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Experimental Investigation of Control-Display Requirements for a Jet-Lift VTOL Aircraft

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A flight experiment using the U.S. Navy variable-stability X-22A V/STOL aircraft was conducted to examine control system and display presentation requirements for a jet-lift VTOL aircraft performing decelerating approaches under instrument flight conditions. Aerodynamic characteristics of the AV-8B Advanced Harrier were simulated for a prescribed decelerating approach profile using the X-22A's variable-stability system; around this simulation, an analog of the AV-8B control system was implemented to investigate a range of realizable control system designs. Combinations of these control concepts and a variety of head-up display formats and information levels were evaluated in flight for simulated instrument approaches.

Introduction

A FUNDAMENTAL problem that must be addressed in the development of operational VTOL aircraft is a requirement to perform decelerating transitions in the terminal area under instrument meteorological conditions. If the aircraft is limited to operating in weather which permits visual transition to hover, a considerable degree of operational flexibility is lost; it has been estimated that the AV-8A Harrier weather minima for VTOL operation (400-ft ceiling, approximately 1-n.mi. visibility), which are a result of requiring transitions in VMC, preclude operations from European land bases one-third of the time, and that achieving the NAVTOLAND project goal of zero-ceiling, 700 ft visibility operations would show an 89% improvement in capability.[1] To achieve an instrument transition capability, it is clear that particular attention must be paid to the aircraft control characteristics in this flight regime and to the type of information that must be displayed to the pilot, because the requirement to control a nonconstant total velocity and the generally poor flying qualities of VTOL aircraft during the transition from aerodynamic to powered lift result in a pilot workload considerably higher than for instrument approaches in conventional (CTOL) aircraft.

In an experiment conducted with the U.S. Navy variable-stability, variable-display X-22A V/STOL aircraft in 1975, the effect of generic levels of control and display parameters on instrument decelerating approaches for VTOL aircraft was investigated in flight for the first time.[2] This program demonstrated two major points: 1) Descending decelerating approach transitions from forward flight to hover may be performed by VTOL aircraft under instrument conditions given satisfactory control and display system characteristics as defined in the experiment. 2) A trade-off between control augmentation complexity and display presentation sophistication exists for generic levels of each. With regard to the second point, it was found that increasing control system complexity reduces the influence of displayed information level on pilot rating, whereas, for the simpler control concepts such as rate-damping-only, sophisticated flight director displays are required to achieve an acceptable control-display combination (Fig. 4 of Ref.2).

The advent of redundant fail-operational digital flight control systems implies that full authority control augmentation designs may be considered, assuming appropriate sensor complements. Examples include the decoupled velocity control system considered in Ref. 2 and the high-gain state-rate feedback procedure used in a recent experiment.[3] Such designs are not applicable, however, to aircraft which rely on less complicated control system implementations. In particular, the AV-8A Harrier and AV-8B Advanced Harrier employ series servos in mechanical flight control links to effect stability and/or control augmentation inputs; flight safety considerations require that the authority of these servos be only a fraction (e.g., 20%) of the total control authority. The limited authority prevents high-gain SCAS designs because of actuator saturation. Hence, the basic questions for this type of flight control implementation become: What is the minimum level of SCAS augmentation that is required in conjunction with sophisticated flight displays, and what task limitations result from the limited augmentation level permitted?

This paper describes a flight experiment using the U.S Navy X-22A V/STOL aircraft that addressed these questions specifically toward the AV-8B Advanced Harrier. The variable stability/control capability of the X-22A was used to simulate the unaugmented AV-8B characteristics during decelerating approach. Around this simulation, an electrical analog of the AV-8B control system and series SCAS servos was implemented to investigate a range of possible control system designs. A head-up display (HUD) unit, as in the AV-8B, was installed in the X-22A and driven by a variable-format digital computer to produce a variety of possible display formats and information levels.[4] Combinations of realizable control augmentation concepts and HUD formats were then evaluated for simulated instrument approaches incorporating a deceleration from 65 knots to hover.

Experiment Design

The control-display interaction for VTOL aircraft may be addressed by considering the number of controllers with which the pilot must interact and the general fashion in which he uses these controllers to perform the decelerating approach task. In the general VTOL problem, there are five controllers to be considered: pitch stick, roll stick, rudder pedals, thrust magnitude controller (e.g. throttle), and thrust direction or configuration change controller. Qualitatively, the pilot's control task is 1) to stabilize and control aircraft attitudes, 2) to command, in conjunction with thrust magnitude and

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direction, translational velocities, 3) to follow prescribed velocity profiles, and/or 4) to integrate the velocities for comparison with translational position commands. In the context of the closed-loop display-pilot-aircraft system, then, each of these control loops must be addressed in the design of displays and control augmentation, and deficiencies in either the control characteristics or displayed information must be accounted for in the design of the other.

