2002 Biennial International Powered Lift Conference and Exhibit
5-7 November 2002, Williamsburg, Virginia

AIAA 2002-6016

EVALUATION OF FLYING QUALITIES AND GUIDANCE DISPLAYS FOR AN ADVANCED TILT-WING STOL TRANSPORT AIRCRAFT IN FINAL APPROACH AND LANDING

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Abstract

A piloted simulation was performed on the Vertical Motion Simulator at NASA Ames Research Center to evaluate flying qualities of a tilt-wing Short Take-Off and Landing (STOL) transport aircraft during final approach and landing. The experiment was conducted to assess the design's handling qualities, and to evaluate the use of flightpath-centered guidance for the precision approach and landing tasks required to perform STOL operations in instrument meteorological conditions, turbulence, and wind. Pilots rated the handling qualities to be satisfactory for all operations evaluated except those encountering extreme crosswinds and severe windshear; even in these difficult meteorological conditions, adequate handling qualities were maintained. The advanced flight control laws and guidance displays provided consistent performance and precision landings.

Introduction

The STOL aircraft configuration investigated in this experiment was the Advanced Theater Transport (ATT) concept developed by the Boeing Company-Phantom Works[1]. Critical aspects of the design of this aircraft concern flying qualities and flight control requirements for a large transport aircraft to perform STOL operations in demanding weather conditions. Existing military and civil guidance for control system design is insufficient for these operations, particularly for a configuration with reduced static stability and advanced control augmentation. Most information that exists comes from STOL flight and simulation experience 30 or more years in the past that relates to aircraft configurations with conventional aerodynamic surfaces, mechanical controls, simple rate damper type stability augmentation systems, and basic instrument displays[2,3]. Modern designs make use of highly augmented digital fly-by-wire controls and sophisticated displays, and the basic aerodynamic configurations tend to have relaxed static stability with minimal or no conventional tail surfaces.

While the overall objective of this simulation experiment was to determine handling qualities, performance and flight control requirements for a variety of aircraft and control system configurations, the data unique to the ATT design is proprietary to Boeing. This paper addresses the topic of what levels of handling qualities and approach and landing performance were attained from the still-evolving ATT configuration.

STOL Transport Aircraft Concept

The ATT configuration shown in Figure 1 features a tilt-wing, with a horizontal stabilizer of reduced size compared to conventional transport aircraft, and without a vertical tail. It is powered by four cross-shafted turboprop engines driving eight-bladed propellers having variable collective and cyclic pitch. The wing planform includes forward sweep of the outboard wing sections, and large trailing edge flaps capable of very large deflection angles. The aircraft is sized to operate with payloads of up to 80,000 lb from an austere airfield of 750 – 1,500 ft in length. The design STOL approach and landing speed is between 65 and 75 knots.

With the wing tilted at the approach configuration and flaps fully deflected, the aircraft operates on the backside of the power-required curve, exemplified by

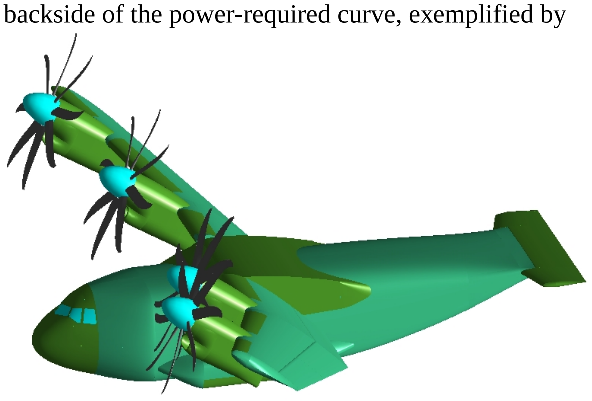

Figure 1. Boeing Phantom Works Advanced Theater Transport

the trend of decreasing flightpath angle with decreasing airspeed at constant power. At constant pitch attitude, flightpath changes can be made with power without appreciably altering airspeed, which is a characteristic that is expected to reduce pilot workload in performing the landing approach. Airspeed is controlled through attitude change, with a gradient on the order of 1.8 knots per degree of attitude. Powered-lift contributions are primarily a result of the large flap deflection, not of wing tilt. Wing tilt may thus be used to change the attitude of the fuselage for a given flight condition without altering the basic aircraft performance.

The block diagram in Figure 2 provides an overview of the flight control system with its significant elements. It includes (1) commands from the associated control response types introduced by the pilot through the inceptors, (2) a regulator that acts on the response type commands and feedbacks from the aircraft's sensors to produce commanded accelerations necessary to achieve the pilot's intended maneuver and to stabilize the aircraft against disturbances, (3) a nonlinear aerodynamic/propulsion model that produces estimates of the aircraft's current accelerations, and (4) the control selector that acts on the difference between the commanded and estimated accelerations to produce commands to the control effectors. The feedback of the aircraft's estimated accelerations acts to cancel (or deaugment) the characteristics of the basic aircraft, leaving the aircraft to respond to the commanded accelerations from the control response types and regulator. Control effectors include aerodynamic control surfaces and propulsion controls. The aerodynamic controls consist of wing tilt, ailerons, fast acting flaps, and a horizontal stabilizer (used only for pitch trim). Propulsive controls include propeller collective and cyclic pitch. Allocation of the control effectors depends on flight conditions and control effector inter-axis coupling.

