Design and Validation of Flight Control Law Changes Intended to Minimize Pilot-Induced Oscillations in a Large Transport Aircraft

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This paper describes the overall approach that was adopted by the Boeing Flight Controls design team to address recent lateral Pilot-Induced Oscillation (PIO) incidents with the C-17A Globemaster III during Approach and Landing. The topics discussed include root cause analyses, design goals and criteria, proposed control law changes, flying qualities analyses, and validation of the design changes. The primary focus of the paper is the revised control laws intended to mitigate the lateral PIO tendencies and the subsequent piloted simulation evaluations. A key feature of the proposed control law design change is to reduce roll command gain and authority by default. Other significant improvements include a more linear roll command gain stick shaping, increased roll rate feedback gains, the addition of roll command lead compensation, elimination of unnecessary command filtering, and increased software surface rate limits. Roll performance concerns resulting from the reduction in roll command gain and authority were mitigated by analysis to ensure that the time-to-bank requirements are always met. Additionally, full roll command authority is restored following all failures in which rolling performance has been severely compromised. Validation of the design changes entailed both off-line analyses and formal piloted simulation tests. The latter option was not exercised until the former produced acceptable results against applicable flying qualities criteria and guidelines. The piloted evaluations involved a wide variety of flight maneuvers that described both gross acquisition tasks and fine tracking tasks. It will be shown that the simulator results supported the off-line analyses, thus further validating the design changes.

I. Introduction

In the early development of the C-17A Globemaster III, incidents of lateral PIO were encountered during the approach and landing phase of flight. Some of these encounters took place during normal high gain piloting tasks, and were driven initially by excessive phase lag within the flight control system, while others took place during large pilot reactions to some external disturbances, and were driven primarily by actuator rate saturation. Changes in the lateral control law architecture were subsequently implemented in order to reduce the phase lag and actuator rate saturation. In addition, the roll control sensitivity was adjusted to further minimize the noted PIO tendencies [1]. For several years thereafter, no PIOs were reported.

Since the onset of Operation Enduring Freedom on 7 October 2001 the lateral PIO tendencies resurfaced as manifested by several reported incidents during final approach and landing, some of which occurred during night operations in a war zone. The highly demanding combat environment, and the associated high pilot workload, clearly was the driving factor behind unmasking these otherwise dormant PIOs. Some of the reported incidents resulted in aircraft damage due to wing scrapes and/or hard landings. The incident aircraft were typically heavily loaded with high roll inertia, at either normal (3/4) flaps or assault (full) flaps.

As a result of these incidents, extensive analyses were performed resulting in proposed software changes. The objective of these revisions was to further reduce the roll PIO susceptibility during approach and landing while, at the same time, ensuring that there would be no unacceptable degradation in the lateral Flying Qualities relative to the baseline aircraft.

The longitudinal flight control system of the subject aircraft has three modes of operation; Pitch Rate Command/Attitude Hold (PRC/AH), which is the basic flight mode, Pitch-Attitude Command/Attitude Hold (PAC/AH), which is the mode for approach and landing, and Aerial Refueling mode. The lateral control response

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system is Roll-Rate Command, while the directional control response system is Sideslip Command. The Angle-of-Attack Limiting System (ALS) is active in all flight modes. On ground, the control system modes are Pitch Rate Damping, Roll Rate Damping, and Yaw Rate Damping. The proposed design changes affect the lateral control laws only, specifically, within the Flight Control Computer (FCC) and Spoiler Control/Electronic Flap Computer (SC/EFC).

II. Approach

A review of the incident data obtained from the Standard Flight Data Recorder (SFDR) revealed that, while the roll stick was active on most approaches, the PIO developed when the roll stick increased beyond a specific threshold. The PIOs involved aileron rate limiting and, subsequently, position limiting. Some rudder activity was also observed around the start of the PIO. Spoiler activity was noted to increase during the oscillations and, following several cycles of aileron rate and position limiting, the spoilers saturated in rate and position, particularly during the longer PIO occurrences. Subsequently, and as expected, an increase in sink rate resulted due to the loss of lift associated with the large spoiler deflections. The analyses of the incident data, which included Power Spectral Density (PSD) analyses, confirmed a classical roll PIO with definite phase differences between input and output, with the dominant PIO frequency being around 2 radians per second.

Several potential culprits were considered during the ensuing analyses. In addition to control surface and control inceptor issues, such as aileron and spoiler rate and position limiting, insufficient spoiler bias, nonlinear aerodynamic effects, and nonlinear roll stick shaping, other control-law-related issues were investigated. These included excessive time delay, slow roll-mode time constant, and possible adverse effects due to the aileron-to-rudder interconnect.

Following additional analyses [2], and in accordance with the resulting recommendations by the Non-Advocate Review team of subject matter industry experts who convened on 1 April 2003 [3], specific areas were targeted for potential improvement or development. These included the forward roll command path gains, roll stick shaping, augmented roll mode time constant, spoiler lead compensation such as a feed forward washout, and the aileron-to-rudder interconnect. Other areas, such as roll rate feedback to the spoilers, roll stick feel characteristics, control reallocation using modern control theory, and spoiler bias reconfiguration, were deemed out of scope not only due to time and budget constraints, but, in some cases, also due to their impact on training.

For the purpose of devising a solution, the control law design team adopted a disciplined and structured approach that is outlined in Figure 1. The process entailed developing design goals and criteria, determining flight control system deficiencies and potential improvements, designing control law architecture and gains, and, finally, validation of the design changes via both off-line analyses and piloted evaluation. Several piloted evaluations were performed, two of which constituted formal evaluations using the training motion simulator facility of the 172nd Airlift Wing, Air National Guard, in Jackson, Mississippi.

As part of the off-line analyses, several applicable flying qualities metrics were used. Although the additional delays caused by excessive roll control surface rate and position saturation (i.e. nonlinear effects) were considered a major contributor to the PIOs, it was deemed necessary that the established design goals and analyses address both linear and nonlinear PIOs.