Consider initially the control augmentation aspect of the problem. If one includes instrument hover in the pilot's task, the previous X-22A results indicate that a satisfactory control-display combination should include attitude command augmentation at least in the pitch axis.[2] Studies performed on terminal area operations of lift/cruise fan VTOL designs[5-7] used attitude command augmentation in pitch and roll plus some directional assistance as baseline control systems for both VMC and IMC situations; similar augmentation was used in X-14 VMC hover tests,[8] and in the VALT helicopter program.[9] The major advantage of this type of control system is that a stick-force-per-attitude relationship, coupled with stabilization of lightly damped (or unstable) oscillatory roots, is provided in hover; if the attitude dynamics are "good," then the inner attitude loop requires reduced attention from the pilot, the force cues provide attitude information, and velocity loops may become dominant in the pilot's scan pattern.

With regard to the Harrier implementation, however, the attainment of "good" attitude command dynamics through a decelerating approach depends heavily on how much augmentation is required for "good," since the limited actuator authorities imply limited augmentation capability. In general, previous work has used augmentation which yields a natural frequency of 1.5 to 2.0 rad/s,[2,9] although ground simulator studies plus the X-14 results indicate levels down to 1.0 rad/s can be satisfactory (pilot rating better than 3½ for *hover*).[8] The question which must be answered for an AV-8B implementation is whether the lower levels of augmentation become feasible with the limited actuator authority and yet still provide satisfactory control characteristics through the deceleration to hover.

In the event that attitude command augmentation at a satisfactory level is not feasible, another question is whether the control-display tradeoff can provide a satisfactory system through increased display sophistication in combination with rate damper or rate-command-attitude-hold control systems. These types of control systems are candidates because inputs to the augmentation actuator may not require as much authority as attitude command augmentation does. In the previous X-22A experiment, rate augmentation in combination with three-axis control director information was found to provide an acceptable ($6.5 > PR > 3.5$) combination *if* the control director logic was carefully developed and wind/turbulence levels were low; crosswinds, for example, degraded the system to unacceptable ($PR = 6.5$).[2] Even though rate and rate-command-attitude-hold control-display combinations can be sensitive to external inputs and desired task performance (pilot technique), it is important to ascertain for the AV-8B application whether the control deficiencies for these types of augmentation can be compensated for, to some extent, with additional display sophistication, since the limited actuator authorities may necessitate these augmentation types.

Consider now the display aspect of the problem. Assuming again the inclusion of instrument hover in the pilot's task, the previous X-22A experiment results indicate that the displayed information must include translational velocity information explicitly.[2] A plan-view velocity vector was also used in the CL-84 HUD flight experiment[10] and one NASA lift/cruise fan VTOL ground simulator experiment.[3] The proposed AV-8B HUD format includes digital airspeed readout, but does not include analog representations of either the velocity vector the pilot must control or of plan-view position information.[11]

Table 1 AV-8B experiment augmentation systems

Longitudinal, rad/s	Lateral directional, rad/s
RCAH	
1.0	2.0
1.5	2.0
2.0	2.0
ACAH	
1.0	2.0
1.5	2.0
2.0	2.0

Previous work has generally considered at least three-axis control director information (pitch, roll, thrust magnitude—e.g. Refs. 2, 3, and 8), whereas the proposed format includes a two-axis director (roll, thrust magnitude). A more basic question relative to HUD formats is the scaling of the pitch attitude display. One-to-one scaling with the real world may be too sensitive for terminal area operations, given the limited vertical field of view, if the airplane exhibits poor longitudinal control characteristics; and in fact headdown attitude indicators typically would scale to approximately 16:1 if shown head-up. The influence of a breakout to visual conditions, for part of the deceleration and/or hover, on the display requirements is also an important question for operational applications.

Based on these considerations from previous research, the design of this experiment was therefore oriented toward the following goals:

1) Investigate control-display requirements for VTOL instrument terminal area operations given constraints on allowable augmentation authority and predicated upon AV-8B aerodynamic characteristics. Use the proposed AV-8B control system and display presentation as a baseline.