Control augmentation for STOL operation consists of pitch, roll and yaw stability and command augmentation systems (SCAS) and a height damper for flightpath response augmentation. Pilot inputs for pitch and roll control are made using a center stick. Pitch control augmentation provides either rate command/attitude hold or attitude command/attitude hold response; response type is selectable by the pilot through a discrete switch on the center stick grip. Roll control augmentation provides rate command/attitude hold response. The pedals command sideslip. Propeller thrust is controlled manually through the throttle levers. The height damper operates through propeller collective pitch and engine power to improve flightpath bandwidth in response to throttle lever inputs.

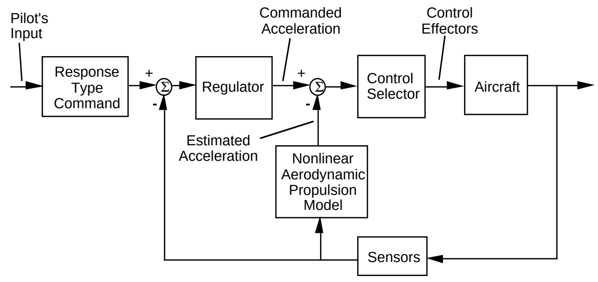

Figure 2. Flight control system architecture

Displays

A head-up display (HUD) and a head-down primary flight display (PFD) provided primary flight information, including aircraft attitude, flightpath angle, airspeed, rate of change of airspeed, altitude, engine power, wing tilt, flap angle, heading, sideslip, and distance from the airfield. An example is shown for the head-up display in Figure 3 while the head-down primary flight display appears in Figure 4. Pursuit guidance symbology added to the display for precision approaches is also shown in the two figures. Course and glideslope guidance were provided in the form of a leader aircraft that followed the desired flight profile. Speed guidance was shown by the airspeed error tape on the left wing of the flightpath symbol that displayed the airspeed error from the desired airspeed. The guidance display was flightpath-centered and presented the pilot with a pursuit tracking task for following the intended transition and approach to landing[4]. The pilot's task was to control the flightpath symbol to follow the leader using engine power and bank angle, and to make airspeed corrections using pitch attitude.

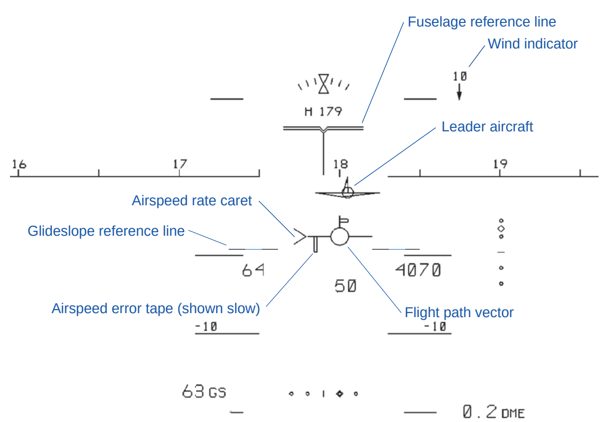

Figure 3. Head-up display configuration

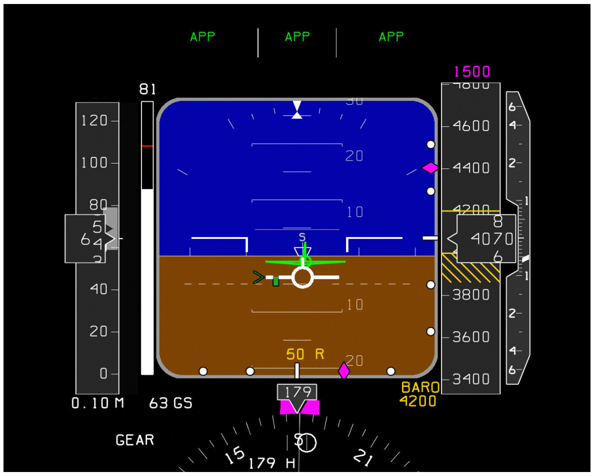

Figure 4. Head-down primary flight display

For the approach and landing task evaluated in this study, the HUD was the primary display used and since the display formats are similar in concept, only the HUD elements will be discussed. The flightpath symbol was quickened to compensate for lags in aircraft response, while the airspeed rate caret was quickened to compensate for lags introduced by filtering to suppress the effects of turbulence. The drive laws for these symbols and a discussion of pursuit displays is described in Ref. 4.

To use the displays for lateral and vertical flight path control down to decision height, the pilot places the flight path vector on the leader, causing the actual flight path to converge exponentially on the desired trajectory. The scaling on the leader (driven by scaled glideslope and localizer errors) was set to give an exponential convergence time constant of 15 seconds at altitudes above 1000 feet, varying linearly to a five second time constant at altitudes below 100 feet.

