Flight Evaluation of Pursuit Displays for Precision Approach of Powered-Lift Aircraft

Charles S. Hynes,* James A. Franklin,† Gordon H. Hardy,‡ James L. Martin,‡ and Robert C. Innis§
NASA Ames Research Center, Moffett Field, California

Flight experiments with NASA Ames Research Center's quiet short-haul research aircraft evaluated the influence of pursuit displays on the ability of pilots to execute precision-instrument flight operations in the terminal area, particularly approaches to and landings on a short runway. The aircraft is a powered-lift, short-takeoff and landing configuration equipped with a modern digital fly-by-wire flight control system, a head-up display, and a color head-down display that make it possible to investigate control and display concepts for full-envelope, powered-lift operations. Flight-path-oriented displays that provide status and command information in a format with minimal clutter were investigated. The pilots could fly the aircraft with the precision associated with flight-director guidance and with a high degree of situation awareness. The primary benefits of this display concept were realized when the pilot was required to execute a complex transition and approach under instrument conditions and in the presence of a wide range of wind and turbulence conditions.

Nomenclature

h	= altitude
$\dot{h}_c$	= filtered vertical velocity
$\dot{h}_p$	= pilot-station vertical velocity
ℓ	= arm from center of gravity to cockpit
MSL	= altitude above mean sea level
q_B	= pitch rate
s	= argument of Laplace transform
T	= time separation of ghost aircraft
USB	= upper-surface blowing
V_A	= airspeed
V_G	= ground speed
y	= lateral-path error
γ	= flight path angle
θ	= pitch attitude
σ	= standard deviation
Ψ	= compass heading

Subscripts

A	= air mass
cmd	= command
D	= display
P	= pilot's station
path	= reference flightpath
pot	= potential
wcr	= critical waypoint

Introduction

TACTICAL military operations from short fields and damaged runways impose stringent demands for precise control of flight path and airspeed over an aircraft's low-speed flight envelope. These operations require the ability to perform a precision approach under instrument meteorological conditions (IMC) down to at least 100-ft ceilings and 1200-ft visual range, and to land in poor visibility in a touchdown zone 200 ft long by 100 ft wide or smaller. Control augmentation systems and cockpit displays that provide precise flight path and airspeed control over the range of flight conditions and aircraft configurations can enable routine achievement of these demanding operations. To achieve good flying qualities for this task, the necessary precision must be provided without the need for the pilot to integrate separate instrument displays to maintain situation awareness.

Up to this time, efforts to provide the capability for these operations have been based on conventional control-system concepts and flight-director displays that provide commands for path tracking and configuration management through transition from conventional to powered-lift flight. Hindson et al.,[1,2] Hindson,[3] and Franklin et al.[4,5] devised concepts of this sort and carried them through flight evaluations on the NASA augmentor wing powered-lift research aircraft; they defined criteria for these systems as well. The work in Refs. 4 and 5 for flight-director design and configuration management during transition was based on principles set forth by Hoh et at.[6] in their report of analyses and ground-based simulator experiments. In each of these cases, the desired precision of performance was achieved with reasonable pilot effort for curved, decelerating approaches under simulated instrument flight conditions, and satisfactory (level 1) pilot ratings were obtained.

Related experience has been acquired from V/STOL aircraft control system and display investigations, particularly for the transition and instrument approach. Results of flight experiments on the X-22A by Lebacqz and Aiken[7] and Lebacqz et al.[8] and on the NASA CH-47B by Kelly et al.[9] and Niessen et al.[10] have demonstrated the ability to achieve level 1 flying qualities for this task with systems based on linear, fixed-operating-point control concepts and with flight-director guidance. Further, ground-based simulation investigations of V/STOL operations aboard ship by Merrick[11] and Farris et al.[12] using flight-path-centered integrated command and situation displays have received comparably good pilot ratings for a curved, decelerating approach on instruments to a visual shipboard landing.

The experience just noted has proved the feasibility of performing such demanding flight operations with powered-

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Presented as Paper 85-1944 at the AIAA Guidance, Navigation and Control Conference, Snowmass, CO, Aug. 19–21, 1985; received April 2, 1986; revision received Feb. 10, 1988.

*Research Engineer, Flight Dynamics and Controls Branch.

†Research Engineer, Flight Dynamics and Controls Branch. Associate Fellow AIAA.

‡Research Pilot, Flight Operations Branch.

§Chief, Flight Operations Branch.

lift aircraft. The objective of the work reported in this paper was to assess a different approach to display design for a similar operational application. An investigation of a nonlinear control system concept that provided full-envelope flight path and airspeed control was conducted in conjunction with the display evaluation using the NASA quiet short-haul research aircraft (QSRA). The control evaluation was reported separately in a paper[13] that should be regarded as a companion to the present one.

The QSRA displays comprise an electronic head-up display and a color head-down display that are flight-path-centered and integrate command and status information in a format intended to heighten situation awareness for terminal-area operation while enabling tracking performance as precise as that obtained with flight-director guidance. The displays are based on concepts investigated by Bray[14] and Bray and Scott[15] for terminal-area operations with conventional transports, but the basic principles of conformality and flight path centering can be traced to proposals made over 20 years ago.[16,17] For example, Baxter[16] proposed a display concept that included symbols for the runway, a lead aircraft, and flight path direction, all of which were driven by laws similar to those of the present work.

Instrument limitations characteristic of this early period, however, often prevented realization of potential display benefits. During a visual approach, the pilot normally perceives attitude errors of a few minutes of arc and controls flight path angle to about 0.25 deg. Instrumentation errors such as the erection error of gravitationally erected attitude gyros could produce display errors an order of magnitude larger than the pilot's normal visual-approach tolerances, and informal evaluations of several early displays by NASA pilots showed that, because of excessive error, the displays proved confusing rather than helpful. Klopfstein's ONERA development work was a notable exception, since he made use of highly accurate inertial reference systems. His flight demonstrations in the Nord 262 aircraft called attention to the practical advantages of flight-path-centered displays, although his display laws lacked certain refinements beneficial for operation in atmospheric disturbances such as wind shear.

