Experimental Investigation of Control-Display Requirements for VTOL Instrument Transition

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A flight research program using the variable stability X-22A aircraft was undertaken to investigate control, display, and guidance requirements for vertical takeoff and landing (VTOL) instrument transitions. The primary purpose of the experiment was to provide meaningful data related to the interaction of aircraft control system and displayed information characteristics on pilot rating and performance during a steep decelerating descending transition from a representative forward velocity (100 knots) to hover completely under instrument conditions. Thirty-eight in-flight evaluations were performed of combinations of five generic display presentations and five levels of control augmentation systems. Primary results of the program include the demonstration of an inverse relationship between control complexity and display sophistication, as was hypothesized in the experiment design, and the definition of acceptable and satisfactory control/display combinations. In particular, it was found that the explicit display of translational velocities is required for a satisfactory system, regardless of control system complexity or automation, and that rate-augmentation-only may be acceptable only if full control director commands are provided in addition to velocity status information.

Nomenclature

p	= body axis roll rate, deg/s
q	= body axis pitch rate, deg/s
X, Y, Z	= components of ground-referenced translation position, ft
$\dot{X}, \dot{Y}, \dot{Z}$	= components of ground-referenced translation rate, fps
$\Delta(\ )$	= perturbation of ( ) = current value minus initial value
δ_{ES}	= longitudinal stick position, in.
δ_{CS}	= collective stick position, deg
δ_{AS}	= lateral stick position, in.
δ_{RP}	= rudder pedal position, in.
$\epsilon(\ )$	= error in ( ) = commanded value minus actual value
ζ	= damping ratio of second order characteristic roots
θ	= Euler pitch attitude, deg
θ_{wo}	= washed-out pitch attitude signal, deg
λ	= X-22A duct angle, measured from horizontal, deg
$\mu(\ )$	= mean value of ( )
$\sigma(\ )$	= standard deviation of ( )
τ	= time constant of first-order response, sec
ϕ	= Euler roll attitude, deg
ψ	= Euler yaw attitude, deg
ω_n	= undamped natural frequency of second-order roots, rad/s
$(\ )_c$	= command value of ( )
$(\ )_e$	= ( ) referred to approach course (Earth)
$(\ )_h$	= ( ) referred to aircraft heading axes
$\|(\ )\|_{max}$	= $\|\mu_{(\ )} \pm 2\sigma_{(\ )}\|$

Introduction

THE development of an instrument landing capability for vertical and short takeoff and landing (V/STOL) aircraft is a prerequisite for the extension of VTOL operations into restricted areas in all weather conditions. To provide this capability, problems must be solved that are more difficult than the corresponding problems for conventional takeoff and landing (CTOL) aircraft, because the landing approach now involves not only control of the spatial position of the aircraft but also precise control of a nonconstant total velocity; this task requires active use of at least one additional controller, and furthermore requires additional information to the pilot concerning the increased dimensions of his task. The pilot's control problem is exacerbated by the generally degraded flying qualities encountered as the dependence on powered lift increases, and, in VTOL configurations different than the helicopter, by an additional control requirement related to the conversion from forward flight to powered lift (e.g., wing tilt, rotor tilt, jet thrust vectoring).

It is clear, therefore, that studies of the VTOL instrument landing approach problem must consider both the definition of required levels of information presentation for the pilot and the determination of required degrees of stability and/or control augmentation for the aircraft. An excellent summary of this problem and recommendations for future research are given in Ref. 1. In this discussion of necessary research, the AGARD Working Group placed a high priority on determining the interplay between display and control complexities. This interplay is schematically illustrated in Fig. 1. The hypothesis is that an inverse relationship exists, for a given pilot rating level, between control complexity and display sophistication; the problem is to quantify to some extent these two axes and attempt thereby to define satisfactory or adequate combinations.

The general goal of the flight research experiment discussed in this paper was therefore to examine combinations of generic levels of displayed information and types of stability/control augmentation. Previous experiments conducted with the X-22A ground simulator[2] and with a CH-46 helicopter[3] were used as a starting point to define a representative approach profile and control system. A flight investigation using the XV-5B lift fan aircraft[4] provided the impetus to develop a configuration change director, while flight tests of the CL-84 tilt-wing aircraft[5] and simulator studies of a helicopter[6] indicated that electronic display presentations (as opposed to electromechanical) should form the basis for the information level. The general framework of the current investigation was based on expanding the results

Presented as Paper 77-599 at the AIAA/NASA Ames V/STOL Conference, Palo Alto, Calif., June 6-8, 1977; submitted June 13, 1977; revision received Dec. 22, 1977.

Index categories: Handling Qualities, Stability and Control; Guidance and Control.