Below decision height, the pilot uses the airspeed error tape and the airspeed rate caret to control airspeed. The scaling on the airspeed error tape and airspeed rate caret were chosen to give approximately a 10 second exponential convergence to the desired speed if the caret is placed opposite to the tape with the same magnitude as the airspeed error; thus if the tape is two degrees below the wing, indicating the airspeed is low, the pilot would pitch down to place the caret two degrees above the wing, to accelerate to the desired airspeed.

In addition to these symbols, sideslip was presented as a flag on the vertical tail of the flight path symbol. Deflection to the right indicates a right sideslip and calls for right rudder to correct to zero sideslip. Equivalent airspeed is digitally presented at the lower left of the flight path symbol with digital barometric altitude to the lower right. Radar altitude is shown directly below the flight path symbol.

The fuselage reference line, in combination with the pitch ladder, indicates the current pitch attitude of the aircraft. This symbol is fixed to the display surface and does not move. Seen in Figure 3, the fuselage reference line is centered laterally in the display and is six degrees above the display centerline.

An extended body centerline (or crab angle indicator line) consists of a line that descends vertically from the center of the fuselage reference line at low altitudes. From zero length above 100 feet altitude above ground level, the extended body centerline grows proportionally as altitude decreases to touchdown, where the bottom of the line is even with the top of the vertical tail of the flight path vector symbol. The extended body centerline provides the pilot a strong crab angle cue at touchdown.

Conventional glideslope and localizer deviations are shown at the right and bottom of the display. They show deviations from desired trajectory during the initial approach, and deviations from the five degree glideslope and localizer on final approach. They are fixed to the display. The scaling of the glideslope is 12 feet per dot below 100 feet of altitude, 100 feet per dot above 850 feet altitude, and varies linearly between 100 and 850 feet. This glideslope scaling is equivalent to conventional instrument landing system (ILS) scaling between 100 and 850 feet of altitude. The localizer scaling is 75 feet per dot below 100 feet of altitude, 300 feet per dot above 850 feet altitude, and varies linearly between 100 and 850 feet, and is more sensitive than conventional ILS scaling.

The glidepath reference line is a dashed line with a gap in the center and is shown displayed five degees below the horizon line for the final approach in Figure 3. The glidepath reference line slides left and right with the flight path vector symbol so that the flight path vector symbol is always centered in the gap.

Simulator Facility

The experiment was conducted on the Vertical Motion Simulator (Figure 5) at NASA Ames Research Center. The simulator provides six degree-of-freedom motion that permits large excursions in the vertical and either the longitudinal or lateral axes, depending on cab mounting orientation. Bandwidths of acceleration in all axes, including pitch, roll, and yaw, encompass the bandwidths of motion sensing that are expected to be of primary importance to the pilot in approach and landing tasks. The cockpit was oriented with its lateral axis along the largest horizontal dimension of the motion system in order to exploit the motion system authority for lateral maneuvers.

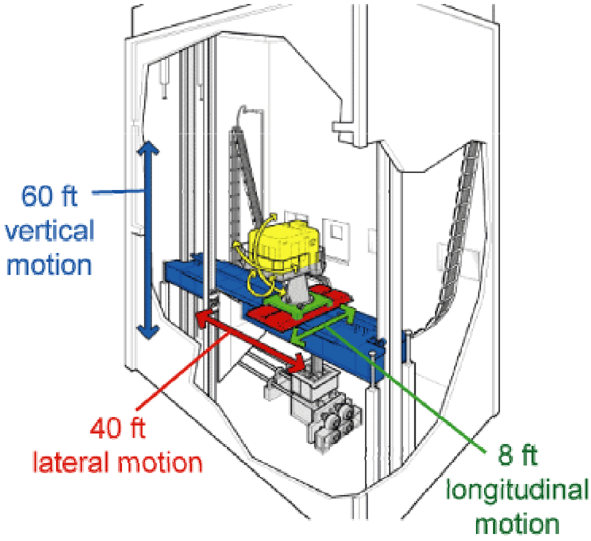

Figure 5. Vertical motion simulator

An interior view of the cockpit is shown in Figure 6. The evaluation pilot occupied the left seat with a test engineer/observer in the right seat. A six-window, computer-generated imaging (CGI) system provided the external view. A dirt strip STOL runway having dimensions of 90- by 750 ft was located among trees in otherwise open terrain. Six panel-mounted displays and the head-up display presented flight information to the pilot and observer. The panel displays included (left to right) a task/pilot performance display, primary flight display, and navigation display and were replicated identically at each seat. The HUD was superimposed on the forward-facing windows of the CGI.

Figure 6. Simulator cockpit

Evaluation Tasks and Procedures

Four pilots, two from NASA and two from Boeing, were the subjects of this experiment. All pilots had previous STOL aircraft experience. Pilot comments and pilot ratings using the Cooper-Harper rating[5] and pilot-induced oscillation (PIO) rating scales[6] were obtained during the experiment.

