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Simulation and Flight Test Evaluation of Head-Up-Display Guidance for Harrier Approach Transitions

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Position and speed guidance displays for STOVL aircraft curved, decelerating approaches to hover and vertical landing have been evaluated for their effectiveness in reducing pilot workload and improving performance. The NASA V/STOL Systems Research Aircraft, a modified YAV-8B Harrier prototype, was used to evaluate the displays in flight, whereas the NASA Ames Vertical Motion Simulator was used to extend the flight test results to instrument meteorological conditions (IMC) and to examine performance in various conditions of wind and turbulence. The simulation data showed close correlation with the flight test data, and both demonstrated the feasibility of the displays. With the exception of the hover task in zero visibility, which was level-3, averaged Cooper-Harper handling qualities ratings given during simulation were level-2 for both the approach task and the hover task in all conditions. During flight tests in calm and clear conditions, the displays also gave rise to level-2 handling qualities ratings. Pilot opinion showed that the guidance displays would be useful in visual flight, especially at night, as well as in IMC.

Nomenclature

D_f = threshold range, ft
d = aircraft range from the selected hover point, ft
d_p = range at which the pilot is alerted to reconfigure the aircraft, ft
d_r = range at which the aircraft should be reconfigured, ft
f_{ae} = length of the speed guidance ribbon, deg
K_{ax} = deceleration error gain, deg s^2/ft
V_w = wind speed, ft/s
V_{xf} = desired longitudinal speed relative to the hover point at the threshold, ft/s
v_x = horizontal longitudinal speed relative to the hover point, ft/s
$\dot{v}_x$ = horizontal longitudinal acceleration, ft/s^2
$\dot{v}_{xr}$ = reference value of $\dot{v}_x$, ft/s^2
$\bar{X}_u$ = slope of the groundspeed vs range line (may be regarded as an average of the stability derivative X_u), 1/s
$\bar{X}'_u$ = factor used to correct $\bar{X}_u$, 1/ft
$\bar{X}_{u_0}$ = slope of the groundspeed vs range line for no wind and thrust vector pointing vertically, 1/s
ΔT = pilot-alert lead time, s
ΔV = final-longitudinal-velocity bias, ft/s

Introduction

NASA's V/STOL Systems Research Aircraft (VSRA) flight research program is aimed at developing and validating critical technologies for advanced V/STOL and STOVL aircraft through the development and evaluation of advanced integrated control and display concepts.[1,2] Previous simulation development and evaluation at Ames Research Center[3-5] and elsewhere[6] has shown the feasibility of these concepts, and it remains for the VSRA to demonstrate in flight the operational benefits promised by the simulation experience. The flight research program is being conducted in two phases that are based upon the appropriate modifications of the aircraft to facilitate the flight research. First phase modifications of the YAV-8B included installation of a complete data acquisition system and sensors necessary for measuring aerodynamic, control, propulsion, and inertial parameters, as well as new Head-Up-Display (HUD) and flight control computers required to implement the new position and speed guidance displays. No new actuators or advanced control laws were implemented in this phase—the original YAV-8B rate damping SAS was left intact. Second phase modifications will include the installation of new actuators and advanced control laws.

At present, Harrier V/STOL operations are restricted to 200-ft cloud ceiling and ½-n.mi. visibility for land-based operations; for shipboard operations the weather minima are 300 ft and 1 n.mi. The standard approach technique starts at a stabilized airspeed between 110–130 kt, using an engine exhaust nozzle angle of 40–50 deg. Somewhere between ½ and 1 n.mi. from the landing point, the pilot reconfigures the airplane by moving the engine nozzles to the hover position of 82 deg. The specific position along the approach path where the nozzles are reconfigured is largely a judgment call by the pilot, based on airspeed and wind. Throughout the deceleration to hover, the pilot continuously increases engine thrust as aerodynamic lift is reduced; pitch attitude is used to modulate the deceleration so as to bring the aircraft to a hover over the desired hover point. At night or with reduced visibility, the task is difficult to perform precisely, and often the closure rate to the initial hover point is too slow. Excessive amounts of fuel can be burned during these inefficient approaches, and dangerous, low-fuel situations can result.