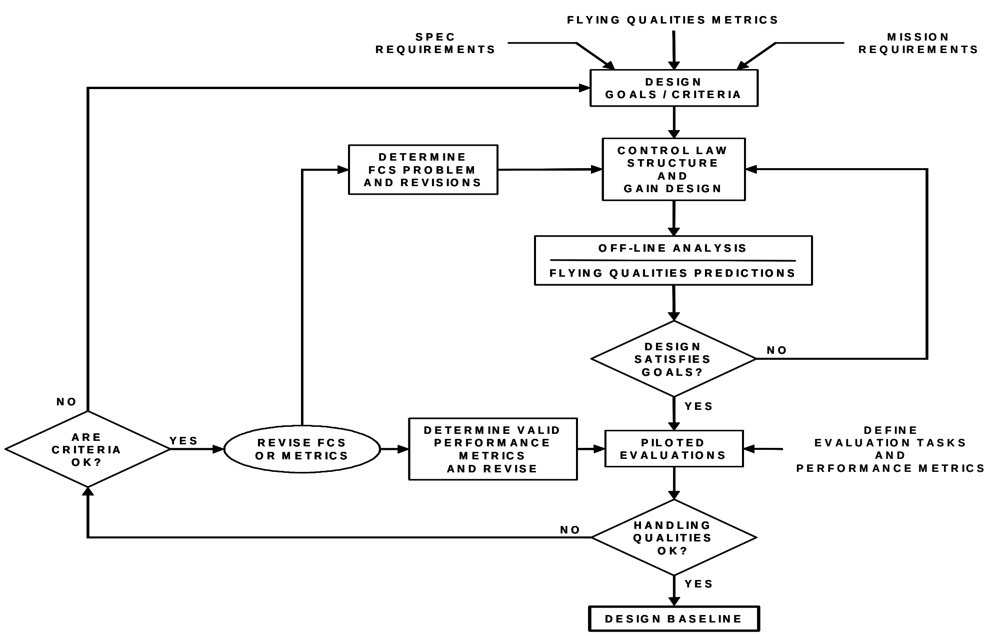

Figure 1. PIO Mitigation Process

III. Flying Qualities Criteria

Several control law design options, some of which included phase compensation concepts, were evaluated via a set of specific Flying Qualities criteria and guidelines. These criteria and guidelines included Roll Axis Bandwidth and Phase Delay, Gibson's Average Phase Rate and PIO Gain Limit Criterion, Roll Control Sensitivity, Roll Mode Time Constant, Roll Control Performance (Time-to-Bank) and Steady-State Roll Rate. Also, the Sideslip Excursions for Small Inputs Criterion, Low-Order Equivalent Systems (LOES), Open Loop Onset Point (OLOP), Limit Cycle Oscillation (LCO), and Hess Pilot Structural Models were used during earlier analyses to evaluate the proposed concepts [4]. Such a relatively large collection of criteria helped ensure that the design goals are met.

It may be noted that all of these criteria are well-known industry wide, and, therefore, were applied using accepted methods, except for the Roll Control Sensitivity criterion that was developed for transport aircraft and is relatively new [5]. For each criterion, a quantitative target was determined following several working group meetings of subject matter experts. The frequency response analysis was performed using both linear and non-linear, validated models of the subject aircraft at various amplitudes of roll stick input.

In addition to the aforementioned tools and methods, the Real-time Oscillation Verifier (ROVER) PIO detection tool that was developed by Hoh Aeronautics, Inc., was used [6]. ROVER, however, was initially calibrated against the available SFDR flight data and was later used to identify potential PIOs from pilot-in-the-loop simulation results.

IV. Control Law Changes

Design Concepts

The objective of the modified control laws is to minimize roll PIO susceptibility during approach and landing while improving the lateral/directional characteristics. The design strategy to achieve this objective is as follows.

1. Reduce phase loss from roll stick to aircraft roll response during approach and landing throughout the flying qualities frequency range at all configurations and stick amplitudes.
2. Improve the roll response predictability by making the rolling effectiveness more linear during approach and landing for all configurations and stick amplitudes.
3. Improve the roll mode dynamics (reduce roll mode time constant) during approach and landing for high wing fuel configurations (high rolling inertia) and large stick amplitudes.
4. Reduce flight path coupling (sink rate) during approach maneuvering for all flight conditions at large stick amplitudes.

A key feature of the proposed control law design change, hereafter referred to as A4.2, is to reduce roll command gain and authority by default, as a means of minimizing the nonlinear roll PIO susceptibility. Other significant improvements include a more linear roll command gain stick shaping, increased roll rate feedback gains, the addition of roll command lead compensation, elimination of unnecessary command filtering, and increased software surface rate limits.

Roll performance concerns created by the reduction in roll command gain and authority were mitigated by analysis to ensure that the time-to-bank requirements are always met. Additionally, new control law functionality is added to restore roll command gain authority when required during failures. This new function is assured by employing limited model reference direct adaptive control laws that restore roll command gain authority in proportion to a rolling performance error signal. Several constraints are placed upon this adaptation that thoroughly bound all possible adaptive stability concerns. One of these constraints is a large deadzone, which prevents adaptation (command gain authority increases) in nominal flight. Any potential objectionable dynamics resulting from dynamic increases in roll command gain authority are now limited to failure cases which already intrinsically contain large unwanted dynamics.

Design Details

The A4.2 Control Law design modifications are depicted at a highly simplified top level in Figure 2. The most important design changes are described in more details below.

1. The rolling spoiler and aileron command gains and authority are reduced during approach and landing for all flight conditions with an emphasis on large stick amplitudes.

   Gain reduction is limited by the time-to-bank Level 1 flying qualities requirements. Reduced command gains result in reduced spoiler and aileron rate limiting (especially for large amplitude stick inputs) while making full use of their most effective region. Phase characteristics are significantly improved at large stick amplitudes. Flight path coupling is reduced.