Pilots' evaluations were obtained for a range of control response type characteristics and levels of dynamic augmentation. Nominal and off-nominal approach conditions and go around, including visual and instrument meteorological conditions along with varying winds and turbulence were used to expose the aircraft to a broad range of anticipated operating environments.

Seven evaluation tasks were selected for the simulation program, encompassing the approach and landing phases of vertical offset, lateral offset, slalom, deceleration, and 30-knot crosswind tasks, and an aborted approach with go-around. The first three tasks were conducted in visual meteorological conditions (VMC), while the last four tasks were flown in instrument meteorological conditions (IMC). Pilots were instructed to fly the tasks to landing, although the conditions were difficult enough that in an operational environment, many of the approaches would have resulted in go-arounds.

Most of the landing tasks were initiated in a five degree descent at an equivalent airspeed in the range of 65-75 knots, with a wing tilt suitable for approach and flaps fully deflected. For these tasks, the attitude command/attitude hold pitch response type was selected. The aircraft was nominally positioned on glideslope and localizer at 800 ft altitude above the runway at a distance of 1.5 nmi from the runway threshold, as shown in Figure 7a. The nominal touchdown point on the runway was located 50 feet from the threshold, and the corresponding visual aim point was marked with an X further down the runway. The leader aircraft guidance symbology was used down to decision height, below which pilots aligned the glideslope reference line on the HUD with the visual aim point, using the flight path symbol to accomplish the landing.

As Figure 7b and Figure 7c illustrate, the offset approaches were initiated with the aircraft displaced either 45 ft above the glideslope or 300 ft laterally from the localizer. In these cases the approach was flown with this offset until the pilot was commanded by the experimenter to maneuver to correct for the offset error. This correction was called for at an altitude of 200 ft above the runway for the vertical offset, or at 250 ft for the lateral offset, at which point the pilot acquired the glideslope or localizer and continued with the landing. No-flare landings were performed at the target touchdown point and approach airspeed. These offset tasks were flown both with the height damper turned off and with it turned on, which nearly halved the time constant of the flight path response.