2) Emphasize display information variations for head-up presentation to improve system performance for less desirable control system implementations.

3) Examine the influence of increasing augmentation authorities. Examine the influence of permitting breakout to visual conditions.

Control System Parameters Design

Table 1 lists the control systems designed for implementation around the simulated AV-8B characteristics; the achieved pitch and roll attitude response dynamics at 65 knots and hover are tabulated in Ref. 4. Brief summary descriptions are given below.

AV-8B SAS

The proposed AV-8B SAS uses pitch rate, roll rate, washed out yaw rate, a small amount of lateral acceleration, and an aileron-rudder crossfeed; it is very similar to the SAS in the AV-8A Harrier. The dynamic characteristics that result are adequate for visual deceleration and hover, although the characteristics at STOL approach speeds (e.g. 65 knots) require extensive pilot attention to airspeed and sideslip control.

Rate-Command-Attitude-Hold (RCAH)

This type of control system adds feedback of pitch and roll attitude which, as implemented here, is switched in when the pilot is not commanding a pitch or roll stick force and is switched out when he is. The rate and attitude feedbacks were selected to provide attitude-hold dynamics with natural frequencies of approximately 1.0, 1.5, 2.0 rad/s, 0.7 damping ratio. The response of pitch or roll attitude to a stick input is that of a rate-only augmentation system, with the level of rate feedback being determined by the $\zeta = 0.7$ condition, because

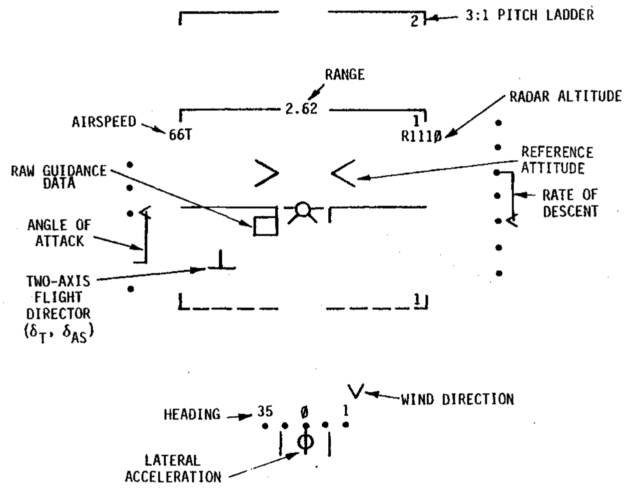

Fig. 1 Proposed AV-8B HUD format (AV8-ϕ).

of the switch-out implementation. In addition to the attitude-hold feature, a much higher lateral-acceleration-to-rudder gain was used to reduce sideslip excursions. As has been discussed, although a rate-command-attitude-hold system does not provide a stick-force-to-attitude relationship, the attitude feedback can be expected to help the aircraft velocity stability both during approach and hover.

Attitude-Command-Attitude-Hold (ACAH)

This type of system maintains the pitch and roll attitude feedback at all times, so that pilot force inputs command an attitude. The same dynamics used for the rate-command-attitude-hold system were investigated. The 2.0 rad/s system is comparable to the ATT system from the previous X-22A experiment.[2]

AV Formats

Several variations on two basic HUD formats were designed for investigation in combination with the control systems described in the previous section. One set was based on the proposed AV-8B HUD format as given in Ref. 10. This format is shown in Fig. 1 (called AV8-ϕ in this experiment); differences from the operational AV-8A HUD[12] include: 1) flight director symbol for vertical and lateral guidance, 2) guidance source marker, 3) digital readout of range, and 4) pitch bars at 10 deg intervals instead of 30 deg intervals in a 3:1 instead of 5:1 (i.e., more sensitive) scaling.

A hierachy of information levels, starting from this basis, is shown in Fig. 2. The intent of these variations was to modify the information level of the basic format (AV8-ϕ) to convert the basic AV-8B display, which is based upon HUD formats used for CTOL aircraft approach and landing, to ones more appropriate for VTOL approach and landing. Specific examples are summarized below.

Three-Axis Control Directors

The basic (AV8-ϕ) format's flight director symbol commands throttle inputs (vertical displacement) and lateral stick inputs (lateral displacement). The display design philosophy used in previous work[2,3,9] requires that one symbol command inputs from one controller; hence, a three-cue flight director, with the current flight director symbol commanding longitudinal and lateral stick inputs and a separate symbol on the left-hand side of the display commanding throttle inputs, was investigated (AV8-3, AV8-6).