More recently, the wide availability of highly accurate inertial instrumentation has enabled display concepts based on fundamental principles to be evaluated and refined over a broad range of operational conditions for conventional transport aircraft[18] by taking advantage of electronic display flexibility and current computational capacity. The present paper describes the application of these display concepts to curved decelerating approaches with a highly augmented powered-lift aircraft, which requires further refinements to match the display concepts both to augmented aircraft dynamics and to the more demanding operational situation.

Experiments have been conducted on simulators at NASA Ames Research Center and in flight on the QSRA to provide pilot evaluations of these concepts for instrument approaches and landings. The influence of the display and control concepts both on the precision of approaches and landings and on the effort pilots must devote to these demanding operations has been defined. This paper describes the principles of the display concepts, the flight experiments (and the powered-lift research aircraft on which they were conducted), and the findings obtained from these experiments.

Display Concepts

Development of the QSRA cockpit displays was guided by the assumption of three design principles that seem fundamental, but that must be justified by the results achieved. First of all, aircraft handling under visual conditions should be satisfactory to the pilot, either naturally or with the aid of control augmentation. This first principle implies that the display designer should not complicate his task by attempting to compensate for dynamic deficiencies in the aircraft itself.

Flying an approach under instrument conditions is inevitably a more challenging task than flying the same approach visually, because the pilot is deprived of position and velocity cues that he normally extracts from the visual scene. The second design principle states that the display should present the cues normally available during visual flight. The most important cues indicate where the aircraft is *pointing* (its attitude) and where it is *going* (the direction of its velocity vector), relative to the runway and the desired approach path. If these important cues can be displayed electronically and made sufficiently compelling, instrument flight should be analogous to quasivisual flight. The pilot can use his normal visual technique and, under our first principle, satisfactory instrument flying qualities should then be assured. The pilot's interpretation of the display should be instinctive and the need for conventional flight directors should be eliminated. In addition, pilot awareness of the aircraft's position and velocity states relevant to his task (situation awareness) should be enhanced.

The third principle may be considered a corollary of the second. It states that the flight path symbol should be the primary element of the display and the element directly controlled by the pilot, replacing in this respect the traditional airplane symbol. In formation flying, the pilot tracks the lead aircraft by pointing his velocity vector at the leader. In the displays to be described, the flight path symbol combines with a symbolic lead aircraft and perspective runway to form a pursuit display that integrates command with situation information. Both lateral and vertical cross-track velocity errors relative to the desired path are directly indicated.

Direct pilot control of the flight path symbol raises the issue of the dynamic lags characterizing the aircraft's vertical and lateral responses. In the detailed discussion that follows, it will be shown that suitable predictive compensation can effectively eliminate aircraft dynamic lag from the pilot's closed-loop flight path control task. This can result in making the flight path symbol as easy to control as aircraft attitude and, therefore, satisfactory (principle 1). Following a brief description of the QSRA aircraft, the displays will be described in detail.

Description of Research Aircraft

The research aircraft on which these flight experiments were performed is a four-engine, powered-lift jet transport (Fig. 1) that uses an upper-surface-blowing (USB) flap propulsive-lift system. The basic airframe is a de Havilland C-8A Buffalo, which was modified to incorporate an integrated wing and propulsion system, including YF-102 turbofan engines.[19,20]

A central computer accepts control commands from the pilot and inputs from the aircraft's motion sensors and generates appropriate outputs to drive the cockpit displays and the control actuators. An inertial reference unit provides accurate body attitude angles and linear accelerations, and microwave landing system (MLS) equipment provides accurate aircraft positions relative to the runway. A head-up optical display unit and a 5-in. color tube present the head-up

Fig. 1 Quiet short-haul research aircraft.

and head-down displays to the pilot. A detailed description of the computer system and its peripheral hardware is given in Ref. 21.

The basic aircraft's pitch, roll, and yaw responses are representative of low-speed, powered-lift aircraft (e.g., Ref. 4). These responses are characterized by poor longitudinal stability and large trim changes owing to thrust and flap variations, low yaw damping, and adverse yawing moments because of lateral controls and rolling velocity. To improve the basic aircraft's pitch, roll, and yaw response characteristics, three-axis stabilization and command augmentation modes were developed based on currently available criteria and conventional response feedback control. These rate-command attitude-hold control modes are similar to those described in Ref. 4 and will be called *attitude SCAS* hereafter. Based on the pilot's evaluations of a similar system for the powered-lift aircraft of Ref. 4, the attitude SCAS was expected to provide satisfactory control of pitch attitude, bank angle, and heading.

To improve control of flight path and airspeed throughout the aircraft's powered-lift envelope, the USB flaps, throttles, and spoilers were driven by a command structure that was based on nonlinear, inverse model-following concepts. This system is described in detail in Ref. 13 and will be referred to hereafter as *flight path airspeed SCAS*. In this mode, the augmentation of pitch, roll, and yaw responses is the same as that just described (attitude SCAS). The flight path airspeed SCAS provides the desired flight path dynamic response throughout the aircraft's flight envelope without small-perturbation restrictions. The flight path response to the primary control (pitch) is characterized by a first-order time constant of 1.0 s at the approach condition.

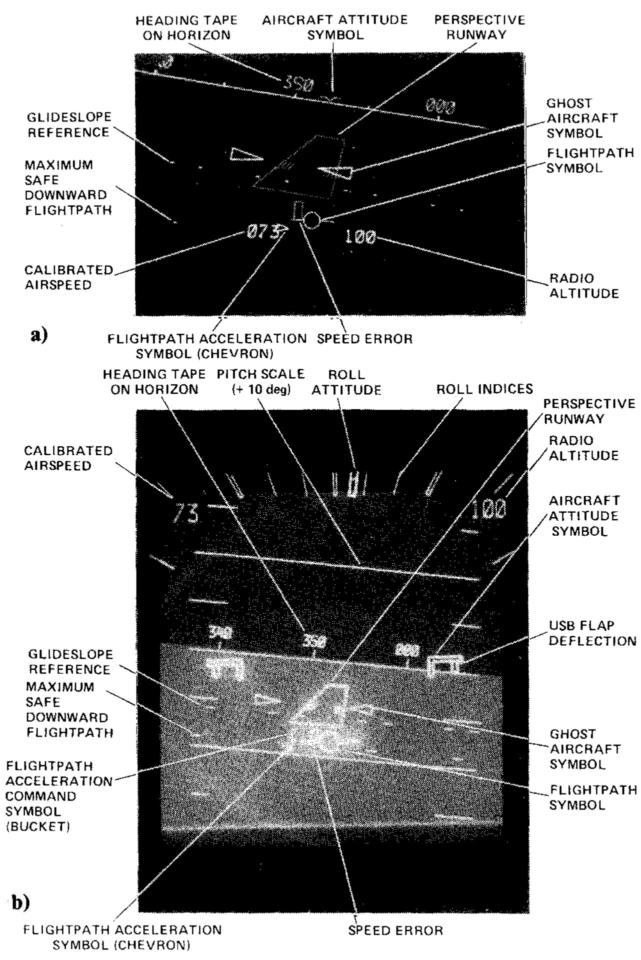

Fig. 2 Electronic primary flight displays: a) Head-up display, and b) head-down display.