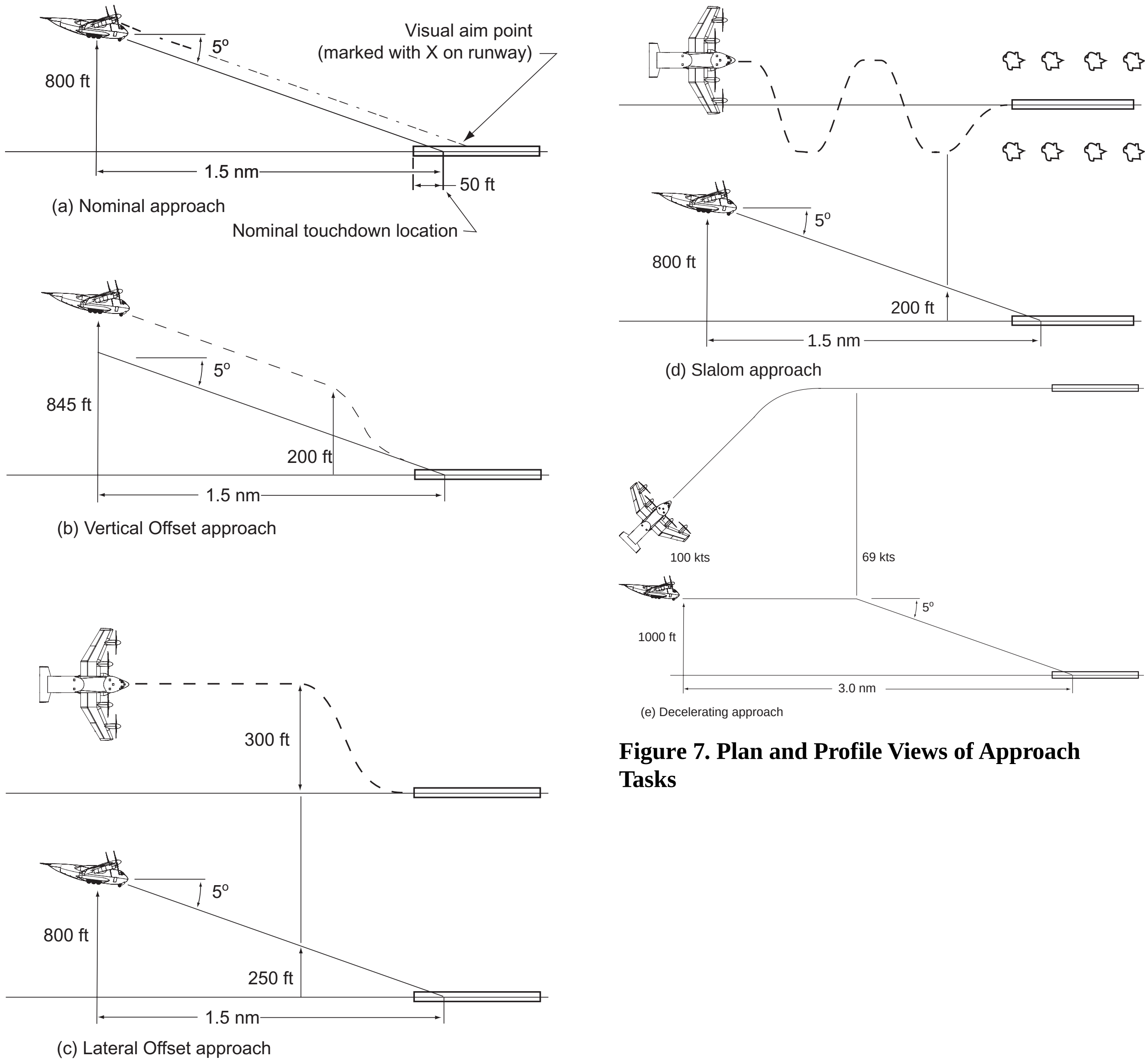

Figure 7. Plan and Profile Views of Approach Tasks

The slalom maneuver shown in Figure 7d was performed while descending on the glideslope by maneuvering laterally, on command of the experimenter, between lines extended from tree rows paralleling the runway, then correcting back to the localizer and completing the landing. The decelerating approach was initiated in level flight at 1000 ft above the runway at a distance of 3 nm from the threshold on a 45-degree intercept path to the extended runway centerline at an airspeed of 100 knots. The pitch response type was set to rate command/attitude hold at the start of the approach. The pilot task was to turn to acquire the localizer, command wing tilt to the approach configuration, decelerate to the final approach speed, acquire the glideslope, select the attitude command/attitude hold pitch response, and proceed on the final approach to landing. This approach profile is shown in Figure 7e. Crosswind and wind shear approaches and go-around approaches were initiated at the nominal altitude and range. All of these approaches were carried to the landing; go-arounds were initiated on experimenter command at 50 ft radar altitude, in the landing configuration and with a target pitch attitude and climb out airspeed selected for maximum climb capability while maintaining runway heading.

The offset approaches and the slalom task were carried out in VMC with light turbulence (3 ft/sec rms). The decelerating approach and approaches in wind shear were conducted in IMC consisting of a ceiling of 200 ft and a visual range of 3000 ft in fog. For crosswind approaches, weather minimums consisted of a ceiling of 300 ft and a visual range of 6000 ft. Crosswind and wind shear approaches and landings were made in moderate turbulence (5 ft/sec rms), while the deceleration task took place in light turbulence (3 ft/sec rms). Discrete longitudinal, lateral, and vertical gusts were introduced for all approach configurations to further complicate the pilot's task. The wind shear task included a horizontal decreasing headwind and a downdraft representative of a thunderstorm situated about 4000 feet prior to the runway threshold. Wind shear approaches were initiated in a steady headwind of 20 knots, which decayed to zero at a rate of 1 knot/sec.

Results

The averaged handling qualities ratings (HQRs) for all pilots and all configurations versus task, for the longitudinal and lateral/directional axes, respectively, are presented in Figure 8 and Figure 9. The approach and landing portions of each task were rated separately. For the offset and slalom tasks, the final correction to glideslope and localizer was considered part of the landing, while for the IMC tasks, the landing was considered to start at decision height.

Neither the vertical or lateral offset nor slalom tasks posed any challenge to the aircraft's longitudinal flying qualities for the approach, and were rated satisfactory. Significant degradations in flying qualities (1-2 HQRs) occurred in IMC, particularly in moderate turbulence, or during wind shear. Given that the turbulence and wind shear were of a moderate to severe magnitude, the flying qualities were considered adequate. Demands of the vertical offset correction prior to landing increased the workload for landing in comparison to the approach and led to degraded ratings, although with the height damper turned on, the ratings were still within the adequate range. The most dramatic difference between approach and landing HQRs, and the poorest average HQR overall, were generated by landings with the height damper disabled; the height damper directly influences flightpath bandwidth. Pilot comments noted the poor flightpath predictability and sluggish response that led to handling qualities degradation.

The small standard deviations of about 0.5 HQR for the approach portions of the offset tasks demonstrate insensitivity in pilot workload to the range of pitch control bandwidths and center-of-gravity locations explored in the Boeing-proprietary portion of the simulation.

The lateral offset and crosswind tasks placed the greatest demands on the pilot for lateral and directional control in the landing. Handling qualities for these two tasks were just adequate in contrast to less demanding straight in landings that were considered to be satisfactory.

Coupling of the degraded flightpath response with the height damper off into the lateral-directional ratings can be observed in the lateral offset landing task. The increased workload required by the longitudinal control task influenced pilots' ability to simultaneously control lateral alignment with the runway.

One pilot rated the 30-knot crosswind landing inadequate (HQR 8) for both longitudinal and lateral-directional tasks, based on his impression that controllability was in question. This rating represented the pilot's first exposure to the crosswind landing task; considering that his subsequent ratings were HQR 6, the HQR 8 rating is likely too severe. One pilot also rated the longitudinal landing portion of the windshear task as inadequate (HQR 9). This rating reflected a near loss-of-control situation following large flightpath and airspeed perturbations close in to the runway. In an operational situation, a go-around would have been initiated.