Command gains and rolling spoiler command authority are adjusted for certain specifically detected failures and always increased to their full authority if the Time-to-Bank Level 3 requirements are not met. This is accomplished by employing model reference direct adaptive control laws that restore roll command gain authority in proportion to a rolling performance error signal. While the analysis of this potential adaptation is beyond the scope of this paper, it is essential for justification of the reduction in command gain and authority to values resulting in less than full command authority, only a top level description is included herein.

Simplified Roll Control Law Conceptual Changes for A4.2 Control Law

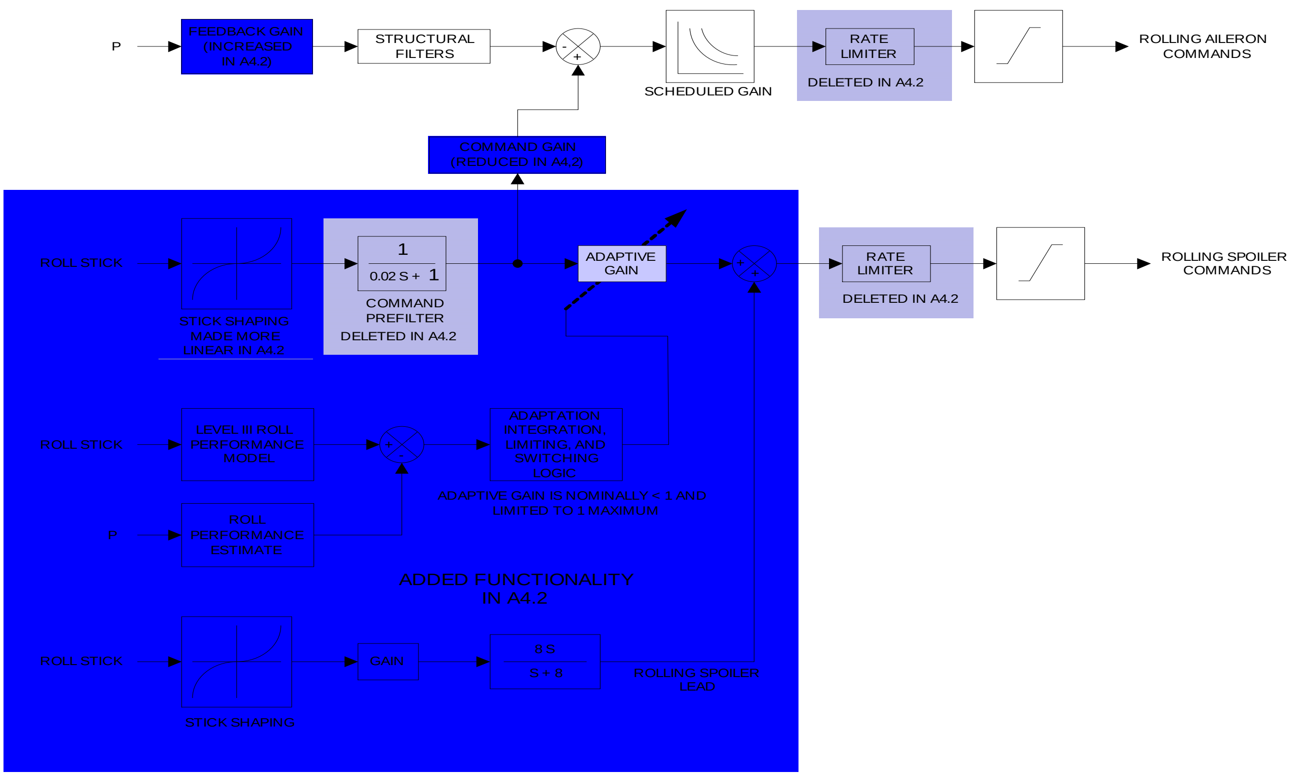

Figure 2. Simplified A4.2 Roll Control Law Conceptual Design Changes

Several constraints are placed upon this adaptation that thoroughly bound all possible adaptive stability concerns. The primary constraint is limiting this adaptation gain to 1.0 which limits the maximum gain and authority to being the same as for the baseline control law. The adaptation is directional and only occurs to increase gains when it is quickly needed to counter a failure or an extreme disturbance. Decreasing gains occur only at fixed rates and are, therefore, not adaptive. Another constraint is a large dead-zone which prevents adaptation (command gain authority increases) in nominal flight including during maximum crosswind landings. The total result is that any potential objectionable dynamics resulting from dynamic increases in roll command gain authority are now limited to failure cases or extreme disturbances which, as stated earlier, already intrinsically contain large unwanted dynamics.

This directional adaptive function uses a roll performance reference model that estimates flying qualities Level 3 steady state roll rate at full roll stick. The prediction of actual steady state roll rate at full roll stick is based on three functions of roll rate, roll acceleration, and roll acceleration rate. If none of the three functions predict Level 3 steady state roll rate at full roll stick, rolling spoiler authority will be increased at a rate proportional to the predicted Level 3 steady state roll rate at full roll stick deficit error (uses maximum predicted roll rate of three functions). The deficit error is the difference between the maximum predicted roll rate of the three functions and the estimated Level 3 steady state roll rate at full roll stick (error between reference model and actual). Additionally, large roll stick deflections are required for any adaptation (increase in gain/authority) to occur. Large stick reversals (significant stick rates in opposite direction) also inhibit any adaptation (gain/authority increase) even at large stick deflections.

Two levels of logic control the reversion from full authority back to nominal lower gains/authority. This is not adaptive since the gains reduction occurs at fixed rates (not proportional to an error signal). This approach was chosen since the need for gain reduction, unlike the need for gain/authority increase following some failures or extreme disturbances, is not urgent, and therefore, does not need to occur immediately. One level restores nominal (reduces) gains and authority quickly when the roll stick values are small. A second level of logic very slowly restores nominal gains and authority when the roll stick is commanding rolling in the opposite direction or when the roll stick magnitude is not large and the roll rate predictions are well above the Level 3 magnitudes for roll performance. This ensures that the full authority/gains control law state cannot get "stuck" high if and when any roll asymmetry or loss of control power is removed. The slow rate provision makes the transition dynamics transparent to the pilot for the case where the roll stick magnitudes remain at moderate levels in the same direction.