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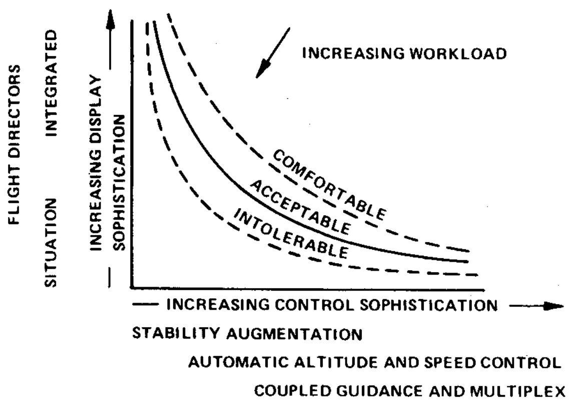

Fig. 1 Trade-off between display and control sophistication (from Ref. 1).

of these previous experimental programs by exploiting the variable stability capability of the X-22A to examine more than one type of control augmentation system and by constructing a programmable symbol generator to provide a variable format on an electronic display.

Specifically, the primary purpose was to provide meaningful data related to the interaction of aircraft control system and pilot display characteristics on pilot rating and performance during a steep decelerating descending transition from a representative forward velocity (~100 knots) to hover under instrument conditions. Accordingly, the experiment was designed to investigate combinations of several types of control system/stability augmentation characteristics with display presentations of varying sophistication, with the objective being the definition of satisfactory or acceptable combinations through the use of pilot ratings and measured performance and workload indices. To reduce the scope of the investigation to a manageable level, it was necessary to select from the many factors involved in ascertaining guidance, display, and control requirements those that were of major importance as variables.[7] The characteristics of the resulting selections are summarized in the succeeding sections, followed by a discussion of the flight results.

Guidance Chracteristics

In the context of this experiment, the term "guidance" is defined as the processing of raw X,Y,Z position data telemetered to the aircraft from a tracking radar to obtain information concerning positions and velocities and to derive the desired command relationships. It is important to recognize that the VTOL terminal area problem generally requires knowledge of, and commands for, both translational rates and positions, either for display to the pilot to aid him in the deceleration or for processing by an automatic control system to perform this operation for him. The implementations of two of the commands that are unique to the VTOL decelerating approach (deceleration profile and aircraft configuration change) are summarized here.

A fundamental problem that must be addressed for VTOL decelerating approaches is the fact that the magnitude of the along-track wind velocity component can be a significant fraction of the commanded aircraft velocity, and in fact becomes comparable as the hover point is approached. If the commanded aircraft velocity is ground-referenced for the entire approach, then guidance system acquisition airspeed will vary from approach to approach, which complicates the pilot's task; more importantly, VTOL aircraft generally have relatively narrow corridors of acceptable airspeed/configuration (thrust tilt)/rate of descent combinations, and forcing differing airspeeds may violate these boundaries. One solution to the problem, proposed in Ref. 8, is to refer the approach path and deceleration profile to the air mass by using either ground- or aircraft-measured wind velocity information to compute the transformation from ground-referenced to air-referenced coordinates. This technique insures that both the path and the deceleration are always the same with respect to the air, thereby maintaining the aircraft within its allowable transition corridor. As a result, however, the ground track (approach angle, flare point) varies with different winds; in addition, in or near hover it is velocity with respect to the ground, both longitudinally and laterally, that must be controlled, and the commands should therefore be ground-referenced at this point.

For this experiment, therefore, the implementation of the velocity commands was to divide the approach into two parts that consisted of commanding: 1) airspeed and aircraft heading during localizer and glide slope acquisition and 2) ground speed components parallel and perpendicular to the desired course during deceleration and hover. The airspeed and course commands were based on determining wind magnitude and direction from airspeed and guidance-derived groundspeed data; this information was used to command a constant airspeed and to derive an aircraft heading command to achieve the desired course by accounting for along-track and cross-track wind components. Table 1 gives these "before switching" commands in terms of ground speed referred to the aircraft axes.[7]

For the "after switching" part of the approach, the ground velocity parallel to the desired course was commanded based on a constant deceleration (0.05-g) with a linear decrease to zero during the final 100 ft, and the component perpendicular to the course as a linear function of lateral position (see Table 1). The parallel component command was implemented as a *zero-wind* velocity profile vs range on a function genrator in the aircraft; this implementation served a dual purpose of providing the "after switching" commands and also of defining the point at which the switching in command logic took place. As implemented for this experiment, this logic was constrained to cases in which a headwind was present, but the extension to include tailwinds is straightforward.

The other guidance implementation worth emphasizing is the configuration change command. VTOL configurations different than the helicopter require substantial configuration changes to convert from forward flight to powered lift in

Table 1 Horizontal velocity guidance commands

Velocity commands	Before switching (airspeed/course tracking)[a]	After switching (deceleration to hover)
Earth-referenced	$\dot{x}'_{e_c} = -\dot{x}'_{h_c}\cos\psi + \dot{y}'_{h_c}\sin\psi$	$\dot{x}_{e_c} \cong \begin{cases} -1.13\sqrt{x_e}, & x_e>0 \\ 1.13\sqrt{\lvert x_e \rvert}, & x_e<0 \end{cases}$
	$\dot{y}'_{e_c} = \dot{x}'_{h_c}\sin\psi + \dot{y}'_{h_c}\cos\psi$	$\dot{y}_{e_c} = -.06\,y_e$
A/C heading-referenced	$\dot{x}'_{h_c} = \dot{x}_h - \Delta u$	$\dot{x}_{h_c} = -\dot{x}_{e_c}\cos\psi\dot{y}_{e_c}\sin\psi$
	$\dot{y}'_{h_c} = -.06\,y_e - \dot{y}_e + \Delta u\sin\psi + \dot{y}_h$	$\dot{y}_{h_c} = \dot{x}_{e_c}\sin\psi + \dot{y}_{e_c}\cos\psi$