To improve flight path response to throttle in the attitude SCAS mode, throttle input drives the spoilers through a washout that complements engine response. Within the 0.1 g spoiler authority, flight path response to the primary controller (throttle) is as rapid as that for the flight path SCAS mode response to pitch.

The control mode in the total absence of augmentation will be called *basic aircraft*.

Description of Electronic Displays

The essential features of both the head-up display (HUD) and head-down display are illustrated by Fig. 2. Eulerian attitude angles from the inertial reference system and a perspective runway derived from ground-based MLS guidance are displayed conformally by the HUD (Fig. 2a) (see horizon line with heading tape, airplane symbol, pitch scale, and roll attitude and indices). A glide-slope reference line displays the selected glide slope, and a fixed line indicates the maximum safe downward flight path. All these symbols represent cues directly available to the pilot during a visual approach.

A moving aircraft symbol represents a lead (ghost) aircraft that flies a perfect approach a few seconds ahead on the selected path. The ghost symbol is driven relative to the runway symbol by scaled localizer and glide-slope errors. If the aircraft followed a real leader in visual flight, the ghost symbol would overlie the real leader just as the conformal symbolic runway would overlie the real runway. The angular displacement of the ghost symbol relative to the runway provides a direct indication of localizer and glide-slope errors. For example, a lateral displacement that aligns the wingtip of the ghost aircraft with the runway centerline corresponds to one dot of localizer error. These cues are also available to the pilot during a visual approach, although in the absence of a leader, the pilot must infer them by reference to a recollection of the correct sight picture during the approach.

The flight path symbol is essential to the display. It represents the direction of the velocity vector, and its angular displacement from the ghost aircraft symbol indicates the errors in flight-path angle and drift angle (i.e., cross-track and vertical velocity errors) relative to the desired path. During the visual approach, these cues also are available to the pilot, who locates the projection of the velocity vector onto the ground plane (the "impact point") by observing the radial spreading of ground texture away from the impact point. Flight path direction is available somewhat more rapidly and accurately from the displayed flight path symbol than from the real world, enabling the display to contribute to flight path perception during wind-shear traversal[15] even under visual conditions.

The flight path symbol group comprises the airspeed error tape, flight path acceleration symbol (chevron), flight path acceleration command symbol (bucket) (shown only in Fig. 2b), and digitally displayed radio altitude and calibrated airspeed. A caution or warning symbol (not shown) alerts the pilot to annunciated messages. All these symbols of the flight path group move together over the display, maintaining a fixed relationship. The use of pictorial elements wherever possible in preference to scales or digits contributes to the simplicity and uncluttered appearance of the HUD.

The head-down primary flight display (PFD) is illustrated by Fig. 2b. It will be seen that the PFD simulates a stylized forward view instead of duplicating a conventional electromechanical attitude ball. Its perspective remains geometrically true, because it results from scaling down the conformal HUD display to a 5-in. cathode-ray tube. The resulting clutter is compensated for by the use of color, which unfortunately is not yet available for the HUD. The attempt was made as a design goal during PFD development to keep its format the same as that of the HUD, but this objective was only partially achieved. For example, scaling down the digital airspeed and altitude made them too small for good readability, and they were moved away from the flight path symbol to the upper left and right corners of the display (Fig. 2b).

The PFD superimposes a yellow horizon and pitch scale on a blue sky and brown earth. The ghost aircraft (command) symbol is green, and flight path is indicated by a heavy white symbol to provide the weight appropriate for the controlled element. The relation of the ghost aircraft to the perspective runway provides optical leverage that amplifies display sensitivity to localizer and glide-slope errors, making separate expanded-scale cross-pointers unnecessary.

A monochrome moving-map display completes the QSRA electronic display complement.

Display Operation

The pilot's task is to fly in loose formation with the lead aircraft by placing the flight path symbol on the ghost symbol. The ghost symbol is driven relative to the runway symbol by scaled localizer and glide-slope errors and provides a direct indication of these errors. Thus, the ghost, runway, and flight path symbols combine to form a pursuit display that integrates command with situation information, instead of presenting the command in isolation as a compensatory flight director does. For example, Figs. 2a and 2b illustrate a representative situation at the 100-ft decision height. The position of the runway touchdown zone (heavy stripes) slightly above the 6-deg glide-slope reference line shows that the aircraft is slightly below the glide slope. It is to the right of the runway centerline in a 6-deg left bank. The ghost therefore appears above the 6-deg glide-slope reference line and to the left of the runway centerline. The flight path symbol predicts that in the absence of path correction, the aircraft would fly into the ground short of the runway threshold. Airspeed is 3 knots fast relative to the selected 70-knot reference speed, and the aircraft is decelerating slightly (chevron below flight path symbol). To correct these errors, the pilot must continue his left turn to center the flight path symbol laterally on the ghost, fly a shallower flight path angle in order to center the flight path symbol vertically on the ghost, and decelerate to align the flight path symbol with the bucket. The guidance laws mechanized by these corrections will be described next.

Lateral Guidance

The display law for the ghost aircraft symbol is derived from the geometry of formation flight (Fig. 3), so that interpretation of the display is instinctive to pilots with formation-flying experience. A small lateral path error y generates a commanded heading (ghost aircraft symbol) according to

$$\Psi_{\text{cmd}} = \Psi_{\text{path}} - \frac{y}{V_G T}$$

where $V_G T$ is the separation distance. The pilot's task is to align the velocity vector (flight path symbol) with the ghost. If we assume that the pilot tracks the ghost closely, exponential convergence to the path is achieved with time constant T, according to

$$T\dot{y} + y = 0$$

Physically, as the ghost aircraft follows the reference path, the real aircraft falls into trail behind. Since the law applies to small perturbations about the reference flight path, it remains valid for curved paths, provided lateral errors are small compared to the turn radius. The QSRA displays use this capability to provide guidance for curved approaches, in contrast to previous ghost-aircraft display formats[14-16] that have provided only straight-in guidance.