2. The roll stick shaping is much more linear. This improves the predictability of the roll response as the stick amplitudes and trim points change (e.g., roll control in crosswinds is more similar to roll control at 0 sideslip).

3. The roll rate feedback gain is increased. This tightens the roll mode dynamics (reduces the roll mode time constant) and improves disturbance rejection. Large increases are precluded by stability and rate limiting concerns.

4. A rolling spoiler command lead function is added. This change improves the roll mode dynamics (reduces the roll mode time constant) and improves phase characteristics. The frequencies are chosen such that the phase lead provided is substantial benefit in the region near ω180 out to 2 ω180 thus both increasing ω180 and reducing phase loss at higher frequencies such as 2 ω180 (τ_p reduced).

5. Remove roll command pre-filtering to reduce associated phase loss.

6. Remove the software rate limits for both the spoiler and aileron commands. This allows full actual actuator rate capability which will reduce rate limiting (and phase loss) by whatever difference exists between the in-flight actuator rate capability and the current software rate limits (60 deg/sec). The C-17 nonlinear 6DOF simulation predicts significant benefits from extending spoilers, but not from spoilers retracting or ailerons. It is unknown how much benefit will be derived in flight.

Design Analyses

The A4.2 control law design delivers significant improvements in phase characteristics across a broad frequency spectrum which assures recognition from a multitude of PIO criteria that emphasize the minimization of phase loss at a variety of frequencies. This is accomplished with a minimal reduction in gain at lower frequencies. This can be better understood from Figure 3, which illustrates a critical case, showing full roll stick amplitude bank angle nonlinear frequency response (Baseline versus A4.2 Control Law Comparison for a high wing fuel ¾ flap approach C-17 PIO flight condition). The A4.2 control law exhibits a considerable reduction in phase loss at all frequencies, significantly higher frequency for any fixed phase reference, and notably reduced gain at any of those phase reference points. These characteristics are representative of a more stable inner loop system providing for additional robustness for a widely varying (pilot) outer loop closure. Note the PIO shown was typical of all C-17 PIOs in that their frequency occurred at or slightly higher than ω180.

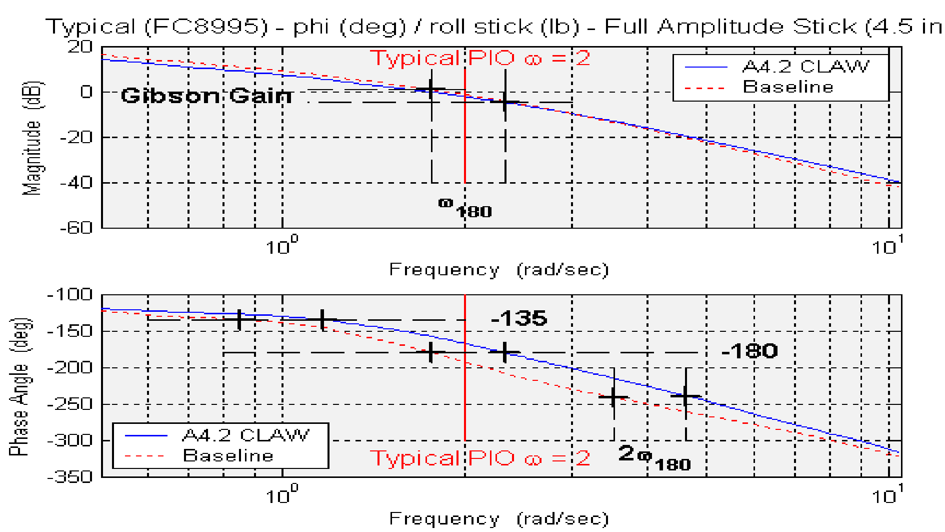

Figure 3. Full Roll Stick Amplitude Bank Angle Nonlinear Frequency Response, Baseline versus A4.2 Control Law Comparison for a high wing fuel ¾ flap approach PIO

The A4.2 control law design provides a reduction in roll mode time constant for all flight conditions at all stick amplitudes. This includes the target region during approach and landing for high wing fuel flight conditions (high rolling inertia) and large stick amplitudes. This can be seen in Figure 4, showing roll mode time constant as a function of roll stick amplitude (Baseline versus A4.2 Control Law Comparison for maximum and minimum wing fuel with full flaps).

The A4.2 control law design roll stick command shaping, as shown in Figure 5, is considerably more linear and provides less than full rolling spoiler surface command authority during nominal flight. The new stick shaping functions were designed taking into account the roll sensitivity requirement at small inputs and the time-to-bank requirement at large inputs. Adaptive roll command gain increases restoring full authority will generally occur for serious failures or extreme disturbances in which roll performance at full roll stick does not meet Level 3 performance. Analysis of these serious failures is beyond the scope of this paper.

Figure 6 shows Roll Stick Command Gain Variation as a Function of Roll Stick Deflection, (Baseline versus A4.2 Control Law). There is much less variation in gain across varying stick deflections with A4.2 Control Law.

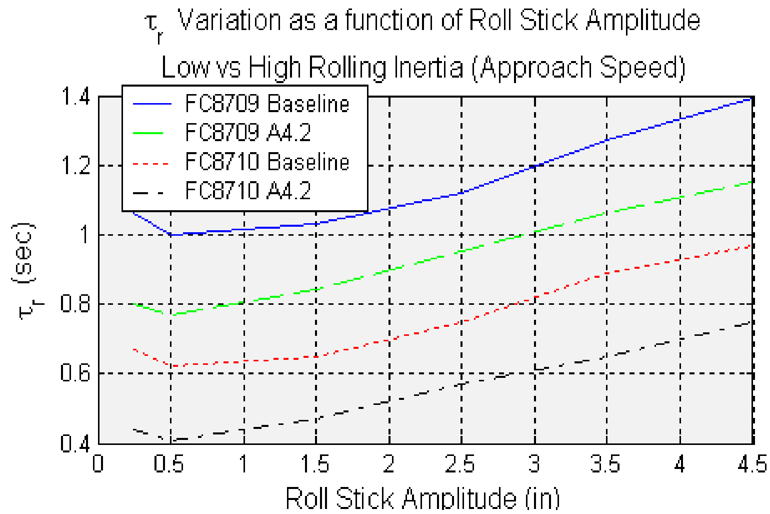

Figure 4. Roll Mode Time Constant as a Function of Roll Stick Amplitude, Baseline versus A4.2 Control Law Comparison for maximum and minimum wing fuel with full flaps

