL MARGIN

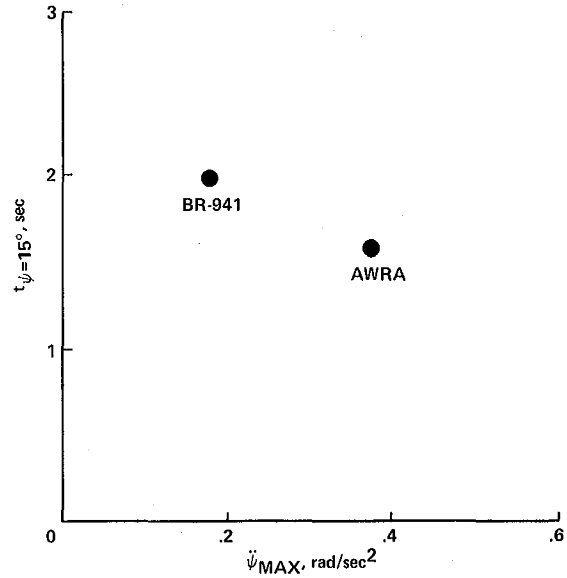


Figure 24. Yaw control authority in transition.

AGARD 577		FAA TENTATIVE POWERED-LIFT AIRWORTHINESS CRITERIA, γ, deg
Δa_z, g's	γ, deg	
±0.1	6° CLIMB -2° GREATER THAN APPROACH PATH ANGLE	LEVEL FLIGHT -4° GREATER THAN APPROACH PATH ANGLE

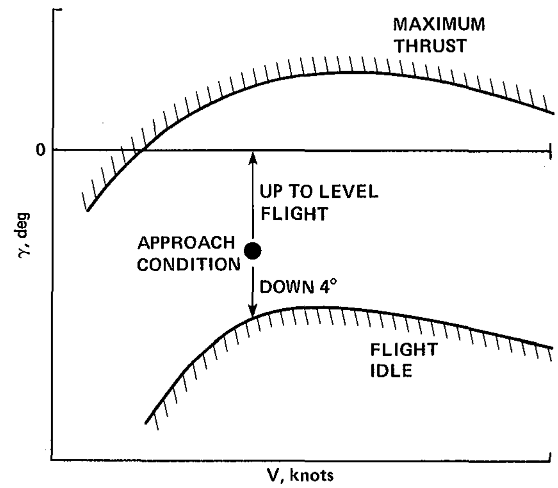


Figure 25. Flightpath control authority in transition.

FLYING QUALITIES REQUIREMENTS	
AGARD 577	MIL-F-83300
ABILITY TO ACCELERATE OR DECELERATE CONTINUOUSLY THROUGHOUT TRANSITION ENVELOPE. ACCELERATION OR DECELERATION UP TO 0.5 g's DESIRABLE DEPENDING ON MISSION. DIRECTION OF TRANSITION SHOULD BE EASILY REVERSED.	ABILITY TO ACCELERATE OR DECELERATE RAPIDLY FROM ANY TRIM POINT WITHIN TRANSITION ENVELOPE. TIME DURATION OF MANOEUVRE IS MISSION DEPENDENT. DIRECTION OF TRANSITION SHOULD BE EASILY REVERSED.

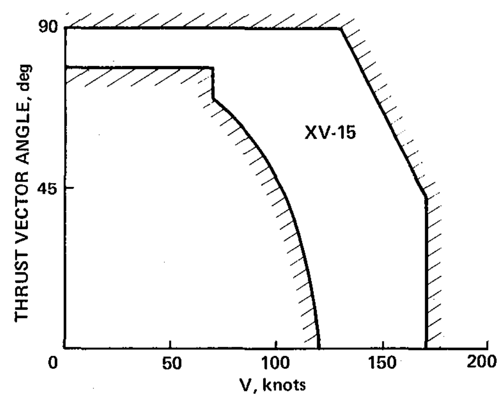


Figure 26. Longitudinal acceleration control authority in transition.

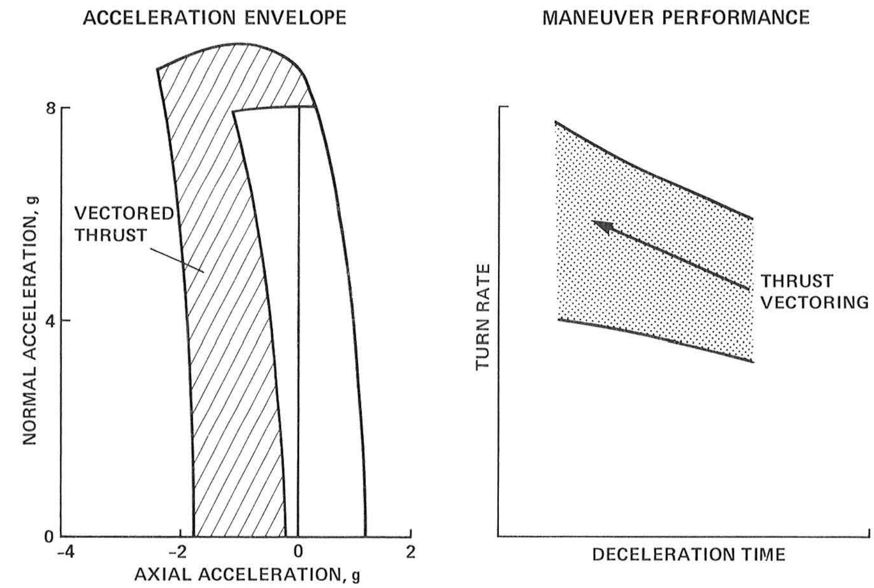


Figure 27. Forward flight maneuver enhancement.

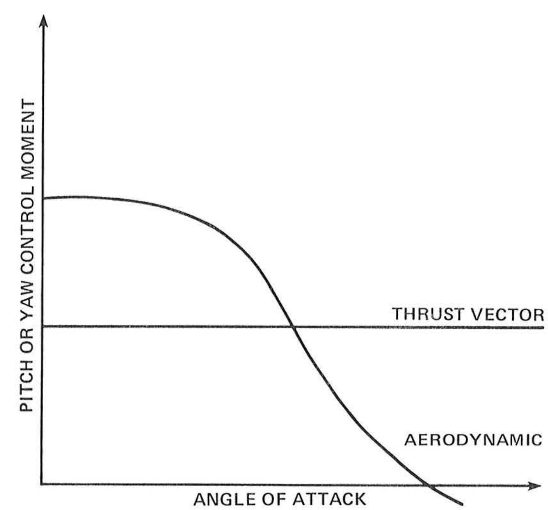


Figure 28. Forward flight attitude control.