The choice of the time separation T must balance tracking performance against pilot workload, just as the choice of gain does for a conventional flight director. A small time separation provides rapid error correction at the expense of increasing the pilot's tracking bandwidth. The separation appropriate to the instrument flight task was determined from preliminary flight and simulation pilot evaluations to be in the ranges of 10 to 15 s for area navigation and 5 to 10 s approaching decision height. This result implies a desirable increase in tracking performance and associated workload as terrain clearance becomes increasingly critical. When the same formation-flight law is applied to MLS localizer tracking with angular deviation as the measure of tracking error, it is found that the well-known increase in localizer sensitivity with decreasing range provides the necessary increase in performance without scheduling the gain.

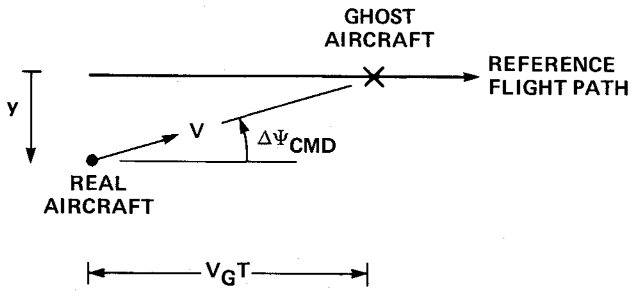

Fig. 3 Display of reference flight path using ghost aircraft symbol.

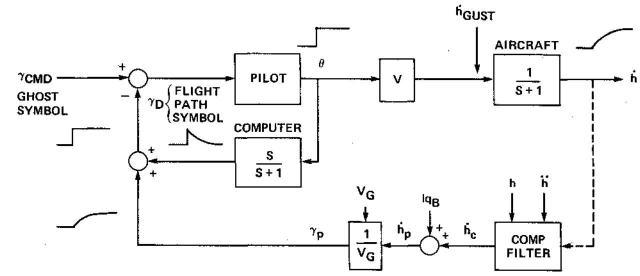

Fig. 4 Flight path display system for flight-path–airspeed SCAS mode.

Vertical Guidance

Vertical flight-path guidance is similar to the lateral law and for area navigation uses the same separation of the ghost from the real aircraft. There are two reasons why this separation is different for MLS glide-slope tracking. First, because the glide-slope transmitter is located near the runway threshold (instead of at the far end of the runway, as with the localizer transmitter), the glide-slope sensitivity increases much more rapidly; as a result, it becomes necessary to decrease the gain below 200 ft to avoid excessive workload. Second, the vertical response to pilot control is rapid (heave time constant 1 s), but the response to directional control (Ψ_{cmd}) through bank angle is effectively much slower, since to turn the aircraft, the pilot must roll into a bank and then roll out. The appropriate bank angle and, therefore, the rate of error correction are limited by the tendency to overshoot the commanded heading during roll-out. The more rapid heave response enables shorter time separation to be used for improved glide-slope tracking without excessive pilot workload.

Display of Flightpath

The computation for the display of flight path is illustrated by Fig. 4 for the display mode corresponding to the flight-path airspeed SCAS mode. Vertical velocity at the aircraft center of gravity is estimated by complementing measurements of altitude and vertical acceleration. The inertial flight-path angle of the cockpit is derived by applying measured pitch rate and estimated ground speed. This method of deriving flight path provides accurate wideband response and is insensitive to vertical gusts too short to influence the aircraft's vertical velocity. In contrast, Klopfstein and others used an alternate method that is deficient in two respects. They subtracted from pitch attitude a vane-measured angle of attack corrected for upwash. Heavy lag filtering of the vane signal is required to reduce gust sensitivity, and large errors can result from upwash uncertainties with a powered-lift aircraft. The upwash at the tip of the QSRA nose boom exceeds 30% of the vane angle and depends on both thrust and USB flap deflection.

The flight path symbol is dynamically compensated to predict the long-term flight path response to the pilot's control inputs. The predicted long-term cockpit flight path response to the prevailing pitch-control input is computed based on a first-order approximation of aircraft dynamic response. In the flight path–airspeed SCAS mode, the QSRA flight path response to pitch control is characterized by a 1-s lag. By referring to Fig. 4, it may be seen that the flight path response of the augmented aircraft to a pitch step is lagged by this characteristic 1-s time constant. By approximate compensation of this heave lag with a complementary washout applied to the pitch attitude command in the computer, the displayed flight path symbol reflects an instantaneous prediction of the long-term response to pilot pitch inputs. Thus, the pilot controls a system that appears to be a pure gain and instinctively generates a pitch step of the magnitude required to correct the path error in the long term. The actual path error then washes out exponentially, while the displayed flight path response remains constant, requiring no further pilot action.

In the other control modes (attitude SCAS and basic aircraft) in which the pilot controls thrust as well as pitch, the flight path symbol is quickened for both pitch and thrust control inputs. For all control modes, the predictive display compensation must complement the effective vehicle response to all pilot control inputs. The display compensation must therefore be adjusted to match vehicle dynamics separately for each control mode and each vehicle configuration over the useful range of airspeed. For small-perturbation tracking, the addition of quickening enables the situation display to function just as well as a compensatory flight director does. This is certainly not the case in the absence of quickening, because the presence of the engine and airflame lags in the forward path increases the workload significantly.

For a control task that is interrupted by instrument scanning, such as flight path or airspeed control, a pure gain is considered appropriate because of the absence of the attention-demanding exponential decay of command that characterizes feedback control of an integrator. However, the resulting workload reduction must be balanced against the need for situation awareness. Clearly, quickening corrupts the purity of the displayed flight path situation to some extent, because in the short term, predicted rather than acutal flight path is displayed. Nevertheless, this error is not significant (or even noticeable) during glide-slope tracking, because the task bandwidth is relatively low and the pilot feels no need to force the response. For a high-bandwidth task like landing flare, in which the pilot does force the response, the flight path error is more significant.