The research described in this article was motivated by the need to reduce the difficulty of performing precise, decelerating approaches in degraded weather conditions and at night. The objective was to provide guidance to perform these approaches using techniques that mimic those currently used by Harrier pilots. The algorithm used in this experiment is an exponential-deceleration speed guidance law[7] that capitalizes on the natural deceleration characteristics of the Harrier and which provides simple nozzle reconfiguration and pitch cues to the pilot on the HUD. Lateral and vertical pursuit[8] guidance is also displayed on the HUD. The speed guidance algorithm is designed to bring the aircraft to a speed of 18 kt

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at a threshold distance of 200 ft from the initial hover point, at which point the pilot visually completes the deceleration to hover. Since no advanced attitude or propulsion augmentation is required, the speed-guidance law is readily adaptable to AV-8B Harrier II operations. A separate display format is also provided on the HUD for hovering operations. The addition of hovering guidance for operational aircraft will require additional precision sensing at the landing site.

This article describes the YAV-8B research aircraft and discusses the HUD displays. A brief description of the guidance algorithm is given, and the evaluation tasks are discussed. The conduct of the simulation and flight testing is discussed. And finally, results and conclusions are presented.

Aircraft Description

The YAV-8B Harrier shown in Fig. 1 is a single seat, high-performance, transonic, light attack V/STOL aircraft that served as the prototype AV-8B Harrier II. A single Rolls Royce Pegasus turbofan engine provides thrust for conventional flight and V/STOL operations, as well as compressor bleed air for the aircraft's reaction control system (RCS). The nozzle system can direct the engine thrust from fully aft to 98 deg below the fuselage reference line. Aircraft attitude is controlled by reaction control jets in hovering flight and conventional aerodynamic surfaces in wing borne flight, with both systems contributing during transition.

The major system components aboard the VSRA consisted of dual digital Flight Control Computers (FCCs) that contained state estimation, guidance, and display drive laws; dual inertial navigation units (INUs) that were used to provide attitudes, body angular rates, linear velocities and accelerations, radar altimeter, a programmable symbol generator used to drive the HUD with guidance and display commands from the FCCs, a mode select panel that provided for pilot mode number (guidance source selection, e.g., radar uplink) inputs as well as a moving map display, airdata sensors, cockpit control sensors, microwave landing system (MLS) range and angle receivers, and an uplink receiver to provide the FCCs with radar and laser tracker measurements. Major ground-based components that interacted with the aircraft included the MLS transmitters, radar tracker, and high-accuracy laser tracker.

HUD Formats

The HUD symbol drive laws and flight path synthesis are described in detail in Ref. 8. There have been some modifi-

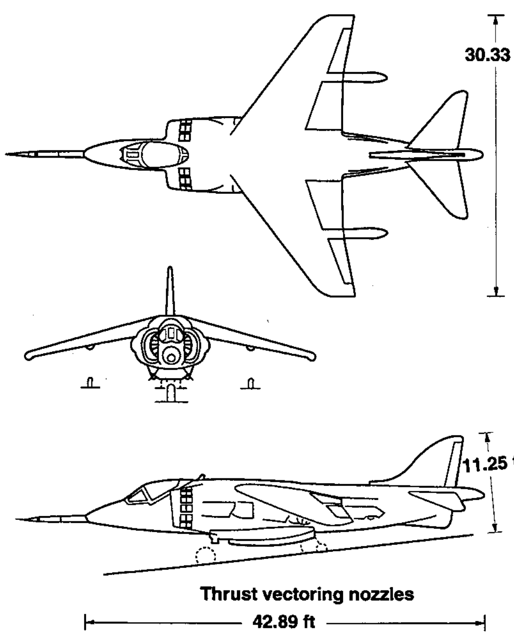

Fig. 1 YAV-8B Harrier (VSRA).