[a] Prime indicates before-switching command.

hover. For jet-lift aircraft (e.g., Harrier AV-8A, Dornier DO-31), the conversion process can be quite flexible, since allowable combinations of thrust inclination and airspeed are relatively unconstrained; for aircraft types such as tilt-duct, tilt-wing, and tilt-rotor, however, a fairly narrow corridor of combinations exists to avoid buzz or buffet. It may be necessary, therefore, to provide the pilot with director information to perform the configuration change safely for these types of aircraft. In a more general sense, the conversion process for any VTOL type may overload the pilot without some information to help him perform it, and hence a configuration change command may be required.

For the X-22A aircraft, the center of the allowable transition corridor is well approximated by a linear relationship between duct angle and flight velocity, which simplified the implementation but is not required. The configuration change command consisted of a commanded duct angle as a function of commanded ground speed parallel to the course, which was implemented with a balance-and-hold circuit to begin functioning at the switch to groundspeed commands. This implementation means that the conversion from the forward-flight configuration was initiated at ranges that varied with the amount of headwind present; since the conversion rate is the same for all situations (same deceleration required), the result was that the final duct angle at hover varied according to headwind, thereby maintaining airspeed-configuration within the allowable corridor.

Display Characteristics

Various independent efforts have been made to establish the information requirements of the pilot of a VTOL aircraft during an instrument approach to hover (e.g., Ref. 1). Because of the plethora of information required by the pilot for the stabilization and control of even a highly-augmented VTOL aircraft during a landing approach, conventional electromechanical instruments have been judged unsuitable for the task due to the excessively high mental workload required for gathering the information and the subsequent decision-making process.[1] The cathode-ray tube (CRT) is the best existing display device for the high data density required in integrated displays and hence was selected as the basis for the X-22A's electronic display system.

The major display variable in this experiment was the electronic display format. Brief investigations of the effects of a separate control director display on the ADI and of the lack of a configuration change director were also conducted in flight. The intent of the variation in the electronic display format was to present the pilot with three generic levels of displayed information. They were 1) ED-1: position and commanded position; 2) ED-2: position, commanded position, velocity, and commanded velocity information; 3) ED-3: position, commanded position, and velocity, with longitudinal (δ_{ES}), lateral (δ_{AS}), and collective (δ_{CS}) control director information. Two variations on the basic display formats were also evaluated. Format ED-2+ was added as a result of preliminary flight testing, which indicated the need for a collective control director due to the high pilot workload required in the control of vertical errors. Format ED-1/FD consisted of the ED-1 electronic display and three-axis control director information displayed on the electromechanical ADI; this display configuration corresponded to the CH-46 format[3] and was included both to verify these results and to reinforce the requirement for integrated displays. The techniques used to display the requried information were drawn primarily from two sources and modified as required; for example, the aircraft symbol and horizontal velocity vector are based upon helicopter display work,[6] while the expanding landing pad symbol was used as part of the display format evaluated in the CL-84 Tripartite Program.[5] Figure 2 shows the final formats.

The synthesis of the logic driving the control director elements of the ED-3 display format constituted a major portion of the display design process. The principles that guided the control director design were:

1) Design condition – the precision hover was the critical portion of the task and hence the design condition for the control director.

2) Simplified logic – an attempt was made to minimize the need for logic switching, error limiting, and gain scheduling.

3) Use of manual control theory – the response of the director elements to control inputs must be acceptable to the pilot and maintain good overall system performance (e.g., stability, response time).

4) Four-axis director – each director element commanded a single control input; therefore, in general, four director elements were required for the task: longitudinal stick, lateral stick, collective stick (thrust magnitude), and duct angle (thrust direction).

Many techniques for control director design based upon the theory of manual control were examined (see for example, Ref. 9). A technique, based upon classical control theory[10] was finally adopted. The technique involves the fulfillment of several guidance- and pilot-oriented requirements. The pilot-oriented requirements are based upon the "crossover" pilot model; basically, the director element must be designed to respond in a manner proportional to the integral of the pilot's control input in the region of potential crossover frequency in order to ensure pilot acceptability and good closed-loop system characteristics for a wide range of pilot gains.