Figure 29. AV-8B Advanced Harrier.

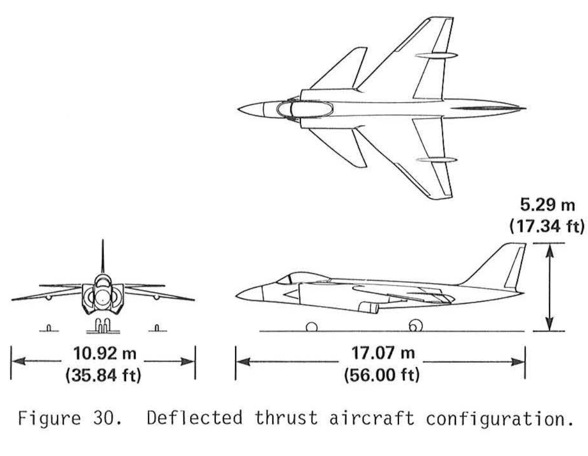


Figure 30. Deflected thrust aircraft configuration.

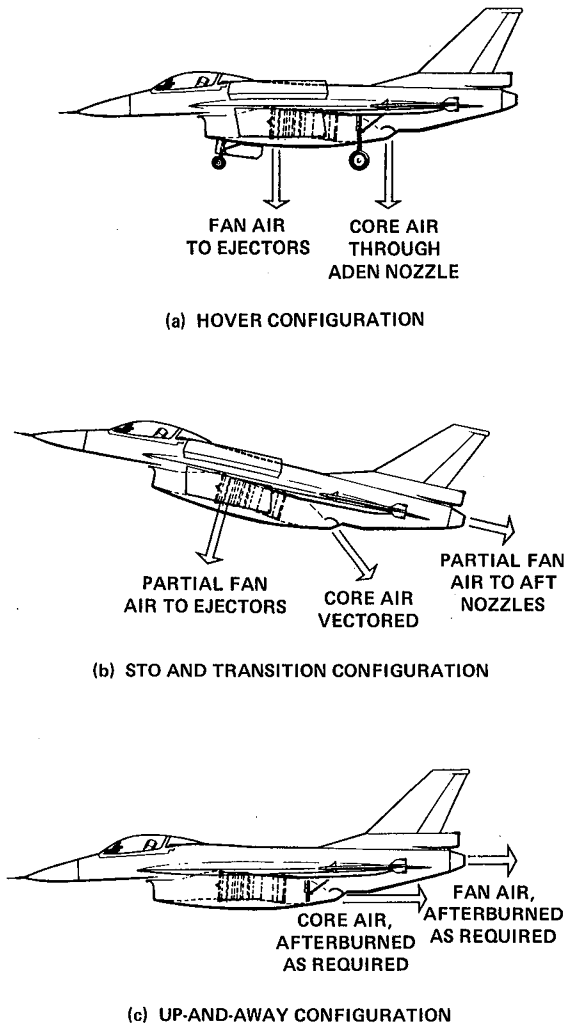


Figure 31. Augmentor-ejector aircraft configuration.

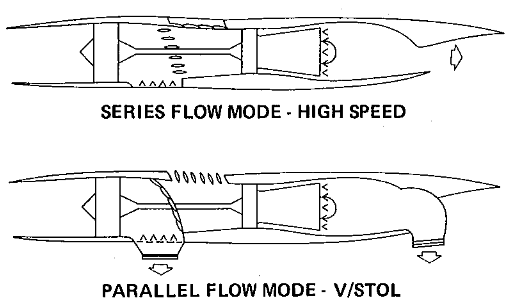


Figure 32. Tandem-fan propulsion concept.

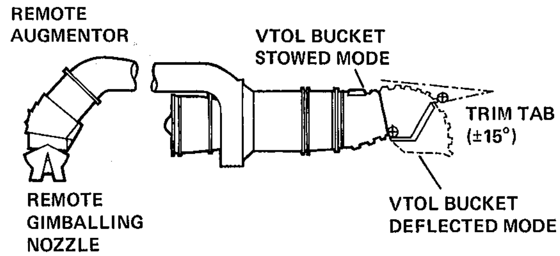


Figure 33. Remote augmented lift propulsion concept.

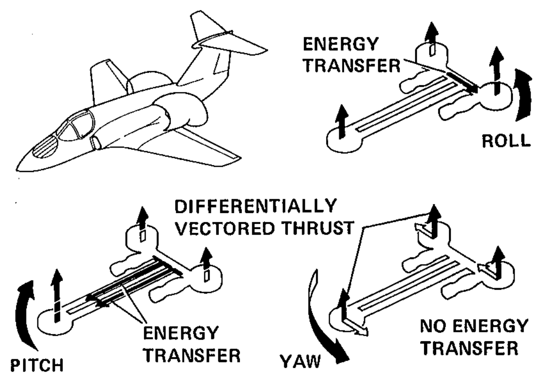


Figure 34. Lift-cruise fan aircraft configuration.

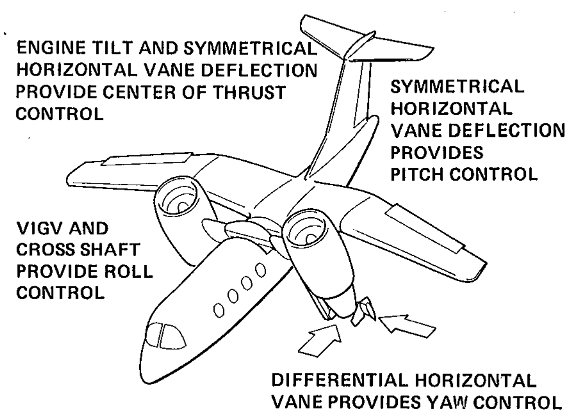


Figure 35. Twin tilt nacelle lift-cruise fan aircraft concept.