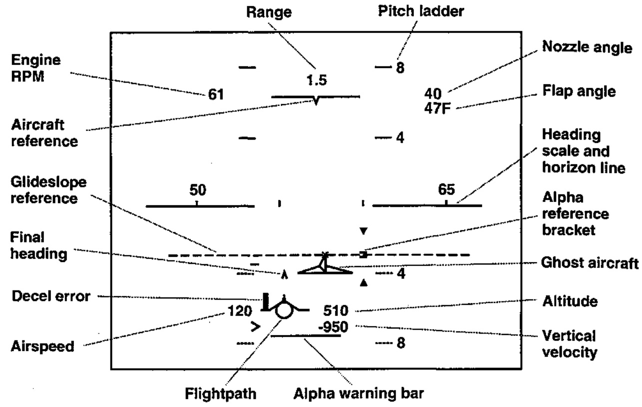

Fig. 2 Approach HUD display.

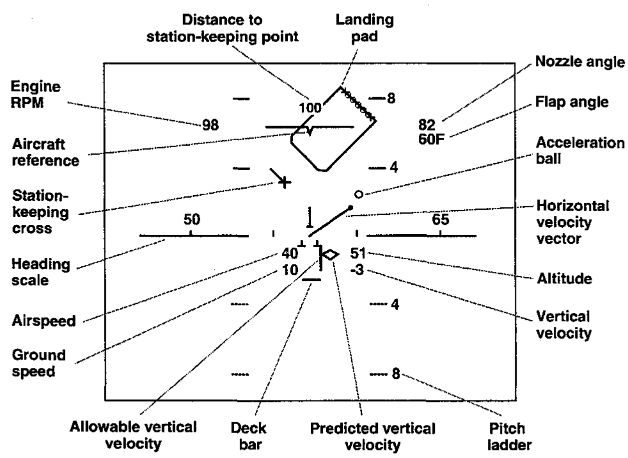

Fig. 3 Hover HUD display.

cations of the display symbologies since they were first implemented, and Figs. 2 and 3 show the displays as they were used during this simulation and flight test. In general the HUD was designed to provide pilots of V/STOL aircraft with complete guidance and control information for Category-IIIC terminal area flight operations. The HUD features different display formats for approach and hover. The approach display is based on the principle of pursuit guidance. The primary guidance information consists of symbols representing a ghost aircraft and the longitudinal deceleration error. The ghost aircraft represents a phantom aircraft that flies 10 s ahead of the real aircraft along the synthesized flight path. The pilot maneuvers the aircraft vertically and laterally using throttle and lateral stick until the flight path and ghost symbols coincide. Any deviation of the aircraft from the synthesized flight path diminishes with a time constant of 10 s. Speed guidance is presented by the deceleration error ribbon on the left wing of the flight path symbol. The drive law for this ribbon is discussed in the next section. Situation information that accompanies the flight path and ghost symbols include aircraft attitude, speed, altitude, engine rpm, engine nozzle angle, heading, longitudinal acceleration, and distance to the initial hover point. Of particular note is the angle-of-attack reference bracket, which is, in effect, a depressed pitch attitude reference symbol and aids the pilot in maintaining a reference pitch angle.

The hover display format is a representation of vertical and horizontal (plan view) aspects. The central element is a fixed "trident" symbol representing a plan view of the aircraft and showing the scaled location of the landing gear and nose boom. The landing pad is presented in both horizontal and vertical aspects. In the horizontal aspect, the pad symbol is geometrically similar to the landing pad and is scaled in both size and relative position to match the trident. In the vertical aspect, the pad (deck bar) is shown "edge on" at a distance below the trident that is proportional to the altitude above the landing pad. The primary guidance information in hover is contained in symbols representing the desired hover point, height above the landing pad (deck bar), vertical velocity, and a limit indication of the maximum allowable vertical velocity for touchdown. In operation, the pilot uses lateral and longitudinal stick to move the acceleration ball symbol to the desired hover point. The aircraft then acquires the hover point with first-order dynamics and a time constant of three to five seconds. During vertical descents, the predicted vertical velocity symbol responds quickly to throttle changes. This symbol is maintained within the span of the allowable vertical velocity ribbon. Additional situational information similar to that of the approach display is provided in the hover display.