The three control director elements on electronic display format ED-3 were a horizontal bar (HBAR) – longitudinal stick (δ_{ES}) command; a vertical bar (VBAR) – lateral stick (δ_{AS}) command; and a vertical tab (VTAB) – collective stick (δ_{CS}) command. HBAR and VBAR were implemented as "fly-to" commands while VTAB represented a "fly-away" command; that is, HBAR down and VBAR right commanded

Table 2 Control director logic

		Full-scale signal				
Director element	Variable	Rate augmentation	Att/rate augmentation	Attitude augmentation	Auto λ	Decoupled velocity control
HBAR	$\epsilon_{\dot{x}}$	± 33 fps	33	33	33	33
	Θ_{wo}	± 37 deg	75	75	75	--
	q	± 130 deg/s	230	230	230	--
VBAR	$\epsilon_{\dot{y}}$	± 42 fps	42	42	42	42
	ϕ	± 20 deg	20	110	110	110
	p	± 67 deg/s	38	296	296	296
VTAB	ϵ_x	± 100	100	100	100	100
	$\epsilon_{\dot{z}}$ ($\lambda = 0$)	± 50 fps	50	50	50	250
	↓	↓	↓	↓	↓	↓
	($\lambda = 90$ deg)	± 10 fps	10	10	10	50

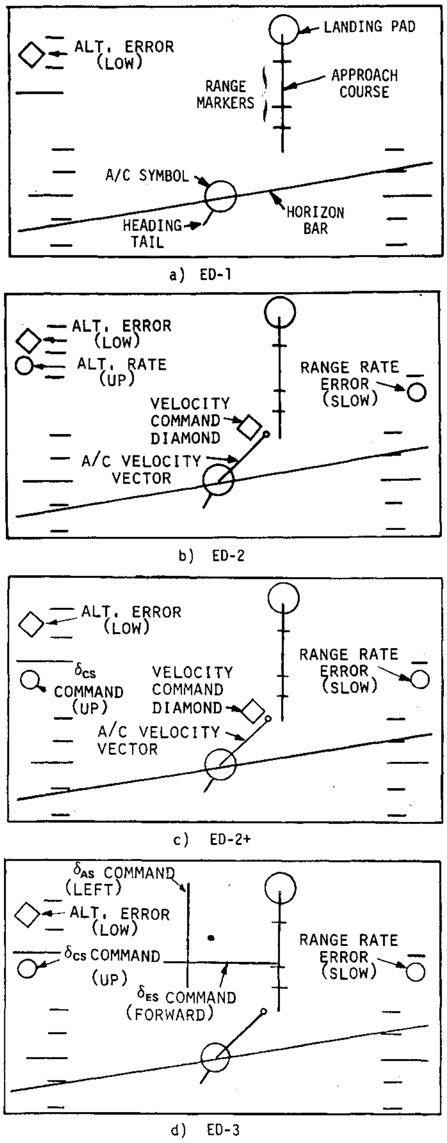

Fig. 2 Electronic display formats.

forward and right center stick inputs, respectively, whereas VTAB down required an up collective input. In general, the HBAR and VBAR control director logic was expressed as follows:

$$\text{HBAR} = K_{\dot{x}}\epsilon_{\dot{x}} + K_{\theta}\theta_{wo} + K_q q$$
$$\text{VBAR} = K_{\dot{y}}\epsilon_{\dot{y}} + K_{\phi}\phi + K_p p$$

The values for the director gains varied as a function of generic controlled vehicle characteristics; the resulting full-scale values are presented in Table 2. VTAB was generated as follows:

$$\text{VTAB} = K_z\epsilon_z + K_{\dot{z}}(\lambda)\epsilon_{\dot{z}}$$

The VTAB gain $K_{\dot{z}}$ was made an increasing function of duct angle to compensate for the decreasing vertical damping of the basic X-22A with increasing duct angle. The full-scale values for the VTAB gains are also presented in Table 2.

The fourth control director element, the configuration change director (or ITVIC, Independent Thrust Vector Inclination Command), was developed in the ground simulator and implemented in the form of a light on the evaluation pilot's instrument panel to give on-off duct rotation commands. This type of control director corresponds to the nature of the duct angle controller, which is a switch on the collective stick that drives the ducts at a constant 5 deg/s rate when activated. During the deceleration portion of the task, the ITVIC light was *on* when a commanded duct angle (λ_c) exceeded the actual duct angle (λ) by 3 deg. The commanded duct angle was a linear function of the commanded ground speed and hence a function of range to the hover point. When the ducts were rotated to reduce the duct angle error to 0.5 deg, the light was extinguished. This particular value of hysteresis in the ITVIC logic was chosen to command a sufficient number of duct rotations to minimize the pitch attitude oscillations required for vernier velocity control during the deceleration, and yet few enough rotations to minimize the pilot's dwell time on this portion of the display as well as to reduce the number and magnitude of the pressure transients in the duct drive hydraulic system.

Two alterations in the display formats occurred at or near the hover under pilot control. The push-button control which selected the automatic turn coordination (ATC) or the heading hold (HH) directional modes also selected the reference frame for the horizontal situation display. When ATC was selected, an approach course-referenced axis system was used for the display or horizontal position and velocity; these axes are the ones shown in Fig. 2. When HH was selected near the hover, an aircraft heading-referenced system was used in which the tail of the aircraft symbol is fixed and the landing pad/approach course symbol both translates and rotates to indicate position and orientation. The heading-referenced display proved to be more effective in conveying to the pilot the information required for the precision hover; however, the earth-referenced system was preferable for the approach. A second format variation for the hover task was a discrete increase in sensitivity of the velocity vector and velocity command diamond selected by the pilot. Both of the above display variations resulted from preliminary flight testing of the display formats.