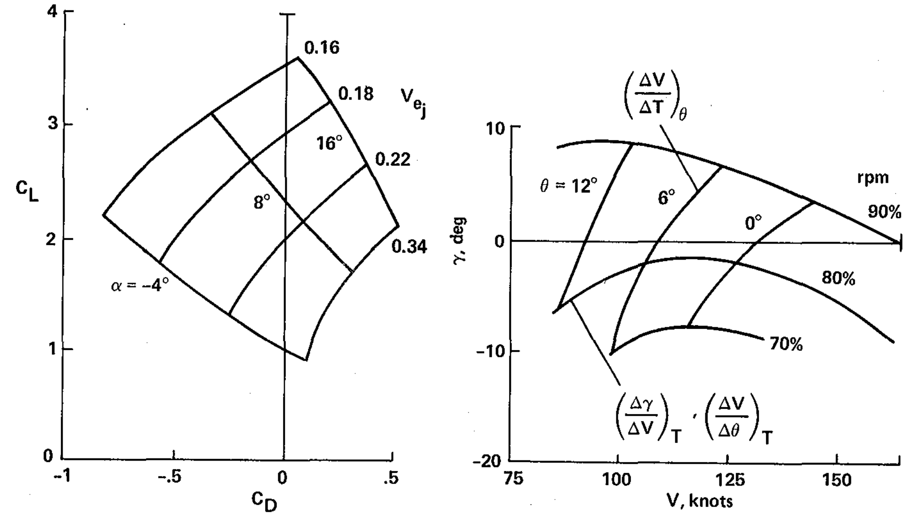


Figure 36. Relationship of steady-state flightpath and airspeed control to lift and drag aerodynamics.

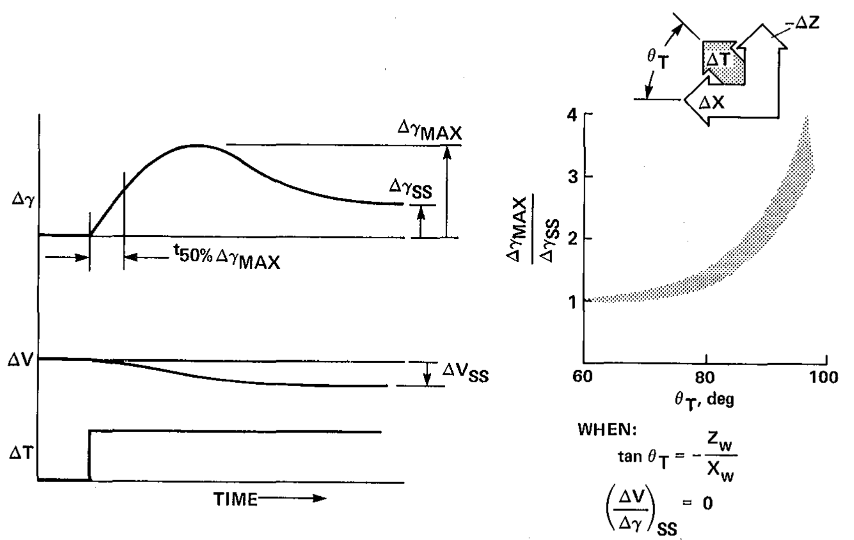


Figure 37. Relationship of flightpath and airspeed dynamic response to lift-drag aerodynamics.

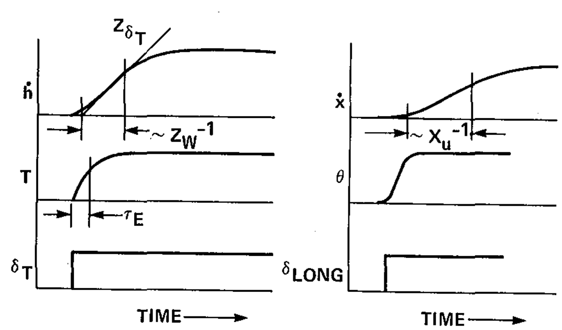


Figure 38. Hover control dynamics.

AXIAL $\ddot{x} - X_u\dot{x} + g\theta = 0$

VERTICAL $\ddot{z} - Z_w\dot{z} = Z_{\delta_T}\delta_T$

PITCH $-M_u\dot{x} + \ddot{\theta} - M_q\dot{\theta} = M_{\delta_e}\delta_e$

$$(s - Z_w)(s^3 - (X_u + M_q)s^2 + X_uM_qs + gM_u) = 0$$

OR

$$(s + \frac{1}{T_h})(s + \frac{1}{T_\lambda})(s^2 + 2\zeta\omega s + \omega^2) = 0$$

HEIGHT CONTROL $\dfrac{z}{\delta_T} = \dfrac{Z_{\delta_T}}{s(s + \frac{1}{T_h})}$ $\quad \dfrac{1}{T_h} = -Z_w$

PITCH CONTROL $\dfrac{\theta}{\delta_e} = \dfrac{M_{\delta_e}(s - X_u)(s + \frac{1}{T_h})}{(s + \frac{1}{T_h})(s + \frac{1}{T_\lambda})(s^2 + 2\zeta\omega s + \omega^2)}$

AXIAL POSITION CONTROL $\dfrac{x}{\delta_e} = \dfrac{gM_{\delta_e}(s + \frac{1}{T_h})}{s(s + \frac{1}{T_h})(s + \frac{1}{T_\lambda})(s^2 + 2\zeta\omega s + \omega^2)}$

AERODYNAMICS NEGLECTED

$\ddot{x} = -g\theta$

$\ddot{\theta} = M_{\delta_e}\delta_e$

$\ddot{z} = Z_{\delta_T}\delta_T$

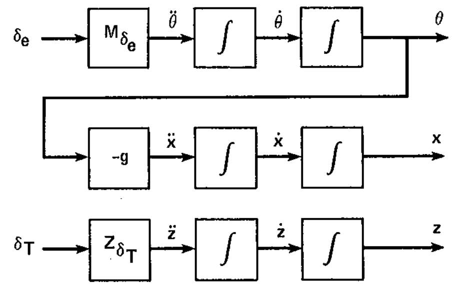


Figure 39. Basic aircraft hover equations.