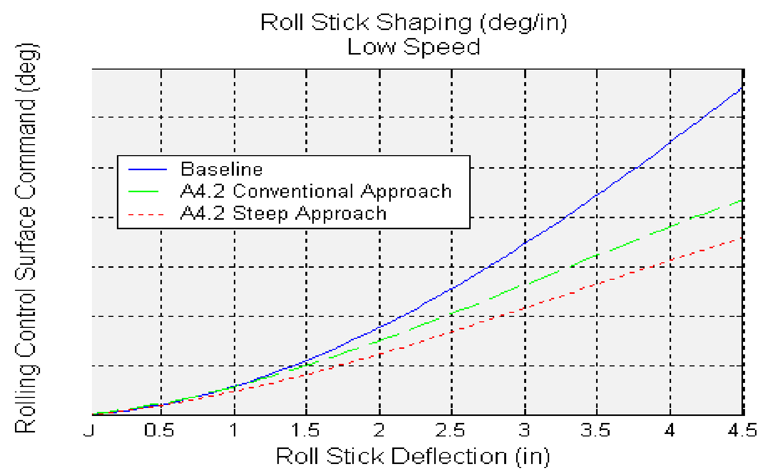

Figure 5. Roll Stick Shaping, Baseline versus A4.2 Control Law

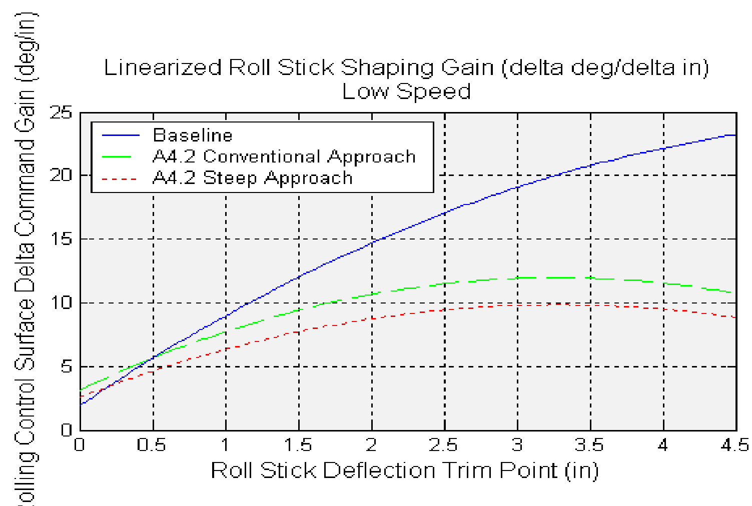

Figure 6. Roll Stick Command Gain Variation as a Function of Roll Stick Deflection, Baseline versus A4.2 Control Law

Phase Delay and Bandwidth, Baseline versus A4.2 Control Law for the worst case maximum wing fuel full flaps approach flight condition is depicted in Figure 7. Figure 8 illustrates the minimum wing fuel case for contrast. Boundary lines are shown for magnitude and directional reference only, since necessary and sufficient condition absolute thresholds to guarantee elimination of all roll PIOs for the C-17 during approach and landing cannot be precisely known. Significant improvements are clearly shown for all roll stick amplitudes with the A4.2 control law changes. Note that no A4.2 control law points are in close proximity with any of the C-17 PIOs.

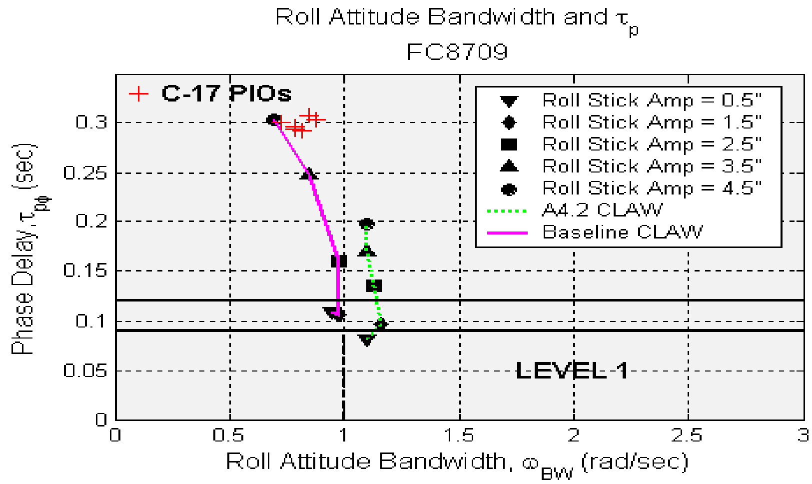

Figure 7. Phase Delay and Bandwidth, Baseline versus A4.2 Control Law for maximum wing fuel