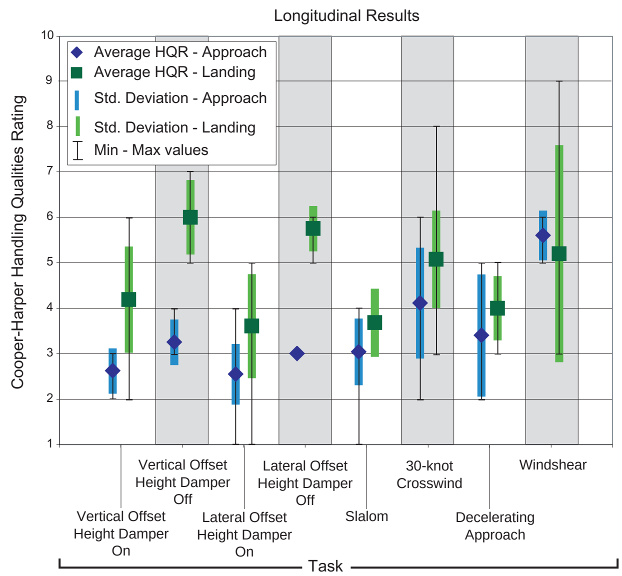

Figure 8. Longitudinal handling-quality ratings

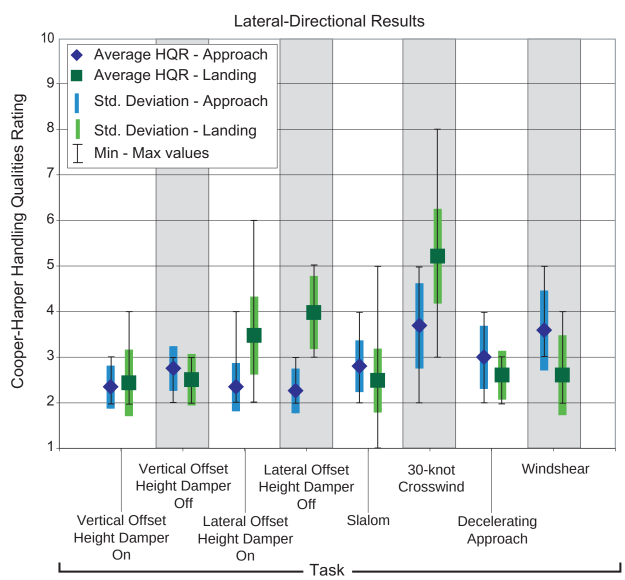

Figure 9. Lateral-directional handling-quality ratings

An insufficient number of HQRs were collected for the go-around task to present them for comparison. However, pilot comments indicated that the approach portion of the task was completely satisfactory. Maintaining a positive climb rate after initiating the go-around proved difficult; precise control of pitch attitude was required to increase airspeed while gaining altitude after application of full power. Pilots initially found the required technique of lowering the nose to initiate the go-around to be disconcerting. The go-arounds were flown in the approach configuration; no investigation of alternate control surface configurations was carried out.

Figure 10 through Figure 14 illustrate the precision trajectory and speed control achieved through the use of the flightpath-centered guidance displays. As seen in Figure 10, for most tasks pilots were able to stay on the glideslope quite well. The windshear encounter was designed to require more than the available power, hence the significant error for this task. Note that data for the vertical offset and slalom tasks are not presented -- large glideslope errors are inherent to the offset task, and glideslope data for the slalom task was not recorded, although no notable deviations were observed. Figure 11 illustrates how accurately the localizer can be tracked, despite significant turbulence, gusts, and crosswinds. The localizer was not tracked on the approach for the lateral offset and slalom tasks; therefore data for these tasks are not presented.

Figure 12 plots the indicated airspeed recorded at touchdown for each of the tasks. Results were generally within the adequate range of ±6 knots from the nominal approach speed, and for tasks demanding less pilot concentration during the landing phase, results within ±1 standard deviation fell within the desired range of ±3 knots from nominal. The crosswind results reflect the difficulty of the multi-axis task in moderate turbulence, with a tendency to carry too much airspeed into the landing. Similarly, the slalom task placed last-minute multi-axis demands on the pilots, as they were required to make a large lateral correction to align with the runway, and the larger spread in airspeed is evident.

Sink rate errors at touchdown are shown in Figure 13. An increase in sink rate can be seen for the offset tasks performed with the height damper turned off; the slower flight path response to throttle inputs prevented pilots from making fine corrections in the last moments before touchdown. As with the airspeed results of Figure 12, the demands of the crosswind task are evidenced by the increased variation of sink rate for the task.