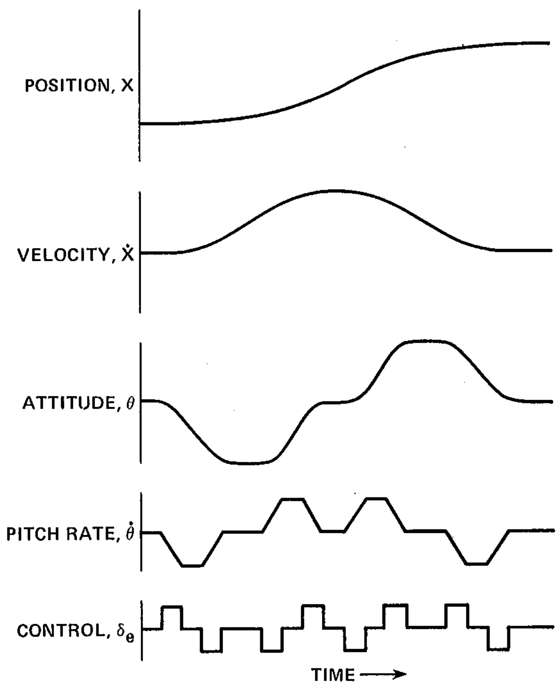


Figure 40. Hover position control.

MIL-F-83300

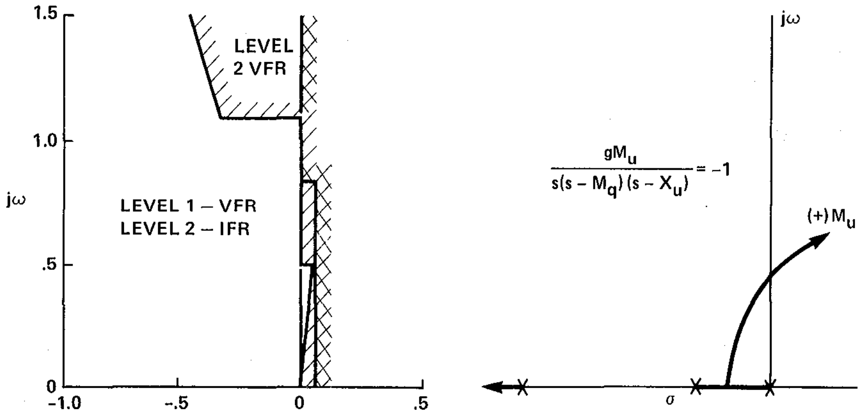


Figure 41. Basic aircraft hover stability.

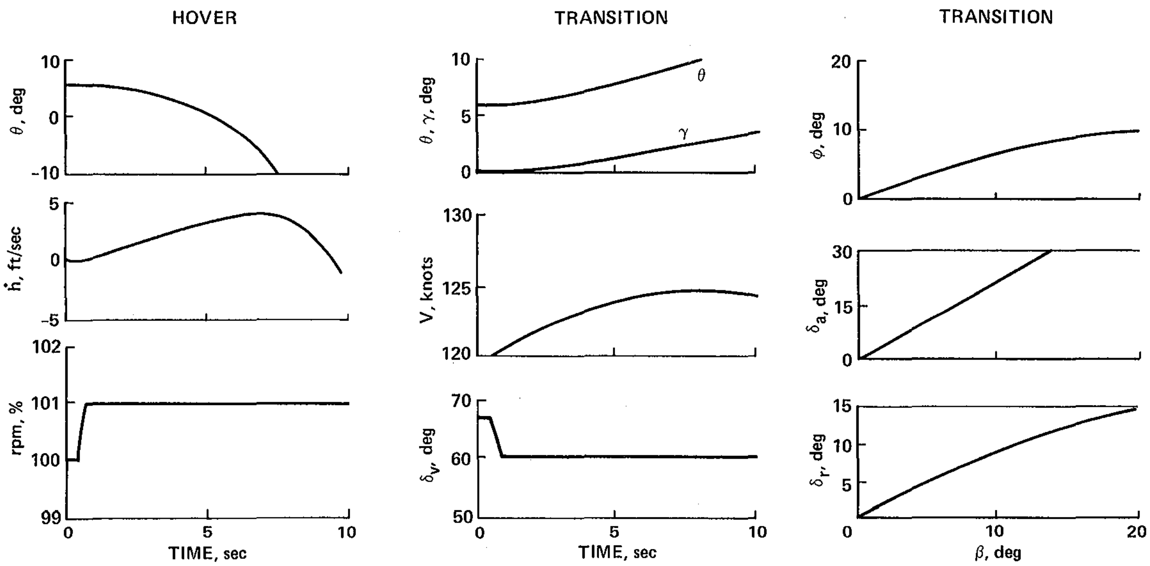
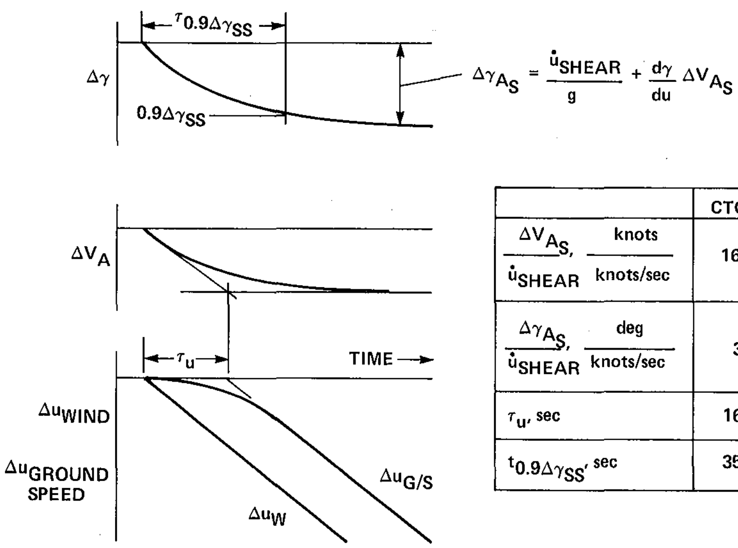


Figure 42. Control cross-coupling examples.