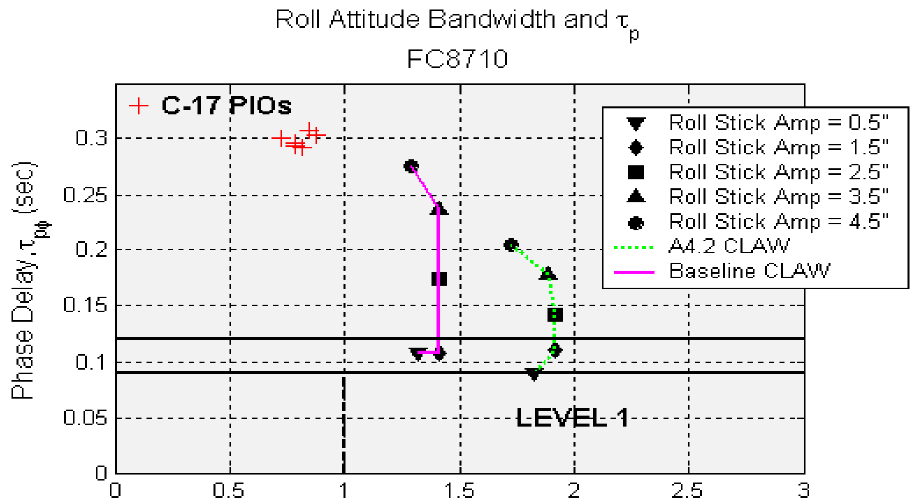

Figure 8. Phase Delay and Bandwidth, Baseline versus A4.2 Control Law for minimum wing fuel

Figures 9 and 10 display Gibson Average Phase Rate and 180 degree phase lag frequency, Baseline versus A4.2 Control Law for maximum wing fuel and minimum wing fuel, respectively. As previously noted, boundary lines are for reference only. Once again, considerable improvements are clearly shown for all roll stick amplitudes with the A4.2 control law modifications. All A4.2 control law points are considerably separated from all of the C-17 PIOs.

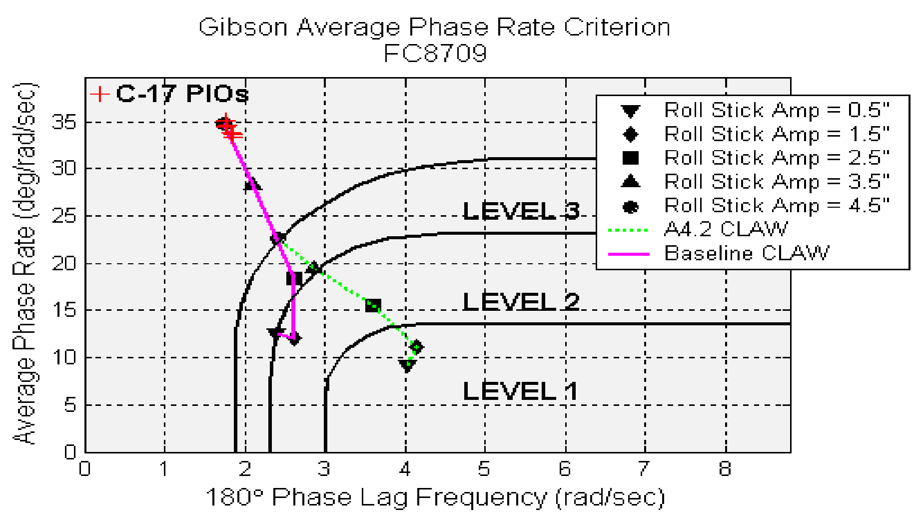

Figure 9. Gibson Average Phase Rate, Baseline versus A4.2 Control Law for maximum wing fuel

The C-17A roll effectiveness flying qualities Level 1 specification requires that the time to make a large bank angle change is within a time threshold. This may be substantially different than a steady state roll rate requirement (the C-17A does not have one) as can be seen in Figure 11. Since the A4.2 control law features reduced rolling command gain and authority that results in a significantly reduced steady state roll rate but also provides quicker dynamics and more linear stick shaping in combination, the overall roll effectiveness is (1) improved for small maneuvers, (2) the same for medium maneuvers, and (3) slightly degraded for large bank angle change maneuvers. This ignores the difficulty with which the baseline control law has of stopping the large bank angle change (due to excessive time delay and poor predictability) which blunts the value of any increased roll effectiveness.

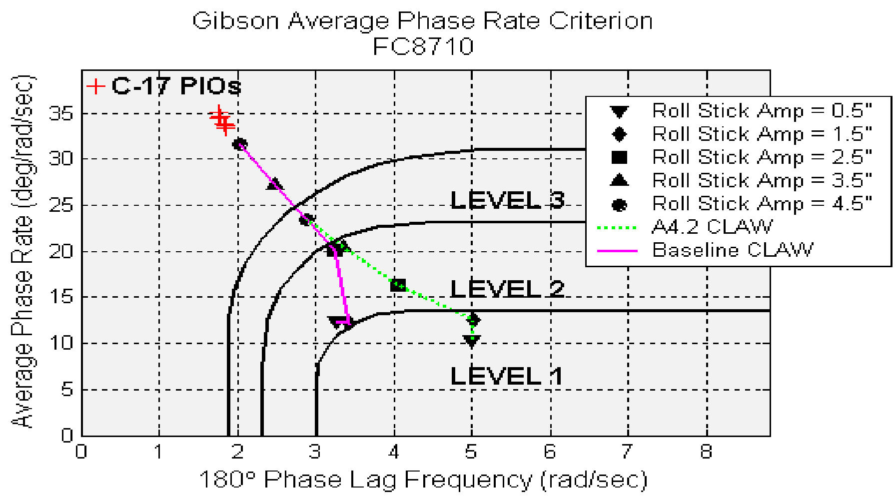

Figure 10. Gibson Average Phase Rate, Baseline versus A4.2 Control Law for minimum wing fuel

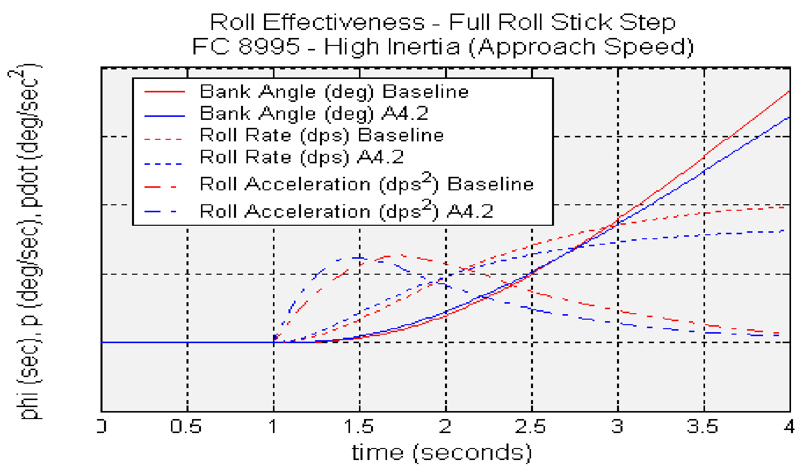

Figure 11. Roll Effectiveness Full Roll Stick Amplitude Bank Angle Response, Baseline versus A4.2 Control Law comparison for a high wing fuel ¾ flap approach PIO