Speed-Guidance Law

The essential elements of the speed-guidance law described in Ref. 7 and used in this experimental investigation are the reconfiguration range and the pitch cues provided to the pilot after aircraft reconfiguration. Despite the Harrier's complex aerodynamics and jet-induced effects during the transition from wing borne to jet borne flight, (i.e., after reconfiguration), the relationship of speed and distance (in the absence of winds) can be reduced to the simple expression

$$d = (-v_x/\bar{X}_u) \tag{1}$$

Differentiating Eq. (1) with respect to time, and noting that $\dot{d} = -v_x$ gives

$$\dot{v}_x = \bar{X}_u v_x \tag{2}$$

Equation (2) shows that after reconfiguration, the aircraft's velocity decays exponentially with time, and it is this characteristic that is capitalized on in the development of the speed-guidance law. Assuming that the thrust vector is pointing in the vertical direction, making simplifying assumptions about the transcendental nature of the solution, taking winds into account, and incorporating threshold speed V_{xf} and range D_f, the integration of Eq. (2), which expresses the relationship between speed and range, is

$$d = -\left[v_x - V_{xf} - V_w \ln\left(\frac{v_x + V_w}{V_{xf} + V_w}\right)\right] \Big/ \bar{X}_u + D_f \tag{3}$$

where

$$\bar{X}_u = \bar{X}_{u_0} + \bar{X}'_u V_w \tag{4}$$

Assuming zero winds (as was experienced in flight test), Eq. (3) simplifies to

$$d = -(v_x - V_{xf})/\bar{X}_{u_0} + D_f \tag{5}$$

It is Eq. (3) [Eq. (5) was used in flight test] that can be used to determine the range d_r, at which the pilot must reconfigure the aircraft by moving the nozzle to the hover position. By allowing for a pilot-reaction time ΔT, the signal to move the nozzle to the hover position is given to the pilot at a range d_p that is ΔT seconds earlier than the range given by Eqs. (3) and (5), thus

$$d_p = d_r + v_x \Delta T \tag{6}$$

As Eq. (2) showed, a reference deceleration that takes into account the Harrier's exponential "bleed-off" of speed can be used to determine the deceleration changes necessary to maintain an exponential deceleration profile. If Eq. (1) is solved for $\bar{X}_u$ and substituted into Eq. (2), we can express the exponential reference deceleration $\dot{v}_{xr}$ as

$$\dot{v}_{xr} = (-v_x^2/d) \tag{7}$$

Since a given final speed V_{xf} is desired, it is necessary to append to Eq. (7) the condition

$$\dot{v}_{xr} = 0 \quad \text{if} \quad v_x \leq V_{xf} + \Delta V \tag{8}$$

The quantity ΔV (typically 3 ft/s) is needed to compensate for the speed loss due to the lag between the commanded and achieved zero acceleration at the end of transition. It will be noted that the condition given by Eq. (8) also avoids the need to deal with the singularity that occurs in Eq. (7) when $d = 0$.

The longitudinal guidance element of the approach display (Fig. 2), also known as the "decel error ribbon," is driven by an amount proportional to the aircraft's deceleration error and provides a cue to the pilot indicating which way to pitch the aircraft. The pilot is alerted to move the nozzle to the hover position by the sudden appearance of the ribbon at a length of +5 deg, measured on the HUD pitch scale. Once the pilot moves the nozzles beyond 75 deg, the guidance law given by

$$f_{ae} = K_{ax}(\dot{v}_x - \dot{v}_{xr}) \tag{9}$$

is activated and the ribbon commences to display the deceleration error. Thus, a deceleration less than the reference causes the ribbon to move upwards, indicating to the pilot to pitch upwards and thereby giving rise to an incremental deceleration. Values of the parameters used in the speed-guidance law are given in Table 1.