	CTOL	STOL
$\frac{\Delta V_{A_S}}{\dot{u}_{SHEAR}}$, $\frac{\text{knots}}{\text{knots/sec}}$	16	8
$\frac{\Delta\gamma_{A_S}}{\dot{u}_{SHEAR}}$, $\frac{\text{deg}}{\text{knots/sec}}$	3	5
τ_u, sec	16	8
$t_{0.9\Delta\gamma_{SS}}$, sec	35	20

Figure 43. Representative response of CTOL and STOL aircraft to wind shear.

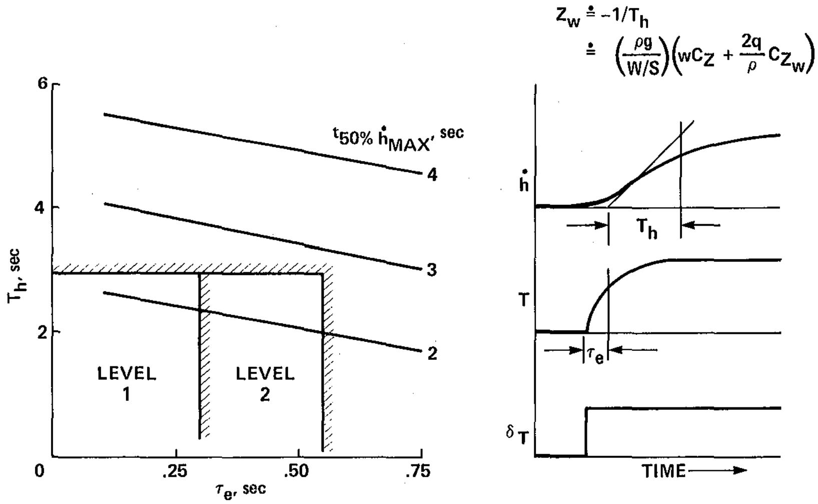


Figure 44. Height control dynamics in hover.

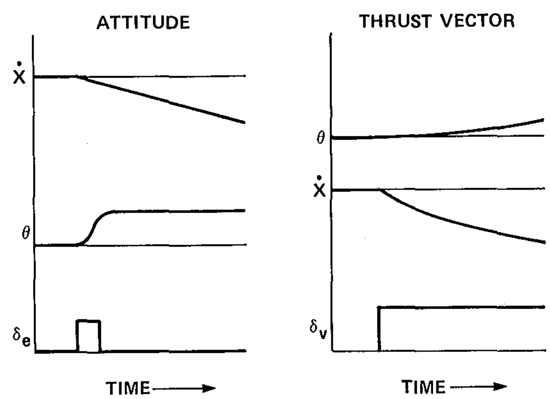


Figure 45. Low-speed translational velocity control.

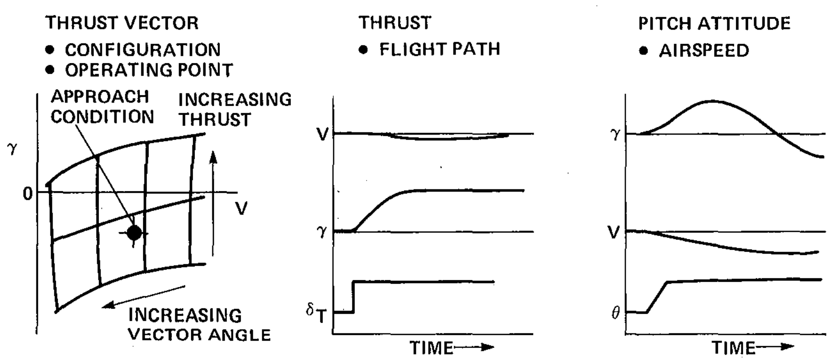


Figure 46. Transition control technique.

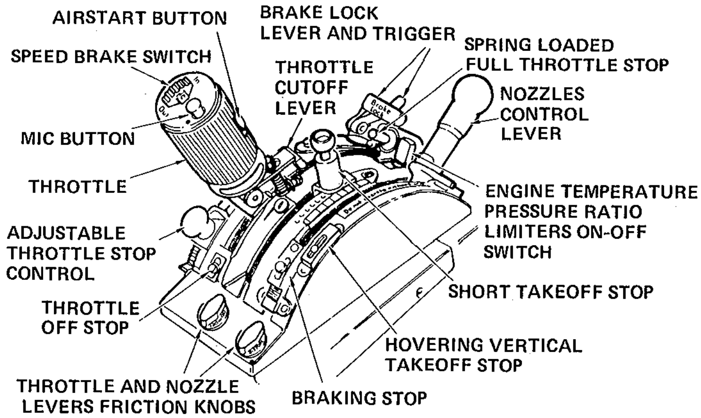


Figure 47. Harrier throttle-nozzle quadrant.

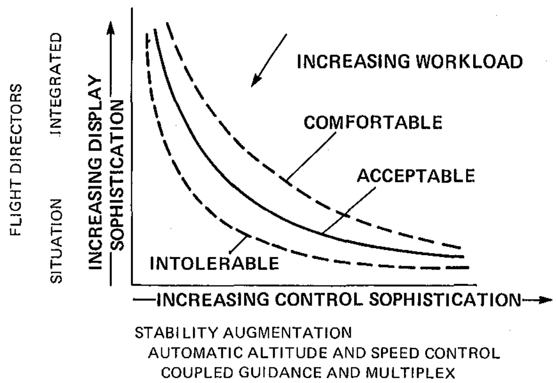


Figure 48. Tradeoff between display and control sophistication (from Ref. 49).