No lateral quickening of the flight path symbol is used in the QSRA displays because simulation indicated that the resulting corruption of situation information over a relatively long time interval after each control input was objectionable to the pilot. Heading command is displayed by the ghost aircraft symbol. The pilots accepted the small workload increase associated with heading command, rather than the addition of roll quickening that would have provided bank angle command.

An alternative method of quickening the flight path symbols makes use of measured body acceleration[14,15] instead of pilot control inputs. This method provides a somewhat simpler mechanization at the cost of sensitivity to atmospheric gusts.[22]

The appropriate predictive compensation is derived from a two-degree-of-freedom model of the pitch-stabilized aircraft and requires knowledge only of the vehicle responses to inputs from each of the pilot-operated controls. From the pilot's viewpoint, the predictive display does not dictate control strategy in the sense that a flight director would. The pilot must know how to fly the airplane under visual conditions. The predictive situation display simply enables him to use his visual technique under instrument conditions. From a design viewpoint, response prediction is different from the development of flight-director laws because the hypothesis of suitable feedback control loop structures can be much less detailed. The design simplicity of the response-prediction approach is particularly significant if vehicle flight-path–airspeed responses to pilot control inputs are strongly coupled, and the appropriate control strategy for coordination of pitch and throttle is not well defined. These conditions characterize the QSRA aircraft in the absence of the flight-path airspeed SCAS system, but the predictive displays enable a wide range of flight conditions from the conventional regime through the transition and powered-lift regimes to be handled successfully for moderately challenging approach trajectories.

The displayed situation information is particularly useful for large-scale maneuvers such as configuration changes or glide-slope capture—that is, tasks that would require feedforward commands in a conventional flight director.

Display of Flight Path Acceleration and Airspeed Error

The computation for the display of flight path acceleration and airspeed error is illustrated by Fig. 5 for the QSRA aircraft with attitude SCAS engaged, but without flight-path–speed command augmentation. The aircraft's airspeed response to a pitch step is approximated by a 7-s lag. To avoid misleading indications in wind shear, the acceleration along the flight path must be referred to the air mass in the long term.[14,15] To derive the air-mass acceleration, pitot-static airspeed is differentiated and then smoothed by a 3-s first-order lag filter intended to reject turbulence, while preserving response to lower-frequency shear disturbances. After smooth-

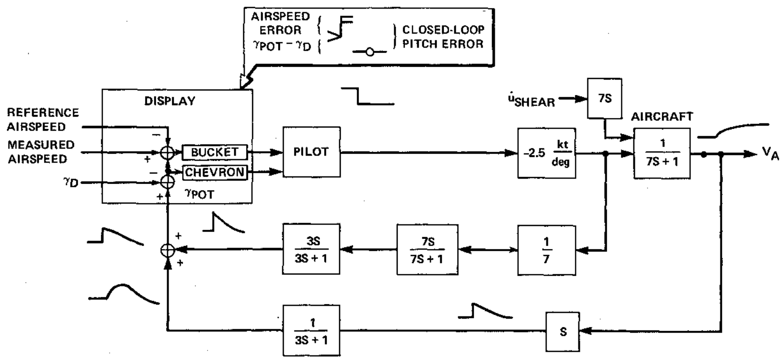

Fig. 5 Flight path acceleration and airspeed error display system.