Lateral and longitudinal touchdown dispersion from the nominal touchdown point is plotted in Figure 14. Lateral results for all tasks are excellent, with standard deviations of only ± 2 to ± 5 feet about the runway centerline. Longitudinal results show greater variation across tasks. The effect of turning off the height

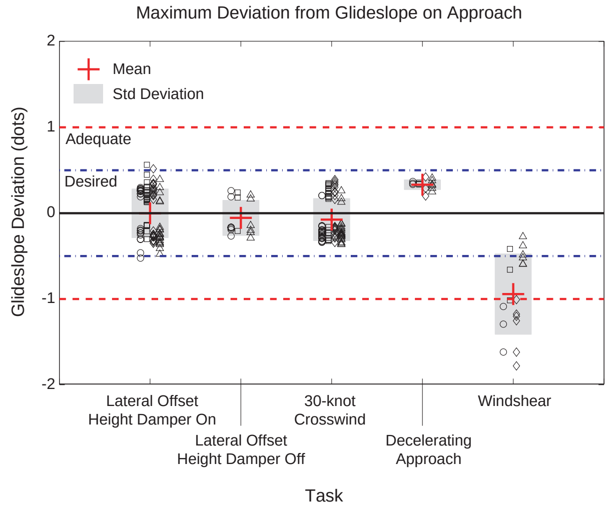

Figure 10. Maximum deviation from glideslope

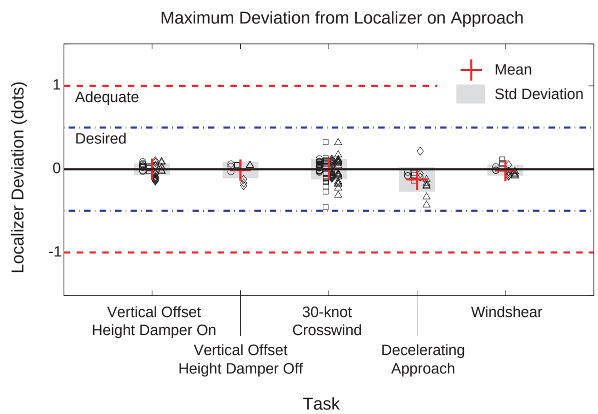

Figure 11. Maximum deviation from localizer

damper is very noticeable in the vertical offset task – with the height damper on, touchdowns were clustered tightly around the nominal, while without the height damper, the average touchdown was 25 feet long, and compares most closely with the windshear task. The lateral offset task required much less throttle activity during the final approach, and this is reflected by comparable results with the height damper on and off. The multi-axis requirements of the slalom and crosswind tasks during the final correction resulted in slightly long average touchdowns, but consistency was generally good for both tasks. The outlying points in the crosswind task resulted from directional control saturation – the 30-knot crosswind was designed to be a limiting task for cockpit (pedal) controls, and demonstrated the thin margin of control available with nearly full pedal displacement required to de-crab the aircraft. In an actual operational situation, pilots would have chosen to abort the landing. Control effectors in this case were not necessarily the limiting factor. In the future, pedal command characteristics may be adjusted