Integrated Vertical Information

Because of the extremely low levels of natural height damping exhibited by the AV-8B in hover and low-speed flight, the altitude tracking task can be a significant problem. The basic format uses separated symbols to indicate angle-of-attack, descent rate, vertical position, and throttle commands. A similar type of display format was used in Phase I of the CL-84 Tripartite Program[10] and, as indicated in Ref. 13, was found to be a major factor in the poor height-keeping performance which was observed in that experiment. The integration of vertical position and rate (or throttle director) information on the left-hand side of the display (to

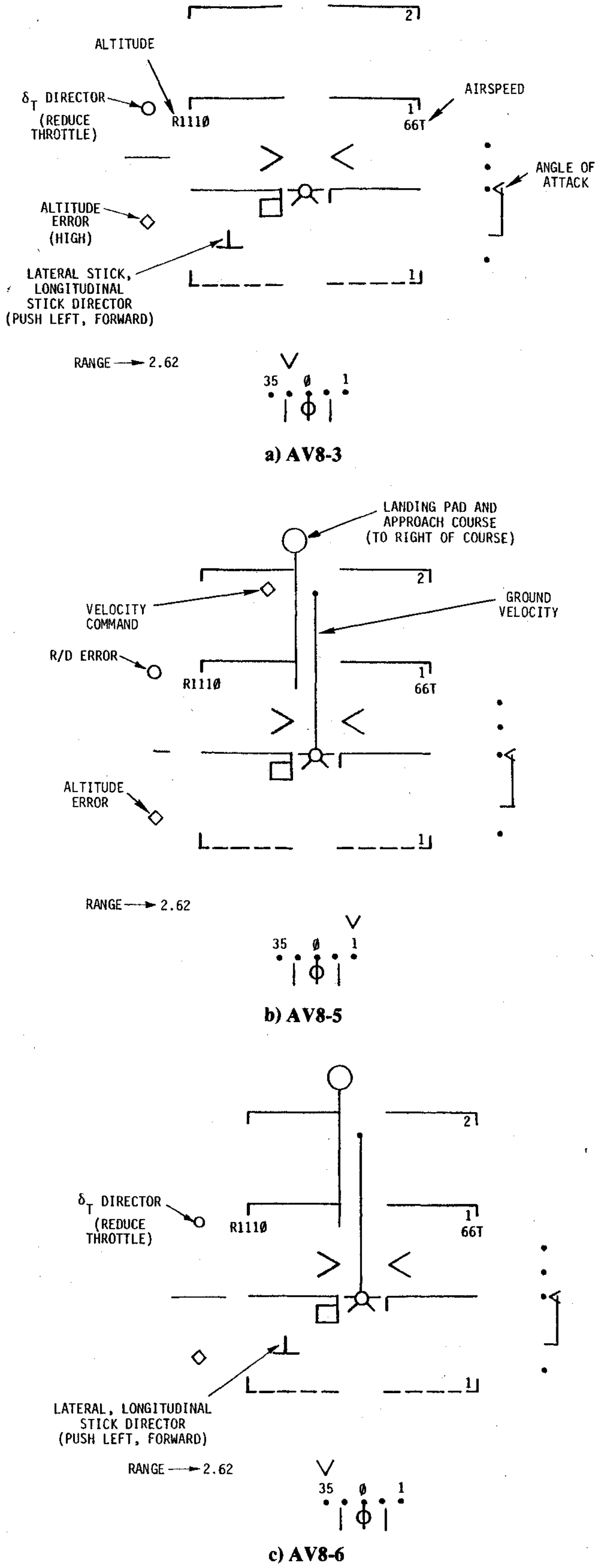

Fig. 2 AV formats.