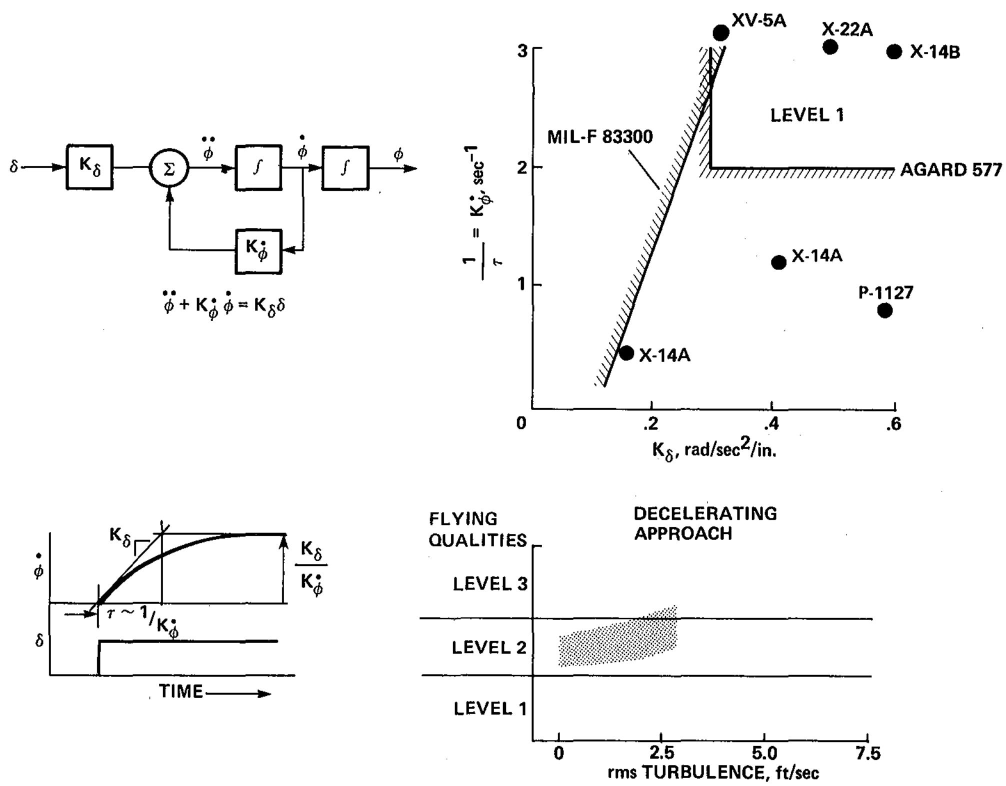


Figure 49. Rate damping stability augmentation.

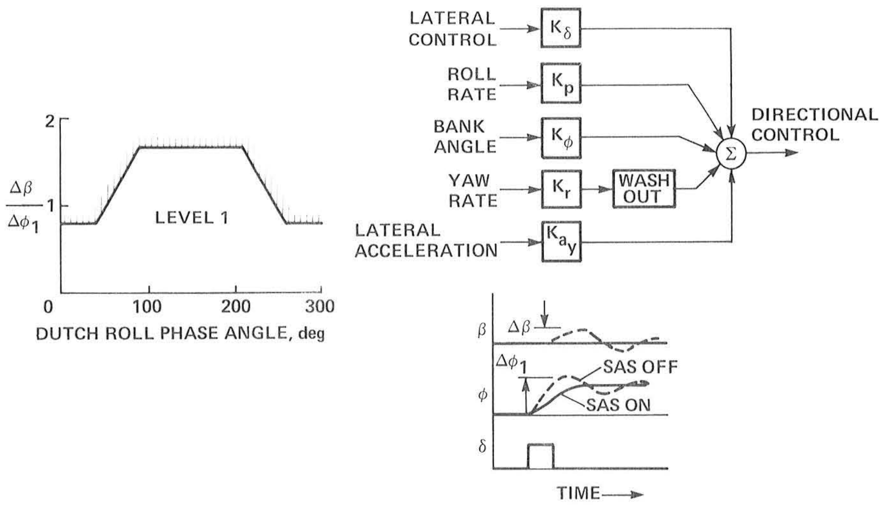


Figure 50. Yaw damper-turn coordinator.

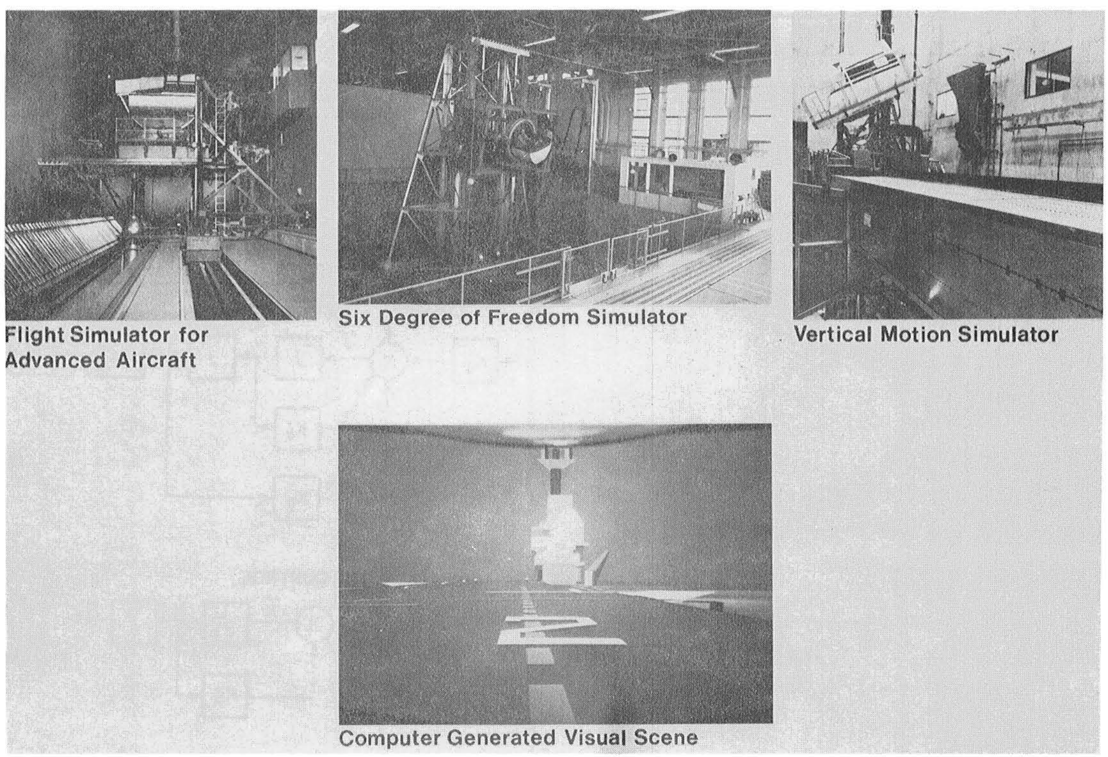


Figure 51. NASA Ames moving base simulators.