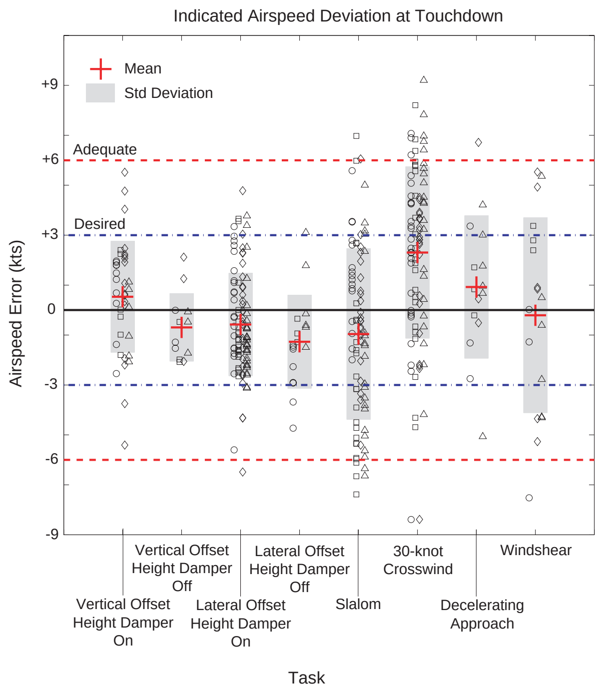

Figure 12. Indicated airspeed at touchdown

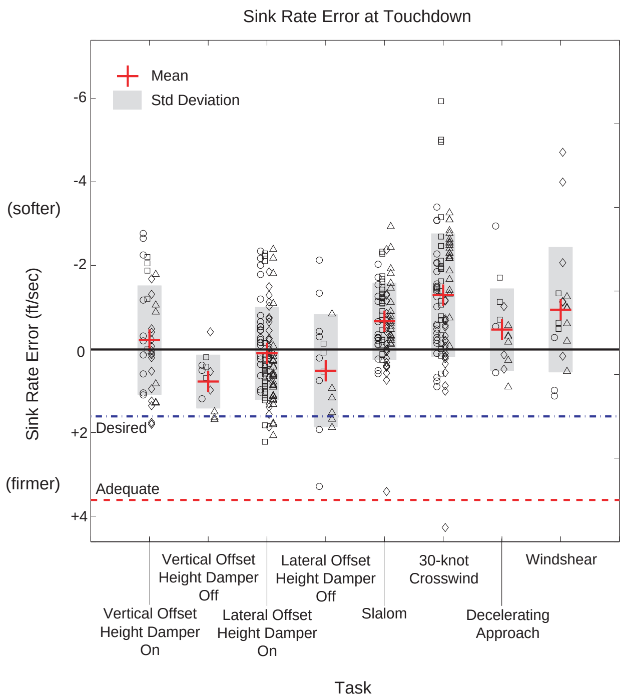

Figure 13. Sink rate at touchdown

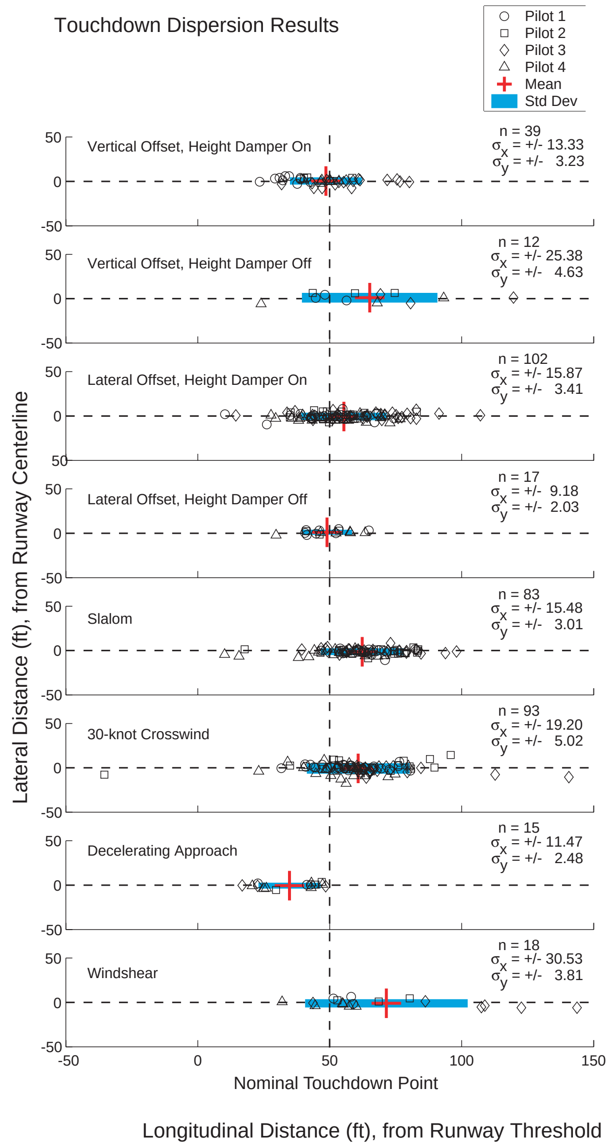

Figure 14. Touchdown dispersion

to address such limitations. The short landings for the decel task are likely due to the higher-intensity longitudinal gusts (16.9 knots) employed for the task, which ramp in 2000 feet from the runway threshold. Landings for the windshear task tended to be long of the target landing point. This was the result of the large power increase required during the shear encounter, which then needed to be reduced quickly as the aircraft exited the shear and approached the runway threshold.

The average of the standard deviations of the longitudinal dispersion, exclusive of tasks performed with the height damper off and the windshear task, was ± 15.07 feet. This result compares very favorably with no-flare touchdown results for the NASA Quiet Short-haul Research Aircraft (QSRA), which achieved a standard deviation of the longitudinal dispersions of ± 18 feet for more normal conditions than evaluated in this study.[7]

Conclusions

Flying qualities of a tilt wing STOL transport during final approach and landing have been evaluated in a large-scale moving-base simulation. A range of control response type characteristics was investigated, and a variety of approach conditions in visual and instrument meteorological conditions, varying winds and turbulence were explored. Evaluations included vertical and lateral offset approaches, slalom maneuvers on the approach, and approaches in limiting crosswind and wind shear to assess the effects of more stressful conditions on flying qualities and susceptibility to pilot-induced oscillations. A decelerating approach from a mid-transition configuration and flight condition to final approach and landing was used to represent a STOL operational task. Flightpath-centered head-up and head-down displays were used, incorporating leader aircraft pursuit guidance symbology. Assessments of these controls and displays were made by pilots from both NASA and Boeing.

The aircraft, control modes, and display combination produced satisfactory flying qualities for all operations except for those in extreme cross winds and in severe wind shear. This test was one of the first piloted simulations of the Boeing ATT concept. Thus, areas for improvement and refinement of the design are one of the valuable outcomes of this test. The need for flight path augmentation was demonstrated by the poorer performance results and HQRs recorded with the height damper turned off. The head-up display provided guidance cues that produced desired approach path tracking performance that yielded precision landing performance.

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