Control System Characteristics

The other major design variable of this experiment was the degree of stability and/or control augmentation provided to the aircraft. The intent during the design of the augmentation systems was to examine generic levels of complexity to aid the design of future augmentation schemes, and so the characteristics of each were chosen to be "good" in the sense of compliance with MIL-F-83300 (Ref. 11) when possible, with verification of the control forces and sensitivities being made during the preliminary ground simulations. The baseline system was selected to be an attitude command augmentation system similar in concept and characteristics to that used in Ref. 3; systems both less and more complex were then designed consistent with past design practice and projected possibilities. The five resulting control systems are described in the following paragraphs; salient characteristics of them are listed in Table 3.

Rate Augmentation

This control system represents the minimum control and stability augmentation system (SAS) complexity considered feasible for V/STOL aircraft. In particular, the system was mechanized as rate SAS only, with pitch, roll, and yaw rate stabilization approximately equal to the basic X-22A SAS chosen as a representative level. Although the resulting dynamic characteristics through transition were therefore dependent on the X-22A aerodynamics and hence not completely general, these characteristics are representative of this class of V/STOL aircraft, and the results for these configurations therefore provide a suitable base for minimal augmentation complexity. Duct rotation was manual.

Attitude Command Augmentation

This system is the baseline configuration chosen to be similar to that used in Ref. 3. The directional axis was dual

Table 3 Approximate attitude transfer functions in form $K(1/\tau)[\zeta;\omega] = K(s+1/\tau)(s^2+2\zeta\omega s+\omega^2)$

	Pitch attitude to δ_{ES}	Roll attitude to δ_{AS}(turn-follow)
Attitude command: Filter + Aircraft		
0 knots:	$\frac{[.7;4.0]}{[.7;2.0]} \cdot \frac{.40(.17)(.25)}{(.17)(.29)[.76;4.13]}$	$\frac{.85(.22)(2.63)}{(.36)(2.63)[.30;2.2]}$
100 knots:	$\frac{[.7;4.0]}{[.7;2.0]} \cdot \frac{.40(.1)(.79)}{(.09)(.62)[.68;4.58]}$	$\frac{.85[.60;2.72]}{[.75;1.90][.50;3.12]}$
Att/Rt command:	Filter + Aircraft	Filter + Aircraft
0 knots:	$\frac{[.7;4.0]}{[.7;2.0]} \cdot \frac{.40(.17)(.25)}{(.17)(.29)[.76;4.13]}$	$\frac{(2)}{(0)} \cdot \frac{.35(.22)(2.63)}{(.37)(2.63)[.50;2.18]}$
100 knots:	$\frac{[.7;4.0]}{[.7;2.0]} \cdot \frac{.40(.1)(.79)}{(.09)(.62)[.68;4.58]}$	$\frac{(2)}{(0)} \cdot \frac{.35[.60;2.72]}{[.90;1.90][.55;3.12]}$
Rate Augment: ⊢ Aircraft		
0 knots:	$\frac{.40(.17)(.25)}{(.17)(3.06)[.19;.46]}$	$\frac{.35(.26)(1.6)}{(1.7)(2.5)[.11;.58]}$
100 knots:	$\frac{.40(.097)(.79)}{(.18)(-.15)[.93;2.56]}$	$\frac{.35[.86;1.31]}{(.22)(3.54)[.79;1.36]}$

Table 4 Decoupled velocity control system design

Feedback variables	Pitch gain, in./unit	Collective gain, deg/unit
$\epsilon_{\dot{x}}$, fps	−0.195	0.07
$\epsilon_{\dot{z}}$, fps	0.19	0.52
$\Delta\theta$, deg	−0.67	−0.236
g, deg/s	−0.33	−0.037
ϵ_{λ}, deg	0.2	−0.145
Feedforward variables		
δ_{ES}, in	5.73	–
δ_{CS}, deg	3.84 ($\lambda=0$) ↓ 0.0 ($\lambda=90°$)	2.26

mode, selectable by the pilot; one mode was automatic turn following (zero sideslip) implemented by feeding back lateral velocity and washed-out yaw rate in the directional channel, and the other mode was yaw-rate-command-heading hold, implemented by closing a heading loop in the directional channel, removing the washout on yaw rate, and using a proportional-plus-integral filter on the rudder commands. Both the pitch and roll axes provided attitude command responses, although the implementations were different. In the pitch channel, the aircraft was highly attitude augmented to minimize turbulence response and coupling inputs from the collective; the pitch stick commands were then shaped through a second-order prefilter "model," with feedforward gains on stick input, model pitch rate, and model pitch attitude used to ensure second-order aircraft response. In the lateral channel, system limitations precluded a similar implementation, and so attitude augmentation only, of a lower level, was used. Again, duct rotation was manual.