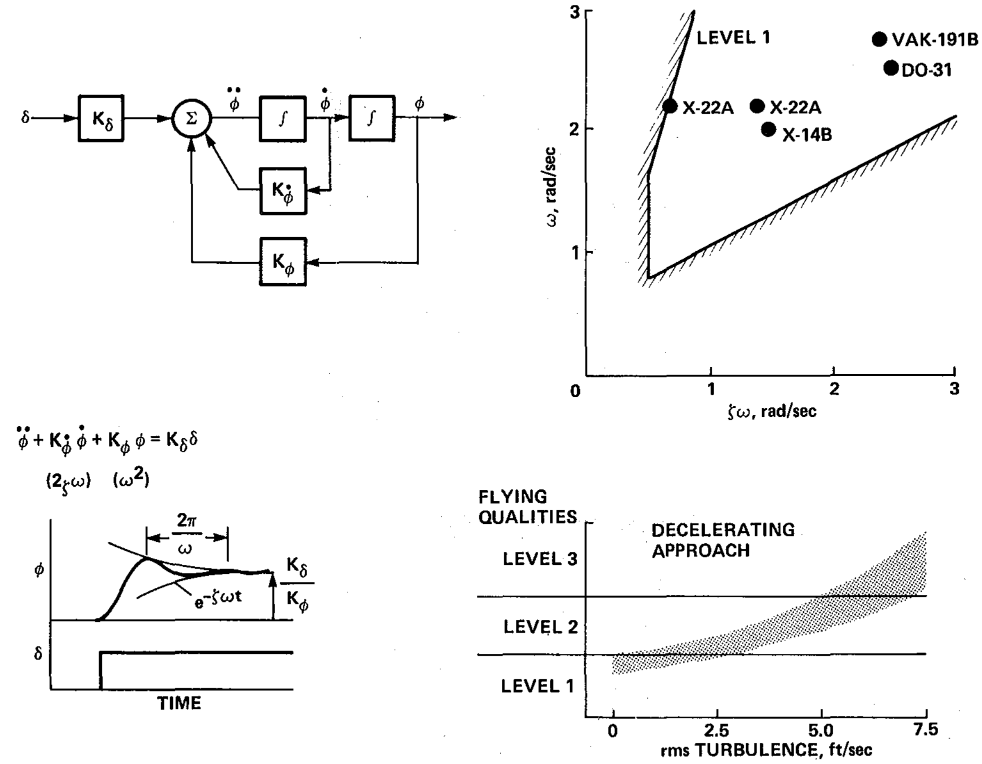


Figure 52. Attitude command systems.

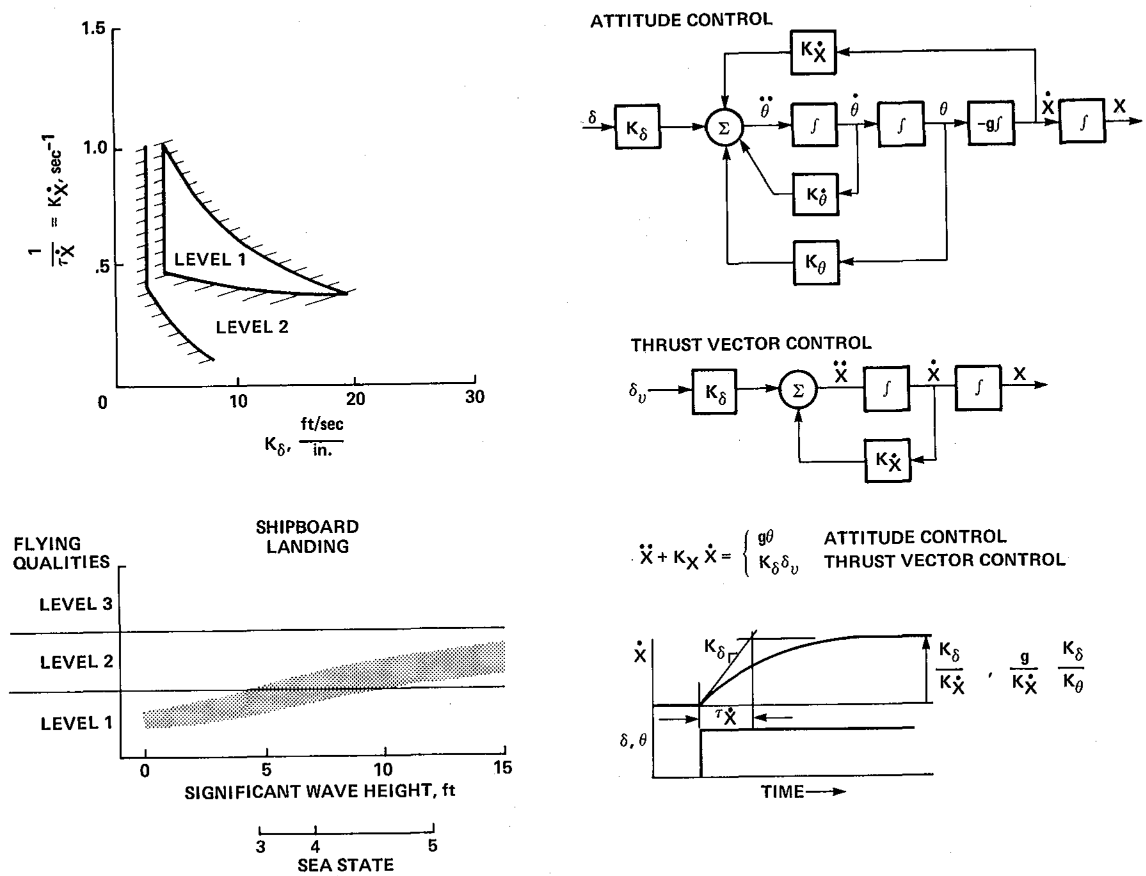


Figure 53. Velocity command systems.