V. Piloted Simulation Evaluation

Overview

As part of the validation and verification plan, two formal pilot-in-the-loop, motion simulator tests were performed using the training facility of the 172nd Airlift Wing, Air National Guard, in Jackson, Mississippi. The first test was performed in July 2004 using an earlier version of the control laws (A4.1), while the second test was performed in November 2004 using a later version of the control laws (A4.2). The basic concepts between the two versions of the control laws are the same and, thus, only results from the first piloted evaluations are presented herein.

Each of the two formal piloted evaluations followed extensive off-line analysis that was performed using the criteria stated in Section 1. Due to the nature of PIO phenomena, the design changes were based, first and foremost, on off-line analyses. Once acceptable improvements were shown against the established design goals, the piloted simulator test was conducted. In other words, the simulator was used as a verification and validation tool, not as a design tool. The final validation, however, will be in the form of a risk reduction flight test yet to be performed.

Objectives

The objectives of the piloted simulator tests were to validate the roll PIO improvements and to demonstrate improved, or at least equivalent, handling qualities, including acceptable roll control effectiveness, while performing representative terminal-area maneuvers.

Test Approach

The simulator test was in two parts, those being Checkout and Formal Evaluation. During Checkout, the control law design changes and related software were confirmed for accurate implementation (Model Checkout), the simulator platform was checked for representative hardware, including control inceptor characteristics, and to ensure accurate duplication of the simulation model commands as much as possible (Simulator Checkout), the pilot tasks and performance metrics were readied and tuned as necessary (Flight Cards Checkout), and the test matrix was prioritized. During Formal Evaluation, the participating pilots provided their formal assessment of the control law design changes through the use of Cooper-Harper Rating and Pilot-Induced Oscillation Rating scales.

For each test, two different sets of control laws were evaluated, the first described the current baseline aircraft and the second described the latest modifications to the control laws (either A4.1 or A4.2). This approach of testing the baseline configuration established a benchmark, from which incremental improvements could be measured, and helped mitigate some simulator fidelity questions that are inherent of all ground-based facilities.

Four different loading configurations, A, B, C, and D, were evaluated, with two (A and C) being representative of actual PIO incidents. Configuration A uses ¾ flaps (with an associated 3 degree flight path angle approach), while Configurations B, C, and D use the more critical full flaps (with an associated 4.2 degree flight path angle approach to a representative Short Austere Airfield, SAAF). Configuration B (high roll inertia) and D (low roll inertia) represented the most critical loading configurations without failures.

The flight maneuvers were evaluated by three Boeing test pilots in the first experiment. Additionally, and in the second test, a USAF test pilot, as well as two Air National Guards pilots, participated in the evaluation. Prior to starting the experiment, each pilot was briefed on the experiment's background and objectives and on the use of the Cooper-Harper Rating (CHR) and Pilot-Induced Oscillation Rating (PIOR) scales. The pilots were made familiar with the simulator and model by primarily flying a nominal approach and landing before proceeding onto the score cards. In general, the test procedure was as follows.

1. Select a piloting task (Flight Card),
2. Allow the pilot to take practice runs as required,
3. Ensure that the pilot performs 3 data runs for the approach and landing flight cards,
4. Provide performance feedback to the pilot after each run, and
5. Collect the pilot's comments, Cooper-Harper Ratings (CHRs), and Pilot-Induced Oscillation Ratings (PIORs) using the provided Pilot Comment Cards.

Both subjective and objective data were recorded during the evaluation for subsequent analysis. The subjective data were in the form of pilot comments and pilot ratings using the Cooper-Harper rating and PIO rating scales. After flying each configuration, the evaluation pilot was invited to complete the applicable Pilot Comment Card, where his opinion regarding possible PIO tendencies, aircraft handling qualities, and available roll control power, was expressed. The objective data, on the other hand, were in the form of audio voice recordings of the evaluation pilot, video camera recordings of the forward field of view and of the cockpit, a computer printout of the task performance statistical data, and a digital record of the time history data.

Test Facility

The training device is manufactured by Flight Safety International in cooperation with McDonnell Douglas Training Systems. The visual out-of-the-window scene, with an associated field of view of 225 degrees horizontal by 50 degrees vertical, is displayed on a back projection system. The cockpit layout and controls are identical to those of the subject aircraft.

The latency of the motion system has been estimated as 30 milliseconds, while the latency associated with the visual system has been estimated as 75 milliseconds. The latency tests were conducted as follows. All parameters are collected and recorded in the motion and controls system (DCM - Digital Controls and Motion) software. A control deflection is then commanded to the DCM from the host. The host monitors the control position within the DCM support software, and triggers a flag when control movement is detected. A series of latency flags are passed within the host through the following systems in sequence, those being DCM support software, FCC model, surfaces model, aero model, airframe model, and visual support and DCM support software.

When the visual support software in the host detects the change in the latency flag, it commands a discrete change in the visual picture (30 deg change in roll, pitch, or yaw). When the DCM support software detects a change in the latency flag, it commands a 0.08" jump in the motion legs. Both the motion and visual delays are in parallel.

The DCM receives visual system input from a connection to the visual system monitor video input. The DCM system records control position, visual signal, and motion vertical acceleration. Those are the signals that can be seen in Figure 12, where VIS_X, ACCZ_F, PITADI, and COLPOS represent the visual, acceleration, pitch, and longitudinal stick. In that plot, which gives the results of a pitch latency test performed on 15 January 2004, the control stick movement starts at 152.243. The motion response begins at 152.277, and the visual signal has a clear change in pattern at 152.321. That particular test gives a motion latency measure of 0.034 seconds and visual latency measure of 0.078 seconds.