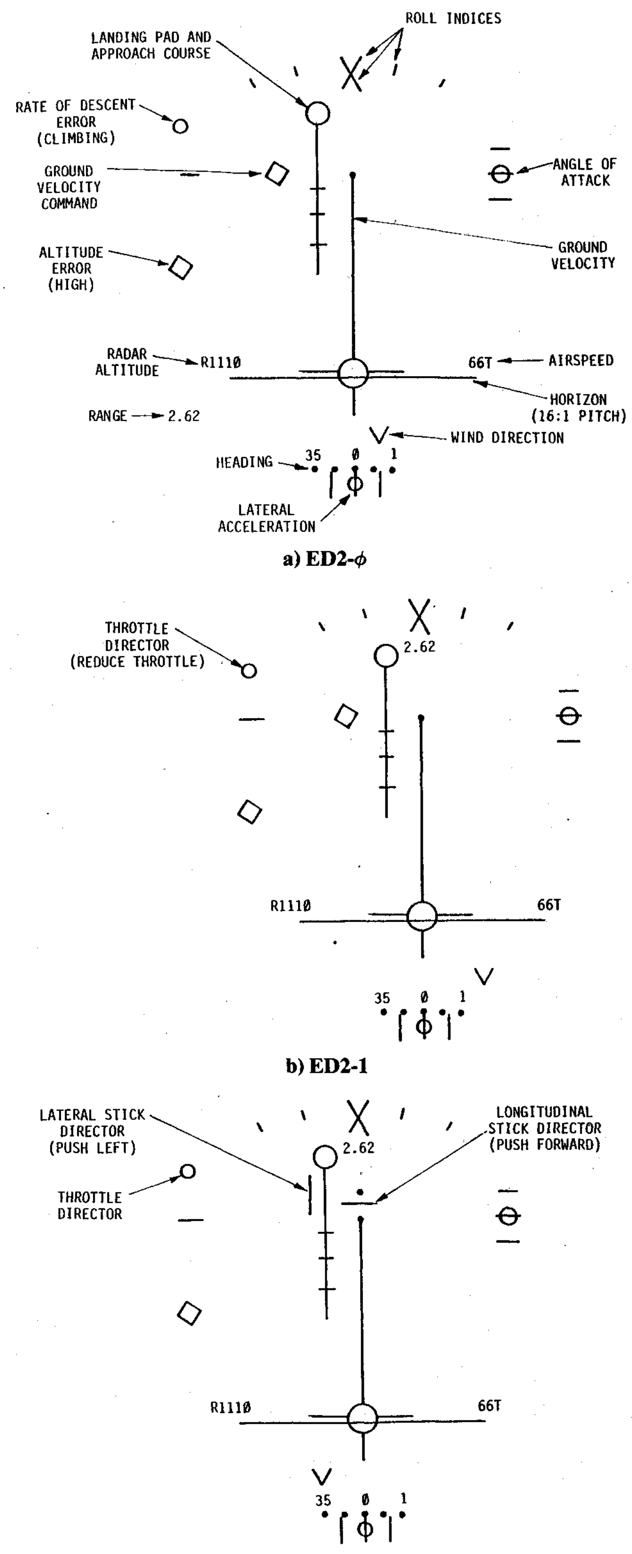

Fig. 3 ED formats.

correspond to left-hand throttle usage) was used in the previous X-22A experiment,[2] and all the formats investigated in flight, except AV8-ϕ, used this modification (AV8-3, AV8-5, AV8-6).

Velocity and Position Information

Finally, in order to adapt the display further to the evaluation task, particularly the final approach to the hover, horizontal position (in the form of a moving landing-pad/approach-course symbol), rate (a velocity vector symbol), and commanded rate (a diamond) are included for display to the pilot in a fashion similar to that found acceptable in the X-22A Task III[2] and CL-84 Phase I[13] programs (AV8-5, AV8-6).

ED Formats

The other basic format is a head-up presentation of those formats investigated head down in the previous X-22A experiment.[2] In this case, the head-down pitch attitude scaling, based on a 3-inch ADI, is maintained for the head-up presentation (approximately 16:1). These three formats are shown in Fig. 3. The information level of ED2-ϕ corresponds to that of AV8-5, and ED2-2 corresponds to AV8-6; format ED2-1 has a single control director (throttle). These formats include the following modifications to the head-down formats investigated in the Ref. 2 experiment: 1) an improved display of pitch and roll attitude, 2) a display of angle-of-attack and limits, 3) a display of side acceleration and limits, and, 4) digital readouts of altitude, range, and airspeed, and a tape readout of heading. Both formats also included a deceleration-initiation command, which consisted of flashing the aircraft symbol at the range (dependent on headwind) when nozzle rotation was to be made. Table 2 summarizes the information levels of all the formats designed for this experiment.