Pitch Attitude Command/Roll Rate Command

This system was identical to the attitude command system described previously except that an integral-plus-proportional prefilter was added to the roll stick input to provide a rate-command-attitude-hold roll response. Although the emphasis of this experiment was on localizer and glide slope tracking through deceleration rather than initial acquisition, it was recognized that roll attitude command is generally disliked by pilots for gross maneuvering because of the necessity to hold a constant force while performing a turn. The purpose of this configuration was therefore to ascertain if tracking and hover performance would be the same for roll rate command and attitude command. As with the baseline control system, duct rotation was manual.

Automatic Duct Rotation

This control system represented an increase in complexity from the baseline attitude command system by making the duct rotation automatic instead of manual. The pitch, roll, yaw, and collective stick implementations and response characteristics were identical to those of the attitude command configuration. The automatic rotation was provided by feeding the ITVIC director signal to the duct rotation system. It should be noted that, conceptually, the elimination of the manual configuration change provides a situation comparable to the helicopter instrument approach studies of Ref. 3.

Decoupled Velocity Control

This control system was the most complex investigated. The intent of the design was 1) to provide decoupled responses to collective stick (vertical velocity with respect to the ground) and duct angle (longitudinal velocity with respect to the ground) over the full range of duct angles from forward flight to hover; 2) to provide augmented damping and hence improved aircraft responses in vertical and longitudinal velocity; 3) to minimize pitch attitude input requirements through the transition. To meet the design goals, the vertical and longitudinal velocity errors as determined by the guidance system were used in feedback loops in the control system in addition to the conventional aircraft quantities. Some degree of decoupling and augmentation was sacrificed in an effort to avoid the necessity of programming all the feedbacks and cross-gearings as a function of duct angle, and in fact in the final design only one programmed cross-gearing (collective to pitch stick) was used. This system again employed automatic duct rotation. Details of the design are contained in Ref. 12; a summary of the implementation is given in Table 4.

Equipment and Procedures

The U.S. Navy X-22A V/STOL research aircraft was used as the inflight simulator for this experiment (Fig. 3). This aircraft incorporates a four-axis (pitch, roll, yaw, thrust) variable stability system, which operates in conjunction with an on-board analog computer to reproduce a wide range of aircraft characteristics and to perform guidance and control system computations. A further capability is a variable-format head-down or head-up display; for this experiment, the head-down display was used. Details of the aircraft systems are given in Ref. 13. The raw X, Y, Z position data were provided by an AN/SPN-42T1 tracking radar, with the guidance computations performed on board the aircraft.

For this experiment, the evaluations were performed by one pilot. The specific tasks to be accomplished for each evaluation consisted of two fully hooded instrument approaches from 100 knots to hover; at the conclusion of the second approach, vertical airwork and an actual hooded landing were options available to the pilot. The elements of the approach consisted of level flight localizer acquisition (1700 ft above ground level, 100 knots); constant speed glide slope acquisition (7.5 deg) at approximately the 12,000-ft range; constant deceleration (0.05 g) on the glide slope, commencing at a range dependent on headwind (zero-wind range approximately 8000 ft); flare to level final approach commencing at approximately 800 ft range, final altitude 100 ft, deceleration continuing to hover; and hover at 100 ft above simulated pad, vertical airwork as desired.

Upon completion of the two instrument approaches, the pilot made comments with reference to a detailed comment card that directed his attention to the characteristics of the display, control system, and his performance which were of interest, and then assigned a Cooper-Harper pilot rating[14] to

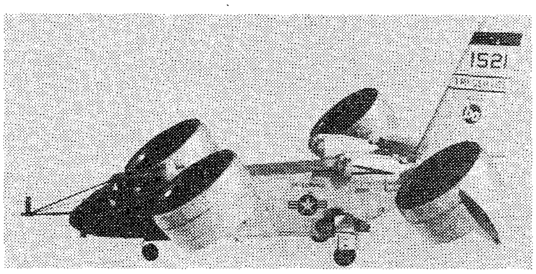

Fig. 3. U.S. Navy variable stability X-22A.

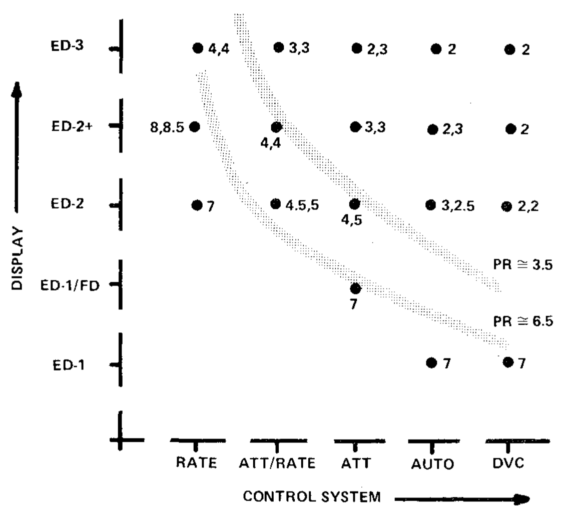

Fig. 4. Pilot rating data (with ITVIC, no crosswind effect).

the aircraft/display configuration as evaluated, although the ratings did not include the effect of actual landings. These comments and ratings plus measured performance and control usage indices constitute the major data obtained in this experiment, which will be summarized in the next two sections.