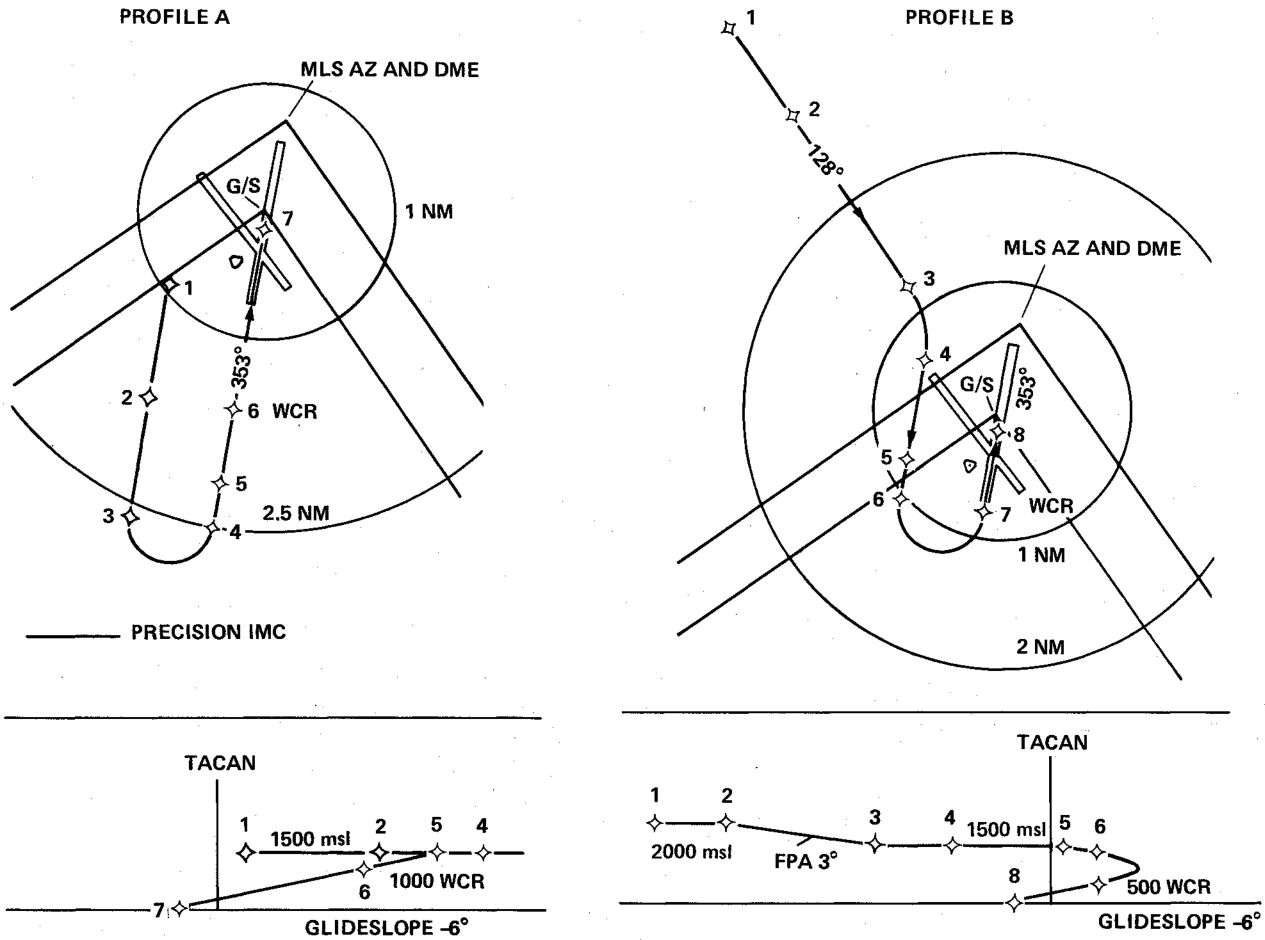

Fig. 6 Reference flight trajectories for transition and approach.

ing, wide-band response to pilot control inputs is restored by complementation (Fig. 5).

In the powered-lift regime without flight-path–speed augmentation, airspeed is controlled with pitch (backside technique), so that a complementary washout is applied to the pilot's pitch input as shown in Fig. 5. In the conventional regime, airspeed is controlled with thrust, and compensation would be applied to throttle position inputs.

After compensation, the acceleration signal is normalized by gravitational acceleration and scaled in degrees. It drives the chevron symbol relative to the flight path symbol. When read against the pitch scale, the chevron indicates the potential flight path that would be achieved in unaccelerated flight. The chevron also serves as an indicator of wind shear. It provides more rapid indication of shear for the attitude-stabilized aircraft than the indication given by the flight path symbol because, in a head-to-tail shear, airspeed bleeds off significantly before flight path decay becomes well established.

Most of the early displays[16,17] and a few more recent ones have driven the flight-path acceleration symbol with inertial acceleration instead of that relative to the air mass. This is a poor choice for wind-shear traversal because the airplane can be accelerating in the ground-referenced inertial frame while airspeed is bleeding off. But it is airspeed that the pilot must hold in order to preserve safety margins.

Airspeed error relative to the reference speed selected is displayed by the airspeed error tape symbol. The same airspeed error signal displaces the flight path acceleration command symbol (bucket) from the chevron. In the flight path–airspeed SCAS control mode, airspeed control is automated, and the bucket is not displayed. For manual control of airspeed, suitable scaling enables the bucket displacement from the flight path symbol to be interpreted as the predicted long-term airspeed error. The bucket indicates the initial acceleration required to nullify the existing speed error in the long term. To satisfy this acceleration command using backside technique (speed control with pitch), the pilot executes a pitch step so as to place the flight path symbol within the bucket. It remains there without further pilot action as the acceleration and speed errors wash out. Again, the pilot controls a system that appears to be a pure gain, but the displayed airspeed error tape enables him to retain situation awareness. The pitch attitude commanded by the bucket is compensated for wind shear by the shear response of the chevron.

Description of Flight Experiments

Flight evaluations of transitions and approaches were performed for two curved profiles (Fig. 6) that differed substantially in regard to the attention and effort required of the pilot. These approach paths consisted of left-hand patterns, the easier of which (profile A) involved entering the downwind leg with the aircraft in the cruise configuration, reconfiguring for the powered-lift regime by deploying the USB flaps, capturing the localizer in level flight at the pattern altitude of 1500 ft, and then capturing the glide slope. Deceleration to final approach speed was performed near glideslope intercept. A more challenging approach (profile B) required the pilot to execute a descending turn within 1 n.mi. of the runway, decelerate during the turn to final approach speed, and acquire the final straight-in segment at an altitude of 500 ft. Profile B was selected to provide the pilot a task representative of approaches along time- or fuel-conservative trajectories synthesized in real time,[23] or tactical military

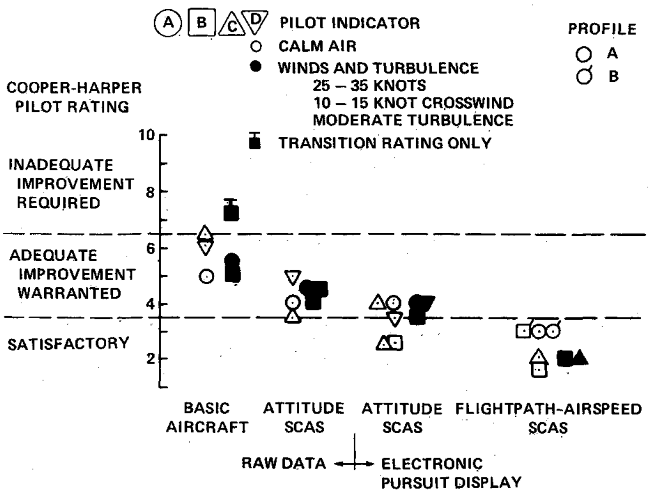

Fig. 7 Flying qualities evaluation of control-display modes for IMC transition and approach.

operations, against which advanced control and display concepts could be evaluated. Approaches were made on a 6-deg glide slope under simulated instrument conditions to a decision height of 100 ft in the wind conditions of the day. Approach guidance was provided by an MLS and tactical air navigation (TACAN) when out of MLS coverage. A final visual segment was flown to landing on a 100 ft by 1700 ft runway, with a designated touchdown zone 200 ft in length starting 300 ft from the runway threshold.