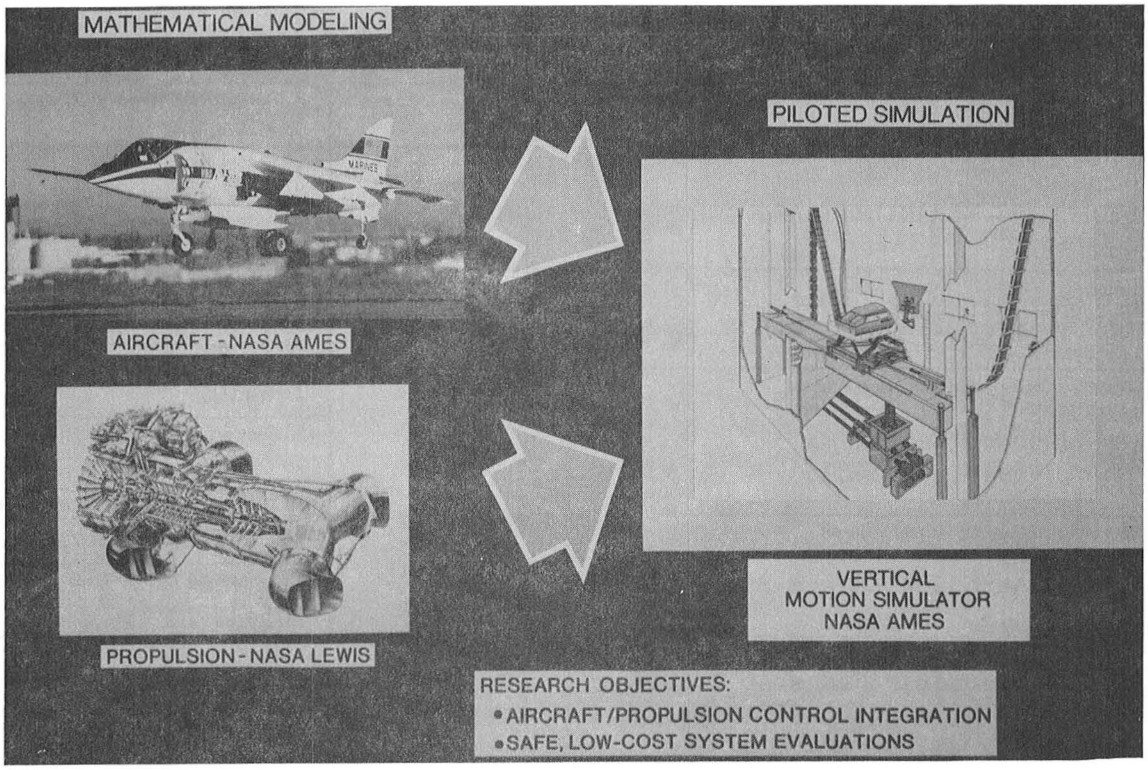


Figure 54. NASA flight/propulsion controls research.

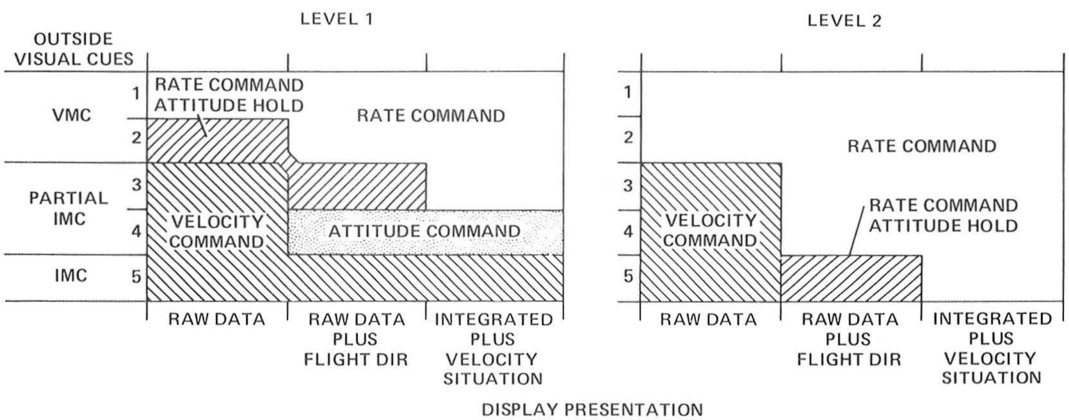


Figure 55. Control/display requirements for low-visibility conditions.

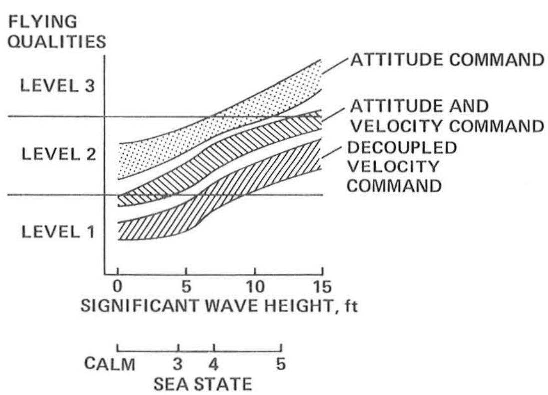


Figure 56. Shipboard landing capability.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-85939		

4. Title and Subtitle	5. Report Date
V/STOL MANEUVERABILITY AND CONTROL	April 1984
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15. Supplementary Notes

Point of contact: James A. Franklin, Ames Research Center, MS 211-2, Moffett Field, CA 94035, (415) 965-5009 or FTS 448-5009.

16. Abstract

This paper deals with maneuverability and control of V/STOL aircraft in powered-lift flight, and in addition, with specific considerations of maneuvering in forward flight. A review of maneuverability for representative operational mission tasks is presented and covers takeoff, transition, hover, and landing flight phases. Maneuverability is described in terms of the ability to rotate and translate the aircraft and is specified in terms of angular and translational accelerations imposed on the aircraft. Characteristics of representative configurations are reviewed, including experience from past programs and expectations for future designs. The review of control covers the characteristics inherent in the basic airframe and propulsion system and the behavior associated with control augmentation systems. Demands for augmented stability and control response to meet certain mission operational requirements are discussed. Experience from ground-based simulation and flight experiments that illustrates the impact of augmented stability and control on aircraft design is related by example.

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