Evaluation Tasks

The approach task (Fig. 4) was a curved, descending, decelerating approach to the initial hover point. The initial conditions were level flight on downwind at an altitude of 600 ft, an airspeed of 120–140 kt, the engine exhaust nozzles at 40 deg, and the landing gear down. From these initial conditions the guidance was initiated. The pilot then controlled airspeed (using a backside control technique) by using longitudinal stick to pitch the aircraft to keep the center of the angle-of-attack reference bracket level with the ghost aircraft. At the same time, throttle (for vertical display corrections) and lat-

Table 1 Exponential-deceleration speed guidance law constants

Parameter	Value	Units
D_f	200	ft
V_{xf}	30	ft/s
$\bar{X}'_u$	0.00015	1/ft
$\bar{X}_{u_0}$	−0.037	1/s
ΔT	2.0	s
ΔV	3.0	ft/s
K_{ax}	0.32	deg s²/ft

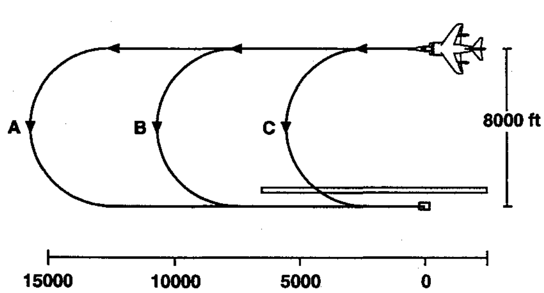

Fig. 4 Approach task profiles.

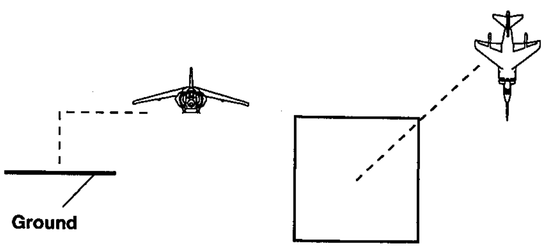

Fig. 5 Hover task profile.

eral stick (for lateral display corrections) were used to keep the velocity vector symbol centered on the flashing beacon on the tail of the ghost aircraft providing pursuit guidance. At the end of the downwind leg the ghost aircraft initiated a 180-deg, 4000-ft-radius turn to final and began a descent down the glideslope. The nominal glideslope was −3 deg, but some steeper approaches were also examined during both simulation and flight test, specifically −4 and −5 deg. At about 1 mile from the initial hover point, the pilot rotated the nozzles from 40 deg to the hover position (82 deg). The cue provided on the HUD for this action was the initial appearance of the deceleration error ribbon on the left wing of the flight path symbol. From this point the pilot used longitudinal stick to keep the deceleration error ribbon zeroed out. This provided an exponential deceleration schedule to arrive at the threshold distance (200 ft from the initial hover point) at the desired final closing speed (18 kt). Throttle and lateral stick were still used to track the ghost aircraft which, upon reaching the threshold distance, leveled off at the initial hovering altitude of 50 ft. During this deceleration, heading guidance was provided by a caret located just above the velocity vector symbol. The approach task was considered complete upon reaching the threshold distance.

The hover task (Fig. 5) was a constant altitude hovering maneuver to the landing pad with let-down to vertical landing. The initial conditions were hovering over the initial hover point at 50 ft. From these initial conditions, the pilot would press a button on the stick that would move the hover cross symbol on the HUD from the initial hover point to the center of the landing pad. The landing pad was located 100 ft forward and 100 ft to the left of the initial hover point. The pilot would then maneuver the aircraft with longitudinal and lateral stick placing the acceleration ball symbol on top of the desired hover point, until the aircraft trident symbol was centered above the hover cross. At the same time, throttle was used to maintain an altitude of 50 ft with the help of the predicted vertical velocity symbol. Once over the landing pad, the pilot would adjust power and descend to a vertical landing while keeping the hover cross centered within the trident symbol.