Pilot Rating Results

The bulk of the pilot rating (PR) data obtained is summarized in Fig. 4 on a "plot" of display sophistication vs control complexity. This presentation of the results is chosen to emphasize the interactive effects; it is emphasized that the axes are ordinal rather than interval, and that the approximate iso-rating lines refer only to the data specifically on the figure. In a general sense, the most apparent result is the demonstration of the hypothesized interaction between control complexity and display sophistication, particularly for a satisfactory rating ($PR \leq 3.5$): as the level of augmentation and/or automation increases, the required display presentation decreases from full integrated control director information (ED-3) to velocity and velocity command information both horizontally and vertically (ED-2). It is also apparent that, for a combination to receive a satisfactory rating, the display must explicitly include velocity status information (ED-2, ED − 2 +, and ED-3). This requirement is primarily hover oriented and is a function of the need to know translational drift velocities accurately for precision station-keeping or touchdown; it is worth noting that, although fully hooded landings were not considered as part of the evaluation task, a few such "blind" landings were actually performed during the course of the experiment. A final general result can be observed by noting that, as long as velocity is explicitly shown, no trend of pilot rating with display sophistication was found for the decoupled velocity control system: if "good" aircraft response characteristics relative to the required task are provided, the details of the displayed information become less important to satisfactory system performance.

Although acceptable system performance for the rate augmentation/full control director (ED-3) combination had been predicted by the ground simulations prior to flight and verified in flight when low headwinds were present, pilot comments in the evaluations noted that control of heading, without the dual-mode directional system used in the more complex augmentation schemes, required additional attention in the hover. This problem would be exacerbated if the pilot were required to perform large heading changes in hover to line up with the wind, and so selected repeat evaluations were performed with a pure crosswind of approximately 10 knots. The resulting data are shown in Fig. 5. As can be seen, the rate augmentation control system was not acceptable even with full control director information. This degradation is a result of the pilot being unable to point the aircraft into the wind during the hover and the concomitant drift velocities that are generated. Note that no degradation was observed for the

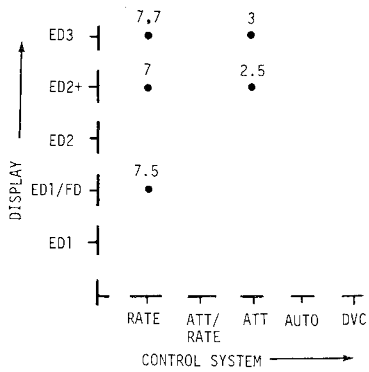

Fig. 5. Effect of crosswind on pilot rating data (with ITVIC).

Table 5 *F*-ratios and significance levels (in parentheses)

Measure / source	$\lvert\dot{\epsilon}_{x_h}\rvert_{max}$, fps	σ_θ, deg	$\sigma_{\delta_{ES}}$, in.	$\lvert\epsilon_z\rvert_{max}$, ft	$\sigma_{\delta_{CS}}$, deg	$\lvert\epsilon_{\dot{y}_h}\rvert_{max}$, fps	$\lvert\phi\rvert_{max}$, deg	$\sigma_{\delta_{AS}}$, in.
Control	34.53	54.14	264.64	4.05	107.97	13.64	7.43	12.88
	(.01)	(.01)	(.01)	(.05)	(.01)	(.01)	(.01)	(.01)
Display	27.58	10.57	64.6	40.76	15.7	10.45	12.39	4.88
	(.01)	(.01)	(.01)	(.01)	(.01)	(.01)	(.01)	(.05)
Cont/disp	8.13	12.79	4.37	9.17	8.03	9.58	9.84	10.81
	(.01)	(.01)	(.01)	(.01)	(.01)	(.01)	(.01)	(.01)

Table 6 Performance/workload comparisons for control/sytstems

Measure / control system	$\lvert\dot{\epsilon}_{x_h}\rvert_{max}$, fps	σ_θ, deg	$\sigma_{\delta_{ES}}$, in.	$\lvert\epsilon_z\rvert_{max}$, ft	$\sigma_{\delta_{CS}}$, deg	$\lvert\epsilon_{\dot{y}_h}\rvert_{max}$, fps	$\lvert\phi\rvert_{max}$, deg	$\sigma_{\delta_{AS}}$, in.
Rate	20.1	3.2	0.91	32.8	2.5	11.5	5.2	0.24
Att/Rt	11.0	1.1	0.33	21.5	1.9	10.7	5.2	0.18
Att	18.2	1.7	0.40	35.1	2.1	10.6	6.0	0.25
Auto	17.1	1.9	0.39	31.6	1.9	9.7	5.5	0.23
DVC	8.9	2.0	0.34	24.3	1.3	8.9	4.5	0.21