AV-8B Simulation and Task Design

To assess the control-display requirements for a jet-lift VTOL in a realistic context, it was decided to use the X-22A variable-stability capability to simulate in flight, as accurately as possible, the stability and control characteristics of the AV-8B for prescribed terminal area tasks. A simplified linear model at six discrete velocities from 0 to 105 knots was defined using force and moment perturbations computed from the AV-8B ground simulator model computer program. Given this linear model, simulation laws were developed to reproduce as nearly as possible the resulting characteristics with the X-22A at these six velocities (0, 30, 50, 65, 80, and 105 knots).[14-16] Figure 4 shows time histories of the resulting longitudinal simulation at 65 knots; similar validity was achieved both longitudinally and laterally at all six velocities. With regard to the deceleration simulation, the problem was that the thrust inclination of the AV-8B is changed essentially instantaneously to initiate a deceleration, while the X-22A duct rotation system permits rotation at only 5 deg/s. Because the drag damping of the AV-8B is quite low, however, the time taken to decelerate to zero velocity could in fact be well matched by programming the X-22A duct rotation to provide an equivalent exponential decrease in airspeed. This procedure was adopted, therefore, using a simulated nozzle-angle controller to initiate the programmed duct rotation. In addition, an attempt was made to match the initial AV-8B throttle response characteristics (thrust inclination) during deceleration by using the X-22A elevon control surfaces in a collective rather than differential fashion for simulated throttle inputs.

As a means of assessing the simulation fidelity from a piloting standpoint, two Marine AV-8A pilots flew two flights each in the X-22A during the course of this experiment. Within the context of a linear simulation and the conduct of a task profile (65 knots to hover) that was not representative of AV-8A operations, both pilots called the simulated response and deceleration characteristics representative of the AV-8A characteristics. Specific differences noted were higher attitudes required in hover to counteract steady winds, and slightly easier altitude control in hover, but both pilots noted that the overall fidelity was good in that the same level of difficulty was produced as in the AV-8A.[17]

The evaluation task consisted of constant speed acquisition at 65 knots of localizer and a 5 deg glide slope starting at 1000 ft AGL, with a one-step nozzle rotation (deceleration initiation) at approximately 0.5 n.mi., and a commanded

Table 2 Task IV display hierarchy

AV8/ED FORMAT	ORIENTATION	POSITION VERTICAL	POSITION HORIZONTAL	RATE VERTICAL	RATE HORIZONTAL	DIRECTOR
BASIC (AV8-ϕ)	BASIC PITCH LADDER; HEADING TAPE; ANGLE OF ATTACK	ILS BOX AND ALTITUDE READOUT	ILS BOX AND RANGE	$\dot{h}$ DISPLAY	V (DISCRETE) READOUT	2-AXIS
BASIC + 3-AXIS FD (AV8-3)	SAME AS ABOVE	BOX AND ALTITUDE: ALT. ERROR DIAMOND	BOX AND RANGE	VTAB	V (DISCRETE/TAPE)	3-AXIS
BASIC + VEL., POS. (AV8-5)	SAME AS ABOVE	ALTITUDE READOUT; ALT. ERROR DIAMOND	RANGE + LANDING PAD	ALT. RATE ERROR	V (DISCRETE/TAPE) VELOCITY VECTOR	NONE
BASIC + VEL., POS. + 3-AXIS FD (AV8-6)	SAME AS ABOVE	SAME AS ABOVE	SAME AS ABOVE	VTAB	SAME AS ABOVE	3-AXIS
VELOCITY/POSITION (ED2-ϕ, ED2-1)	ATTITUDE DISPLAY; HEADING TAPE; ANGLE OF ATTACK + LIMITS; HEADING TAIL; OPT. ROLL DISPLAY	ALTITUDE READOUT; ALT. ERROR DIAMOND	RANGE READOUT; LANDING PAD	ALTITUDE RATE ERROR OR VTAB	VELOCITY VECTOR; V (DISCRETE/TAPE)	NONE
VEL./POS. + 3-AXIS FD	SAME AS ABOVE	SAME AS ABOVE	SAME AS ABOVE	VTAB	SAME AS ABOVE	3-AXIS

level-off at 100 ft AGL during the deceleration prior to hover. Each evaluation consisted of two complete approaches, with ratings assigned and comments recorded after the second approach.