Flight Simulation

The NASA Ames Vertical Motion Simulator (VMS) (Fig. 6) provides large amplitude vertical and longitudinal linear translation capability of ±30 and ±20 ft, respectively, and only ±4 ft laterally. Pitch, roll, and yaw angular capability was ±18, ±18, and ±24 deg, respectively. A continuous, three-window, computer-generated image system provides unobstructed views of the visual scene (Fig. 7).

The VSRA mathematical model was derived from a YAV-8B model developed from wind-tunnel and engine test data by McDonnell Douglas Corporation (MDC),[9] and an AV-8B model developed by parameter identification techniques from flight test data by Systems Control Technology (SCT).[10]

The approach and hover tasks were performed in various conditions of wind and turbulence, ceiling and visibility, glideslope angle, and length of the final approach segment. The wind conditions were calm, 15 kt headwind with 3 ft/s rms turbulence, and 30 kt headwind with 6 ft/s rms turbulence. The visibility conditions were clear, 200-ft ceiling with $\frac{1}{2}$ mile visibility, 100-ft ceiling with $\frac{1}{4}$ mile visibility, and 0-ft ceiling with 0 mile visibility. The glideslope angles were −3, −4, and −5 deg, and the length of the straight-in segment on final approach was varied between 1000, 6000, and 12,000 ft.

Four pilots participated in the simulation: three from NASA Ames and one guest pilot from the U.S. Navy Flight Test Center at Patuxent River, MD. Of the NASA pilots, one had 2700 h mostly in military combat aircraft, including 1000 h in Harriers and 300 h in the YAV-8B. Another had 10,000 h in

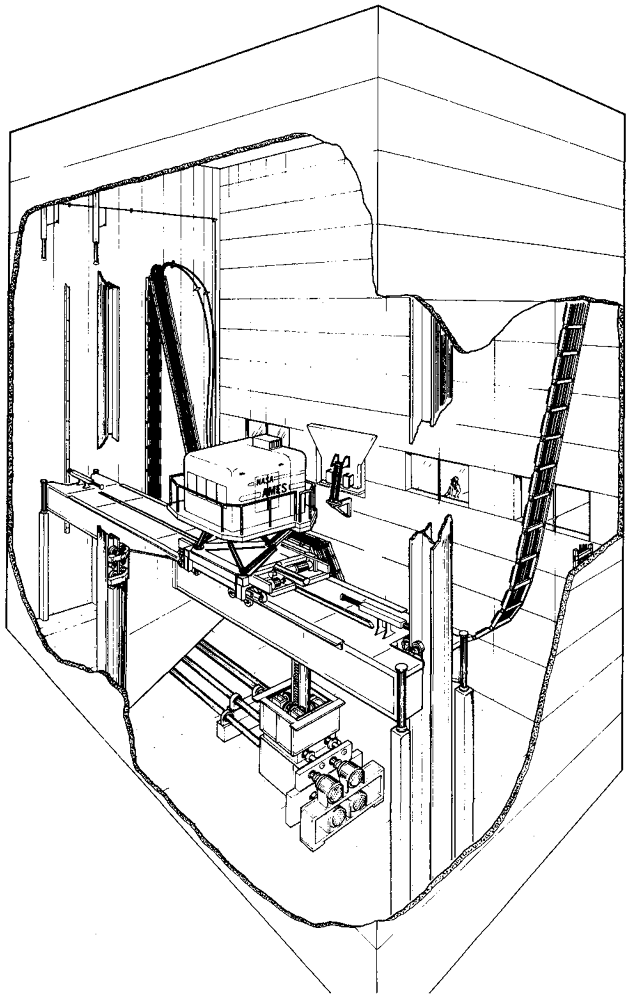

Fig. 6 NASA Ames Vertical Motion Simulator.