Four NASA research pilots who were highly experienced in display evaluation participated in this flight program. Each pilot made as many approaches as necessary for evaluation, usually five to ten approaches for each test condition, and gave a single rating for that test condition, taking into account pilot performance according to the Cooper–Harper scale.[24] Ratings and commentary summarizing the factors influencing each rating were obtained for the control-display combinations of Table 1. Configurations were paired to permit independent assessment of improvements in controls and displays. It will be seen from Table 1 that both raw data and

Table 1 QSRA flight-experiment variables (X evaluated; O, not evaluated)

Display mode	Control mode	Approach profile	Decision height, ft	Test program
Raw data display	Basic aircraft	A	100	O
	(no control		200	X
	augmentation)	B	100	O
			200	O
	Attitude SCAS	A	100	O
	(pitch/roll/yaw		200	X
	augmentation)	B	100	O
			200	O
Pursuit display	Attitude SCAS	A	100	X
(head-down)			200	X
		B	100	O
			200	O
	Flight-path–	A	100	X
	airspeed SCAS		200	O
		B	100	X
			200	O

Table 2 Tracking performance at decision height for IMC approach

	Longitudinal error from glide slope, ft			Lateral error from localizer, ft			Airspeed error, knots			
Configuration	Mean	Standard deviation	Maximum deviation (long/short)	Mean	Standard deviation	Maximum deviation (left/right)	Mean	Standard deviation	Maximum deviation (fast/slow)	Number of approaches
Basic aircraft raw data display Decision height = 200 ft	3.2	164	268/316	30.3	69.4	119.3/87.7	1.1	2.6	6.3/3.9	19
Attitude SCAS raw data display Decision height = 200 ft	22	156	366/158	30.8	25.6	13.7/73.6	1.5	2.2	6.1/−3.3	28
Attitude SCAS pursuit display Decision height = 100 ft	29	89	290/306	6.4	13	19.9/42.6	0.4	2.2	7.3/−5.5	73
Flight-path–airspeed SCAS pursuit display Decision height = 100 ft	19	42	93/149	0.2	11.8	38.6/29.0	−0.2	0.6	1.6/−1.8	73

pursuit displays were evaluated with attitude SCAS, and both attitude SCAS and flight path airspeed SCAS were evaluated with the pursuit displays.

The raw data presentation consisted of altitude displayed on a conventional altimeter and air-mass vertical speed displayed in analog form on the PFD, together with digital airspeed and altitude. Heading and MLS cross-pointers were displayed on a conventional horizontal situation indicator (HSI). These instruments (PFD and HSI) were the primary instruments used during the raw data evaluations.

Discussion of Results

Pilot Evaluations

Results of the pilots' evaluations for the transition and approach are shown in Fig. 7. Cooper–Harper ratings illustrate the trends in flying qualities for the instrument approach for the control-display combinations. Each data point represents the evaluation of an individual pilot and is based on experience accumulated from several approaches. No averaging or statistical manipulation of any kind has been performed, and all the evaluations obtained during the flight program are shown. The following findings are based on Fig. 7.

For profile A, data are shown for essentially calm winds and strong cross-winds with light to moderate turbulence. The basic aircraft with raw data display was considered marginally adequate for executing the instrument approach, and the operational minimum decision height for this configuration was restricted to 200 ft. The basic aircraft was considered marginally adequate for performing the instrument approach in turbulence. The basis for the pilots' evaluations was the excessive effort required both to track the localizer while maintaining reasonably coordinated flight and to maintain airspeed in the presence of the throttle and flap activity associated with performing the transition and tracking the glide slope. Factors influencing this critique were the aircraft's poor Dutch roll damping, sideslip excitation from the lateral controls, trim changes owing to thrust and flap, and the concentration required for the instrument scan. The provision of control augmentation for the pitch, roll, and yaw axes (attitude SCAS) improved those aspects of the aircraft's control so that the approach flying qualities were clearly adequate; nevertheless, considerable effort might still be required of the pilot for speed control and for the instrument scan. These results are comparable to evaluations obtained for a similar aircraft in Ref. 4.

To achieve satisfactory flying qualities, it was necessary to use the pursuit displays in combination with the attitude SCAS. The combination of precision guidance and a well-integrated format of situation information reduced the demands of the instrument scan to a minimum. Pilots rated tracking performance and the attention required to perform the task to be comparable to that associated with a conventional flight-director approach, and the results correspond to evaluations of a three-axis flight-director configuration from Ref. 4. The pilots considered the pursuit display superior to a conventional compensatory flight director in regard to situation awareness. Finally, when the pursuit displays were used in combination with the flight path airspeed SCAS, demands on pilot effort and attention were minimized, and the associated flying qualities were assessed to be fully satisfactory.

From the evaluations for profile B (flagged symbols), it will be seen that the advantage of the pursuit displays in combination with the flight path airspeed SCAS was most apparent when the pilot had to perform a tight, curved decelerating approach. Based on the present results, the pursuit displays and, at least, attitude SCAS are essential if flying qualities are to be adequate for executing the approach on a curved path such as that of profile B. For such a demanding maneuver, which may typify operations from short fields or damaged runways, the aircraft is considered inadequate unless it is equipped to a standard at least this high.

Tracking Performance

The results of a statistical analysis of tracking error at the decision height are presented in Table 2. For each control-display combination (Table 1), Table 2 shows the mean error, standard deviation, and maximum deviations of error relative to the mean for the longitudinal error from the glide slope, the localizer error from the centerline, and the airspeed error relative to the reference approach speed. All data obtained are included, and the number of approaches in each control-display category is shown at the extreme right. Measurement precision from the laser tracking system was about ± 10 ft longitudinally and ± 2 ft laterally.

By considering the longitudinal errors first, it will be seen that the mean errors are much smaller than the decision height window tolerance of ± 120 ft (Ref. 25) for all four control-display categories. The standard deviation for the basic aircraft with raw data display exceeds the window tolerance by about 37%, and the addition of attitude SCAS provides only slight improvement. Adding the pursuit display brings the standard deviation well within the window tolerance, and flight path airspeed SCAS provides a further reduction in standard deviation by more than a factor of 2, so that 2σ deviations remain well within the window tolerance.

Turning to lateral performance, the mean errors for the two categories with the raw data display are rather large, about 75% of the window tolerance of ± 40 ft (Ref. 25). The standard deviation for the basic aircraft with raw data display exceeds the window tolerance by about 74%. The addition of attitude SCAS reduces the standard deviation by a factor of 2.7. Adding the pursuit display reduces the standard deviation by another factor of 2 and brings the 2σ deviations well within the window tolerance. As expected, the addition of flight path airspeed SCAS provides little further improvement because it does not change the aircraft's lateral response characteristics. The airspeed errors show the same general trend of improvement over the four control-display categories as that for the longitudinal and lateral errors, although all the airspeed errors are small relative to the 20-knot airspeed safety margin available.[26] The performance trends summarized by Table 2 are consistent with the pilot opinion ratings of Fig. 7.