Experiment Results

Figures 5 and 6 present the majority of the pilot rating results obtained in this experiment. The numbers are conventional Cooper-Harper ratings,[18] and the letters are turbulence effect ratings, with "A" denoting no influence on the evaluation and "D" denoting a moderate effect on the evaluation.[4] Two ratings on Fig. 5 were for evaluations in which breakout to visual conditions occurred at 100 ft AGL, ~ 100 ft range; the remainder of the ratings were for simulated IFR conditions during the entire approach, including hover. Simulated actuator authority limits were exceeded significantly in only one evaluation, and so the distinction between evaluations with the simulated AV-8B limits (20% in pitch and roll) and a few evaluations with no simulated limits is not pertinent and not indicated.[4] Reference 4 also discusses four evaluations in which configurations were downrated due to control sensitivity difficulties; these configurations are not included in Figs. 5 and 6: the control sensitivities are within an acceptable band for the data shown. Finally, it was found in the previous X-22A experiment that rate-damping control system suitability was strongly influenced by ambient winds/turbulence.[19] For this reason, post-experiment analyses on measured air-referenced and ground-referenced data have been used to separate the ratings into two categories. In general, the data shown in Fig. 6 were obtained when a tailwind component was present, a crosswind of more than 45 deg was present, or measured turbulence rms velocities in excess of 4.0 ft/s were present. The data given in Fig. 5, therefore, are for "good" atmospheric conditions.

Consider initially the "no-environment-effect" data of Fig. 5. The first immediately seen result is that the control-display tradeoff exhibited in the Ref. 2 experiment is not apparent to the same degree; in fact, if configurations incorporating either the basic rate-damping control system (AVSAS) or HUD format (AV8-ϕ) are excluded, the pilot ratings for all of the other configurations are within the normally expected

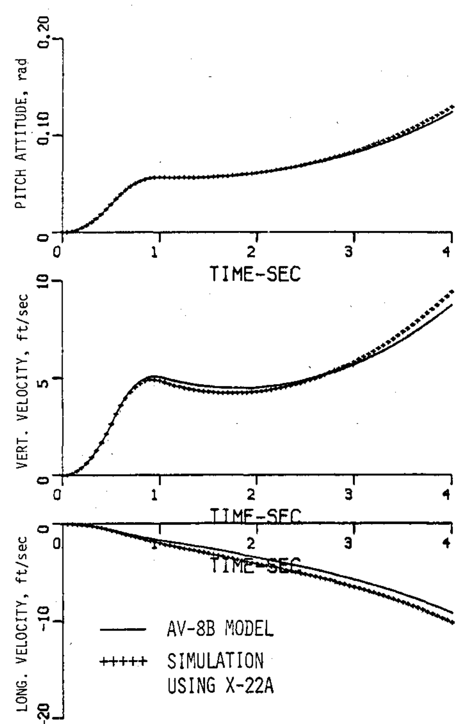

Fig. 4 Simulation time histories (pulse stick input).

variation for any given configuration ($\Delta PR \leq 1$), and generally are on the borderline for "satisfactory" ($PR \leq 3\frac{1}{2}$). The lack of a tradeoff for these configurations is probably due to less marked information differences on the displays than in the previous experiment, plus the fact that both rate-command and attitude-command implementations used attitude feedback to eliminate the positive real root in the longitudinal dynamics and significantly higher directional feedback, to augment directional stiffness, than does the basic rate-damping control system (AVSAS).[4] None of the configurations shown in Fig. 5 showed any substantial exceedence of the basic actuator limits ($\pm 20\%$ in pitch and roll). Hence a

DISPLAY / CONTROL SYS.	AVSAS	1.0 RCAH	2.0 RCAH	1.0 ACAH	1.5 ACAH	2.0 ACAH
ED2-2	1½ A			2½ C		
ED2-1	5B 5½ C					
ED2-Ø	3B 3A	3C	4A 3C	3A 3 4A	4	
AV8-6	4B					
AV8-5	2½ C 7A	3	2½	4B		
AV8-3			3		4	
AV8-Ø	7 5C 5C(B.O.)				3(B.O.)	

Fig. 5 Pilot rating results—no environmental effect influence. B.O. = breakout at 100 ft AGL, ~1000 ft range.

DISPLAY / CONTROL SYS.	AVSAS	1.0 RCAH	2.0 RCAH	1.0 ACAH	1.5 ACAH	2.0 ACAH
ED2-2	7A 3C					
ED2-1				6D		
ED2-Ø	7D	6D				
AV8-6	5½ C 6C					
AV8-5	5½ 4½ D	5	3A			7½ D*
AV8-3	6D					
AV8-Ø					7	

Fig. 6 Pilot rating results—evaluation influenced by ambient crosswind, tailwind, and/or turbulence level. * = extensive SAS actuator limiting.

general result indicated by these data is that it is possible to implement, within the simulated actuator authority limits, control systems employing sufficient attitude feedbacks to provide satisfactory controlled-element dynamics.