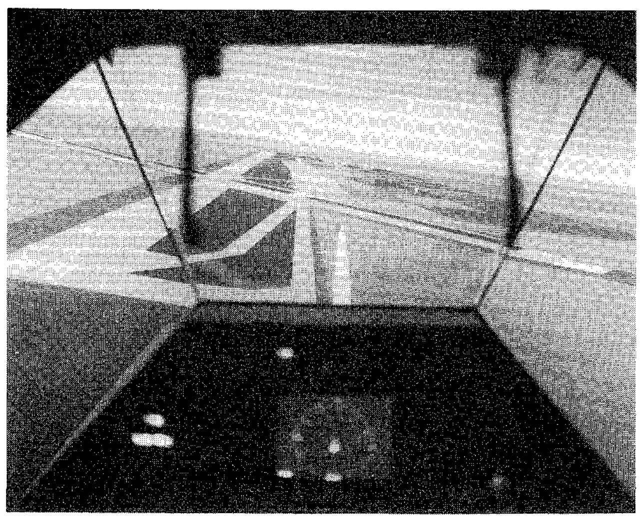

Fig. 7 Simulator visual scene.

various civil and military aircraft, including 1000 h in a variety of STOL aircraft, VTOL aircraft and helicopters and 100 h in Harriers. The third had 12,000 h in civil and military aircraft, with 1000 h in various V/STOL aircraft and 250 h in Harriers. Each pilot flew multiple sessions in the VMS, first, familiarizing themselves with the tasks and displays, and then repeatedly performing the tasks under the various conditions. Cooper-Harper Handling Qualities Ratings (HQRs) were rendered following each task.[11] For the approach task, desired performance was considered as being able to keep the flight path symbol fixed on the ghost aircraft symbol within the wingspan of the ghost laterally and vertically. This gives an error that is proportional to groundspeed, for example at 200 ft/s the ghost wingtip corresponds to a position error of 52 ft with no crosstrack velocity error. Tracking the ghost within twice the tolerance for desired performance was considered adequate performance. For the hover task, desired performance was considered as controlling altitude, lateral position, and vertical position within ±5 ft, and adequate performance was ±10 ft.

Flight Test

Flight evaluations were conducted at Ames Research Center's experimental flight facility at the Crows Landing Naval Auxiliary Landing Field. Development flights were conducted as part of the system shakedown and debugging process. Unreliable MLS hardware necessitated the use of radar and laser tracker measurements to provide the high-accuracy position information to the guidance law. Seven flights were accomplished during data collection with the system fully functioning. Two pilots flew several curved approaches (12,000-ft final segment and −3- and −4-deg glideslope) and performed the hover task in clear and calm conditions as well in conditions of light winds and clear visibility. Cooper-Harper HQRs were given for the two tasks by each pilot.

Results

Figure 8 shows the Cooper-Harper HQRs for both the simulation and flight tests. The flight test ratings correlate very closely with the simulation ratings lending credibility to the simulation results. Pilot comments also indicated that performing the tasks during simulation was very similar to performing the tasks in flight.

Simulation results show that visibility had no effect on handling qualities ratings for the approach task; however, the aircraft was very difficult to control during the hover task in zero visibility. Winds had a slight degrading influence on the ratings, as the tasks proved more difficult with increasing winds and turbulence. Glidepath angle had no effect on ratings. Overall, averaged Cooper-Harper HQRs were level-2 for both tasks in all conditions except hover in zero visibility, which was level-3. It should be noted that, although the AV-8B Harrier has level-1 flying qualities in conventional flight, it is more demanding in the powered-lift regime below 120 kt, so Marine pilots limit powered-lift operation to flight under visual conditions. This guidance system attempts to provide a capability that is currently not available.