Conclusions

In summary, the primary benefits of the QSRA pursuit displays were realized when the pilot was required to execute precisely a complex transition and approach under simulated instrument conditions and in the presence of a wide range of wind and turbulence conditions. Flight-path-centered head-up and head-down electronic displays provided well-conditioned guidance commands for following the reference approach paths and maintaining situation awareness under a complex instrument flight environment. The pilots could fly the aircraft with the precision and workload associated with flight-director guidance and with a high degree of situation awareness. The display concepts and their design criteria have been refined to the point that they are ready for consideration in future aircraft designs that must provide for demanding mission requirements, whether military or civil.

References

[1]Hindson, W. S., Hardy, G. H., and Innis, R. C., "Flight-Test Evaluation of STOL Control and Flight Director Concepts in a Powered-Lift Aircraft Flying Curved Decelerating Approaches," NASA TP-1641, 1981.

[2]Hindson, W. S., Hardy, G. H., and Innis, R. C., "Flight Experiments Using the Front-Side Control Technique During Piloted Approach and Landing in a Powered-Lift STOL Aircraft," NASA TM-81337, 1982.

[3]Hindson, W. S., "Analysis of Several Glidepath and Speed Control Autopilot Concepts for a Powered-Lift STOL Aircraft," NASA TM-84282, 1982.

[4]Franklin, J. A., Innis, R. C., and Hardy, G. H., "Flight Evaluation of Stabilization and Command Augmentation System Concepts and Cockpit Displays During Approach and Landing of a Powered-Lift STOL Aircraft," NASA TP-1551, 1980.

[5]Franklin, J. A., Innis, R. C., and Hardy, G. H., "Flight Evaluation of Configuration Management System Concepts During Transition to the Landing Approach for a Powered-Lift STOL Aircraft," NASA TM-81146, 1980.

[6]Hoh, R. H., Klein, R. H., and Johnson, W. A., "Development of an Integrated Configuration Management/Flight Director System for Piloted STOL Approaches," NASA CR-2883, 1977.

[7]Lebacqz, J. V. and Aiken, E. W., "A Flight Investigation of Control, Display, and Guidance Requirements for Decelerating Descending VTOL Instrument Transitions Using the X-22A Variable Stability Aircraft," Rept. AK-5336-F-1, Calspan Corp., Buffalo, NY, 1975.

[8]Lebacqz, J. V., Radford, R. C., and Beilman, J. L., "An Experimental Investigation of Control-Display Requirements for Jet-Lift VTOL Aircraft in the Terminal Area," Naval Air Development Ctr., Warminster, PA, NADC-76099-60, 1978.

[9]Kelly, J. R., Niessen, F. R., Thibodeaux, J. J., Yenni, K. R., and Garren, J. F., Jr., "Flight Investigation of Manual and Automatic VTOL Decelerating Instrument Approach Capability," NASA TN D-7524, 1974

[10]Niessen, F. R., Kelly, J. R., Garren, J. F., Jr., Yenni, K. R., and Person, L. H., "The Effects of Variations in Controls and Displays on Helicopter Instrument Approach Capability," NASA TN D-8385, 1977.

[11]Merrick, V. K., "Simulation Evaluation of Two VTOL Control/Display Systems in IMC Approach and Shipboard Landing," NASA TM-85996, 1984.

[12]Farris, G. G., Merrick, V. K., and Gerdes, R. M., "Simulation Evaluation of Flight Controls and Display Concepts for VTOL Shipboard Operations," AIAA Paper 83-2173, 1983.

[13]Franklin, J. A., Hynes, C. S., Hardy, G. H., Martin, J. L., and Innis, R. C., "Flight Evaluation of Augmented Controls for Approach and Landing of Powered-Lift Aircraft," *Journal of Guidance, Control, and Dynamics*, Vol. 9, Sept.–Oct. 1986, pp. 555–564.

[14]Bray, R. S., "A Head-Up Display Format for Application to Transport Aircraft Approach and Landing," NASA TM-81199, 1980.

[15]Bray, R. S. and Scott, B. C., "A Head-Up Display Format for Transport Aircraft Approach and Landing," NASA CP-2170, 1980.

[16]Baxter, J. R. and Workman, J. D., "Review of Projected Displays of Flight Information and Recommendations for Further Development," Australian Defence Scientific Service Aeronautical Research Lab., ARL/H.E.2, Melbourne, Australia, 1962.

[17]Gold, T., "Quickened Manual Flight Control with External Visual Guidance," *IEEE Transactions on Aerospace and Navigational Electronics*, Vol. ANI-11, Sept. 1964, pp. 151–156.

[18]Steinmetz, G. G., Person, L. H., and Morello, S. A., "Have We Overlooked the Pilot's Role in an Automated Flight Deck?" AIAA Paper 81-2262, Nov. 1981.

[19]Cochrane, J., Riddle, D., and Stevens, V., "Quiet Short-Haul Research Aircraft—The First Three Years of Flight Research," AIAA Paper 81-2625, 1981.

[20]McCracken, R., "Quiet Short-Haul Research Aircraft Familiarization Document," NASA TM-81149, 1979.

[21]Watson, D. M., "Quiet Short-Haul Research Airplane Mode Select Panel Functional Description," NASA TM-84243, 1982.

[22]Joppa, R. G. and Nicholson, R. C., "Flight Deck Displays for Managing Wind Shear Encounters," SAE 1984 Aerospace Congress and Exposition, Long Beach, CA, Oct. 1984.

[23]Erzberger, H. and McLean, J. D., "Fuel-Conservative Guidance System for Powered-Lift Aircraft," *AIAA Journal of Guidance and Control*, Vol. 4, May–June 1981, pp. 253–261.

[24]Cooper, G. E. and Harper, R. P., Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.

[25]Watson, D. M., Hardy, G. H., Innis, R. C., and Martin, J. L., "Flight Evaluation of a Precision Landing Task for a Powered-Lift STOL Aircraft," AIAA Paper 86-2130, Aug. 1986.

[26]Hynes, C. S., Scott, B. C., Martin, P. W., and Bryder, R. B., "Progress Toward Development of Civil Airworthiness Criteria for Powered-Lift Aircraft," NASA TM X-73,124, 1976.