Table 7 Performance/workload comparisons for DVC

Measure / display	$\lvert\epsilon_{\dot{x}_h}\rvert_{max}$, fps	σ_θ, deg	$\sigma_{\delta_{ES}}$, in.	$\lvert\epsilon_z\rvert_{max}$, ft	$\sigma_{\delta_{CS}}$, deg	$\lvert\epsilon_{\dot{y}_h}\rvert_{max}$, fps	$\lvert\phi\rvert_{max}$, deg	$\sigma_{\delta_{AS}}$, in.
ED-3	7.9	2.2	0.30	19.9	1.5	9.4	5.2	0.25
ED-2+	9.4	1.9	0.35	24.6	1.2	9.8	3.5	0.16
ED-2	9.5	1.9	0.30	28.5	1.3	7.6	4.9	0.22
ED-1	12.9	2.1	0.14	41.4	1.6	29.7	6.1	0.24

attitude command system in crosswinds because the turn-following (zero sideslip) mode of the directional control channel pointed the aircraft into the wind automatically. It is possible that a display of wind direction information to the pilot could alleviate this problem for the rate augmentation control systems. Without this information, the control system must perform the pointing function to achieve a satisfactory or acceptable system.

Performance/Workload Results

The pilot comments and ratings obtained for the configurations were supplemented by analyses of measured indices of workload and performance using analysis of variances (ANOVA) techniques. The metrics that were used are given in the Nomenclature and Table 5 and correspond generally to those typically considered in measuring performance and workload. Reference 7 summarizes the data processing required to obtain them in a form suitable for ANOVA procedures.

A summary of the F ratios for the selected metrics during the descending deceleration part of the task, and the resulting significance levels, is given in Table 5 for the five control systems and three most sophisticated display presentations. Considering here only the major effects of either control systems or displays, independent of each other, it may be seen that the level of significance was 0.01 for all the metrics analyzed except two: height tracking ($\lvert\epsilon_z\rvert_{max}$), for which control system changes were significant to only 0.05, and lateral stick usage ($\sigma_{\delta_{AS}}$), for which display changes were also significant at only 0.05. The height-tracking result is probably due to the fact that only the decoupled velocity control system specifically addressed augmenting the vertical axis of the aircraft. The reduced significance of display format on lateral stick usage is somewhat surprising; the raw data actually show decreasing tracking performance laterally but nearly constant lateral stick usage with increasing display sophistication,[7] and so, apparently, the increasing information levels resulted in more concentration by the pilot on the longitudinal controllers (δ_{ES},δ_c) to the detriment of lateral tracking.

One may also see the effects shown by the F tests by examining the actual performance/workload metrics used in these analyses. Considering first the effect of the control system independent of display presentation, Table 6 lists these measures for the five control systems examined. In general, the performance was best with the DVC system and the workload was least (e.g., $\lvert\epsilon_z\rvert_{max}$ and $\sigma_{\delta_{CS}}$). Note in particular that the collective stick, which primarily commands vertical velocity during the approach, had the lowest standard deviation with this control system; altitude control is a high workload aspect of VTOL approaches because of the low inherent height damping of most machines, and the influence of augmenting this damping can be clearly seen as a workload reduction. It is also interesting to note that the lateral tracking was best, and maximum roll angle the least, with this control system: improving the longitudinal characteristics permits increased attention to the lateral-directional control axes.

The second aspect of interest is the influence of display format on these metrics for a given control system. The decoupled velocity control system provides a good example, and the results are given in Table 7. First, as the pilot ratings also indicate, the performance without explicit display of velocities (ED-1) is significantly worse than with the other formats. Although, with velocity information provided, no trend in pilot rating with display sophistication was found to exist for the DVC system, the F tests showed that performance and workload differences did occur, and these differences can be seen in Table 7. The display of control director information (ED-3) yielded better performance in the longitudinal degrees of freedom and a higher collective workload; for similar performance levels, the ED-3 format also yielded a higher lateral workload. It appears therefore that the overall reduction in mental and physical workloads as a result of the "major" control system effect had a greater bearing on pilot rating than did the effect of variations in displayed information so long as velocity was explicitly included as part of that information.

Concluding Remarks

Several general conclusions may be drawn from the results of this flight program.

1) Descending decelerating approach transitions from forward flight to the hover may be performed by VTOL aircraft under instrument conditions given satisfactory control and display system characteristics as defined by this experiment.

2) A tradeoff between control augmentation complexity and display presentation sophistication exists for generic levels of each.

3) Precision hover under instrument conditions requires explicit display of translational velocity for a satisfactory system.

Some specific results relate to previous experimental work.

1) Pilot comments indicate a preference for attitude command in both pitch and roll for precision instrument hover.

2) Pitch and roll control directors are not required for a satisfactory system if attitude command control systems with good dynamic characteristics in pitch and roll are provided.

3) Pitch and roll control directors are required for an adequate system if rate augmentation only is provided.

4) A configuration change director (ITVIC) is required for a satisfactory system when configuration changes must be performed manually.

Acknowledgment

The research discussed herein was supported by the Naval Air Systems Command under Contract No. N00019-73-C-0504.

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