Some individual pilot comments during flight testing give a description of flying the combined tasks using the HUD guidance: "The control task around the alignment circle and up to the nozzle drop was quite easy and smooth. The control task from nozzle drop to the point where I switched to the hover display is also easy and smooth." The pilots agreed that capturing the initial hover point was the high workload part of the task, but they had different perspectives on the hover task. One pilot comments:

> After switching to the hover display to capture the initial hover point, translate to the pad, and set up for landing, I find the workload increases significantly. There are three high frequency tasks (controlling position in the *X*, *Y*, and *Z* directions). Vertical landings were all very consistent. The display requires a fairly high workload and concentration which means I must concentrate on the HUD for landing. This is uncomfortable, as I normally like to look primarily to the sides for h and hdot cues.

But another pilot comments: "Station keeping, transition, and vertical landing are very comfortable using the hover display."

Previous simulations using the VMS have shown that the addition of an advanced control system (such as rate command/attitude hold or velocity command) would improve the handling qualities ratings to level-1.[5,7] During this simulation, advanced control systems were briefly examined, and pilot commentary verified that the handling qualities ratings would be improved to level-1 with an advanced controller.

The purpose of the HUD displays was to provide guidance in instrument conditions, but the pilots felt the displays would reduce workload and improve performance in VFR conditions as well, especially at night. Marine Corps pilots at Yuma Marine Corps Air Station, after watching a videotape of the HUD during a flight test approach, said the guidance system could reduce pilot workload and improve performance during approaches to a ship, especially at night when sparse visual cues make it difficult to determine closure rate.

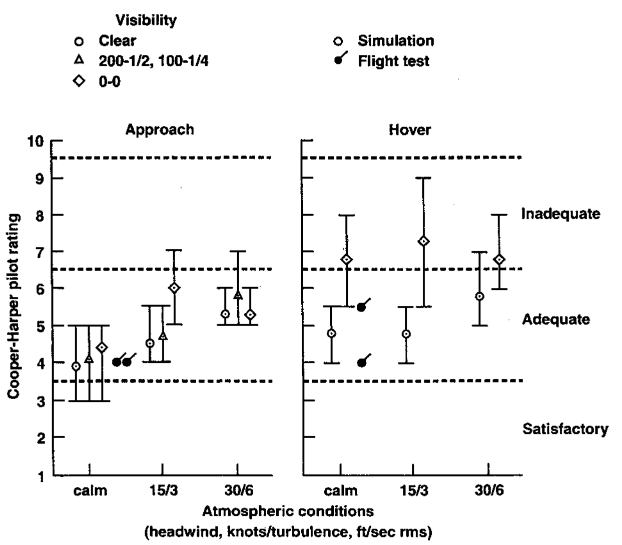

Fig. 8 Cooper-Harper handling qualities ratings.

Conclusions

The simulation and flight tests were successful in that they proved the feasibility of the guidance system. The handling qualities ratings attained indicate that IFR landing minima for the AV-8B could be reduced significantly if this system were implemented. The assistance provided to pilot by the deceleration cue would be a valuable asset to current AV-8B operations in marginal VFR conditions. The results also indicate that level-1 handling qualities can be expected with the incorporation of an advanced control system. The next phase of NASAs VSRA research is to incorporate just such a control system into the YAV-8B to prove the feasibility of the combined system and to provide a V/STOL advanced controls research platform.

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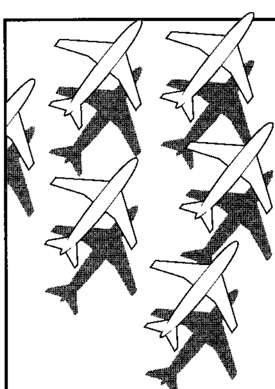

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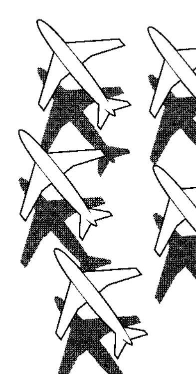

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