Turning to the configurations using the basic rate-damping control system (AVSAS), several interesting results may be observed. First, the proposed HUD format (AV8-ϕ) in combination with the basic SAS (AVSAS) did not receive pilot ratings of satisfactory ($PR < 3½$) even when a breakout to visual conditions prior to the hover was included. According to the pilot comments, this control-display combination did not alleviate sufficiently longitudinal attitude, height, or directional control problems even during the initial portion of the acceleration prior to breakout. Although there are holes in the data base, it may be inferred from pilot comments that the basic HUD format (AV8-ϕ) is, in fact, not suitable for full instrument decelerations to hover regardless of control system because of the lack of analog position and velocity data in hover; note, however, that with an attitude command system and a breakout to visual conditions, the AV8-ϕ format is satisfactory, indicating the importance of stabilizing the longitudinal unstable root.

The "no-environment-effect" data of Fig. 5 indicate the difficulty of trying to provide an instrument deceleration capability with the basic rate-damper SAS through display improvements alone. For example, the AV8-5 format with this control system received pilot ratings of 2½ and 7 in wind/turbulence conditions that were almost identical.[4] The difference in ratings occurred because in one case the pilot attempted a wing-down approach to cope with the crosswind (approximately 5 knots from the left), and ended up cross-controlled with substantial "ball out" lateral accelerations ($PR = 7$), whereas in the other case, he permitted the aircraft to crab into the wind as he decelerated. These ratings highlight the importance of the directional characteristics of the aircraft for decelerating instrument approaches, which was also observed in the Ref. 2 experiment; it is worth noting that cross-control problems were not noted in any of the RCAH or ACAH configuration approaches, which is probably attributable to the much higher value of lateral-acceleration-to-rudder feedback used (Dutch roll frequency approximately doubled to 1.5 rad/s).

While the Fig. 5 data appear to indicate that satisfactory performance can be achieved with the AVSAS rate-damper control system for some of the formats, it can be seen from Fig. 6 that significant degradation occurs in the presence of off-nominal winds/turbulence. None of the displays were rated better than "acceptable but unsatisfactory" with AVSAS in these conditions. As was also found in the Ref. 2 experiment, a major difficulty with rate-damper control systems for VTOL instrument approaches appears to be their sensitivity to external inputs, as the AVSAS data demonstrate again here. Therefore, although it is interesting that ratings of satisfactory could be obtained even without control directors (e.g. ED2-ϕ) for the AVSAS, the important point is that this type of control system results in controlled element dynamics that are susceptible to environmental disturbances and pilot technique, and hence should be considered satisfactory for this task only in restricted circumstances.

A final point of interest that is not specifically shown by the pilot ratings nor the analyzed approach data in Ref. 4 is that the ED2 presentation of attitude information was somewhat preferable to the pilot over the AV8 presentation; preferable information presentation characteristics were the separate roll attitude index and the solid (as opposed to broken in the middle) horizon line. It should also be noted that the difference in pitch attitude presentation scaling (3:1 attenuation for AV formats, 16:1 for ED formats) appeared to the pilot as differences in aircraft pitch control sensitivity for configurations in which this characteristic was actually the same. Since the attitude sensitivity of the display is what the pilot interprets during pitch inputs on instruments, it is possible that further investigations to find the "best" scaling are warranted.

Conclusions

The flight experiment discussed in this paper was conducted using the X-22A V/STOL aircraft, which is capable of varying stability characteristics, control augmentation systems, and display presentations in flight. In this case, the aerodynamic characteristics simulated were representative of a jet-lift VTOL aircraft, and the control systems investigated were predicted on a particular form of implementation; hence, the dynamic situations investigated were constrained to those typical of Harrier-class VTOL aircraft. On this basis, and subject to the results of further environment and performance analyses, the following general conclusions may be tentatively drawn:

1) It is possible to provide control-display combinations within the proposed AV-8B capabilities, as simulated in this experiment, that permit instrument approaches with a deceleration from 65 knots to hover.

2) A pitch attitude command system with a 1.0-rad/s natural frequency can be implemented for this approach task within the AV-8B SAS actuator authority limits as simulated, and provides a good control system.

3) The proposed basic AV-8B rate-damper control system is sensitive, in terms of task suitability, to display information nuances and environmental variations.

4) The proposed basic AV-8B HUD format does not give a satisfactory system ($PR < 3.5$) for the full instrument approach regardless of control augmentation.

5) The X-22A V/STOL aircraft provided a representative simulation of the AV-8B for the approach profile examined.

Acknowledgments

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