It should be noted that the host software load was not being stressed heavily during the above latency test. If the simulator were being stressed such that most of the available execution time per frame was being used, as in the case of some of the demanding maneuver flown in the Phase I test, the above latency measures could increase by about 15 to 20 ms.

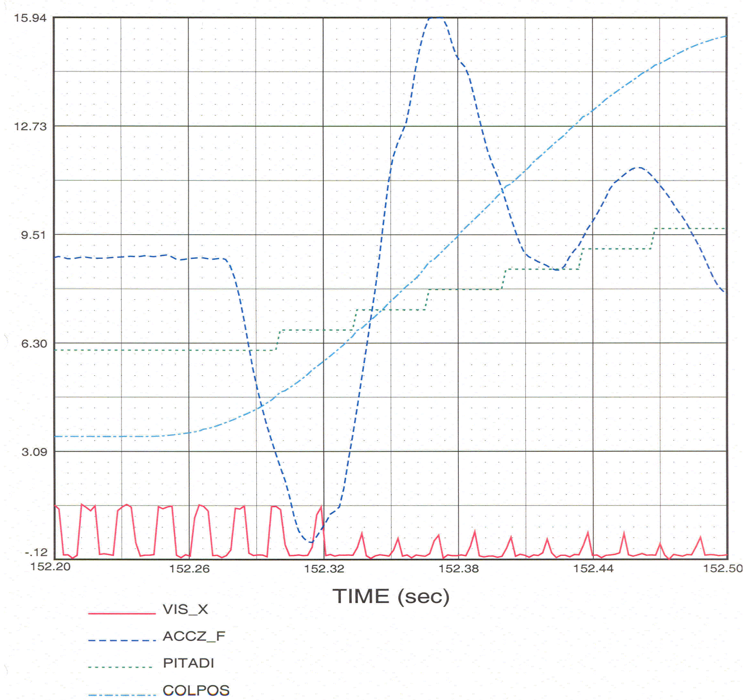

Figure 12. Pitch Latency Characteristics of the Simulator

Flight Maneuvers

The selected pilot tasks were designed to facilitate a comprehensive assessment of the effects of the modified flight control system on the aircraft's tendencies for PIO in the roll axis, handling qualities, and available roll control power. As such, the selected flight cards, some of which were designed specifically to excite PIO tendencies, included both fine tracking and gross acquisition tasks. The following provides a brief description of the maneuvers used, some of which included failure states.

1. Lateral Offset Approach and Landing – The pilot tracks the glide slope and localizer, which is offset laterally by 300', and then, upon called to do so by the test engineer, corrects to set up for landing, ensuring that the aircraft is wings level at threshold crossing.
2. 30deg Intercept Approach and Landing – The pilot visually tracks the flight path and aircraft ground track whilst on a 30 degrees intercept course from 600' AGL, and then, upon called to do so by the test engineer, corrects aggressively to set up for landing.
3. 30kt Crosswind Approach and Landing – The pilot tracks the glide slope and localizer in a 30 kt crosswind condition and, at 500', initiates a decrab maneuver to landing. At 200' AGL, the pilot would be instructed to land or touch and go.
4. Slalom Approach and Landing – Whilst descending on conditions, the pilot maneuvers the aircraft ground track to capture and hold position along left, right, or center lines of the runway, in response to random call-outs by the test engineer, then land.
5. Roll Reversal – Whilst maintaining altitude the pilot rolls right to capture 30 degrees bank angle, then, using full stick, rolls left holding full stick until the aircraft reaches wings level before attempting to capture 30 degrees bank angle in the opposite direction.
6. Steady Heading Sideslip – Whist in straight and level conditions on a cardinal heading, the pilot applies slow and smooth rudder and simultaneous lateral stick to achieve full steady heading sideslip, at which point the pilot performs a one-inch roll stick doublet before repeating the maneuver in the opposite direction.

7. Target Tracking – The pilot establishes stabilized flight behind the tanker maintaining the tip of the boom in the center of the HUD for one minute, then closes in on the tip of the boom.
8. 15 kt Crosswind Approach and Landing with Failure – The pilot tracks the glide slope and localizer in a 15 kt crosswind with either failed outer engine or stick jam and, at 500', initiates a decrab maneuver to landing.

Results

Only lateral-directional Cooper-Harper Ratings (CHR) and Pilot-Induced Oscillation Ratings (PIOR) were collected for the baseline and the modified control laws. The results for each flight maneuver and loading configuration are given in Figures 13 and 14 for PIOR and CHR, respectively.

In general, the lateral ratings show an improvement, or no change, in almost all of the test cases. The improvements due to the modified control law are very apparent, not only in PIORs but also CHRs. The exception was in the 30kt Crosswind Approach and Landing cases of Configurations B and C. In the case with the most degradation, the pilot appeared bothered by the fact that he did not get the 50'AGL callout and was distracted by his attempt to flare rather late. Interestingly, in all of these exceptions, a degradation in the CHRs that mirrors that of the PIORs, were also noted by the pilots.

It is important to note that, in general, not only did the median ratings improve in almost all of the test cases, but the actual spread of the ratings also narrowed, thus indicating widely agreeable and more consistent aircraft characteristics. In other words, the pilots provided more consistent ratings with the new build. This was also reflected through the Pilot Comment Cards.

It may be noted that undesirable control stick characteristics, such as slight asymmetries, were observed by some of the evaluation pilots, adversely impacting their ratings. For instance, Flight Card 8a was given a PIOR of 3 and a CHR of 6 by a particular pilot when he flew the modified control laws. Later in the formal evaluation, the same pilot applied a half-unit Left-Wing Down (LWD) trim in order to counteract the effects of the stick asymmetries. After flying the same configuration again, but this time with the LWD trim, he gave a PIOR of 1 and a CHR of 3 for the same control laws.

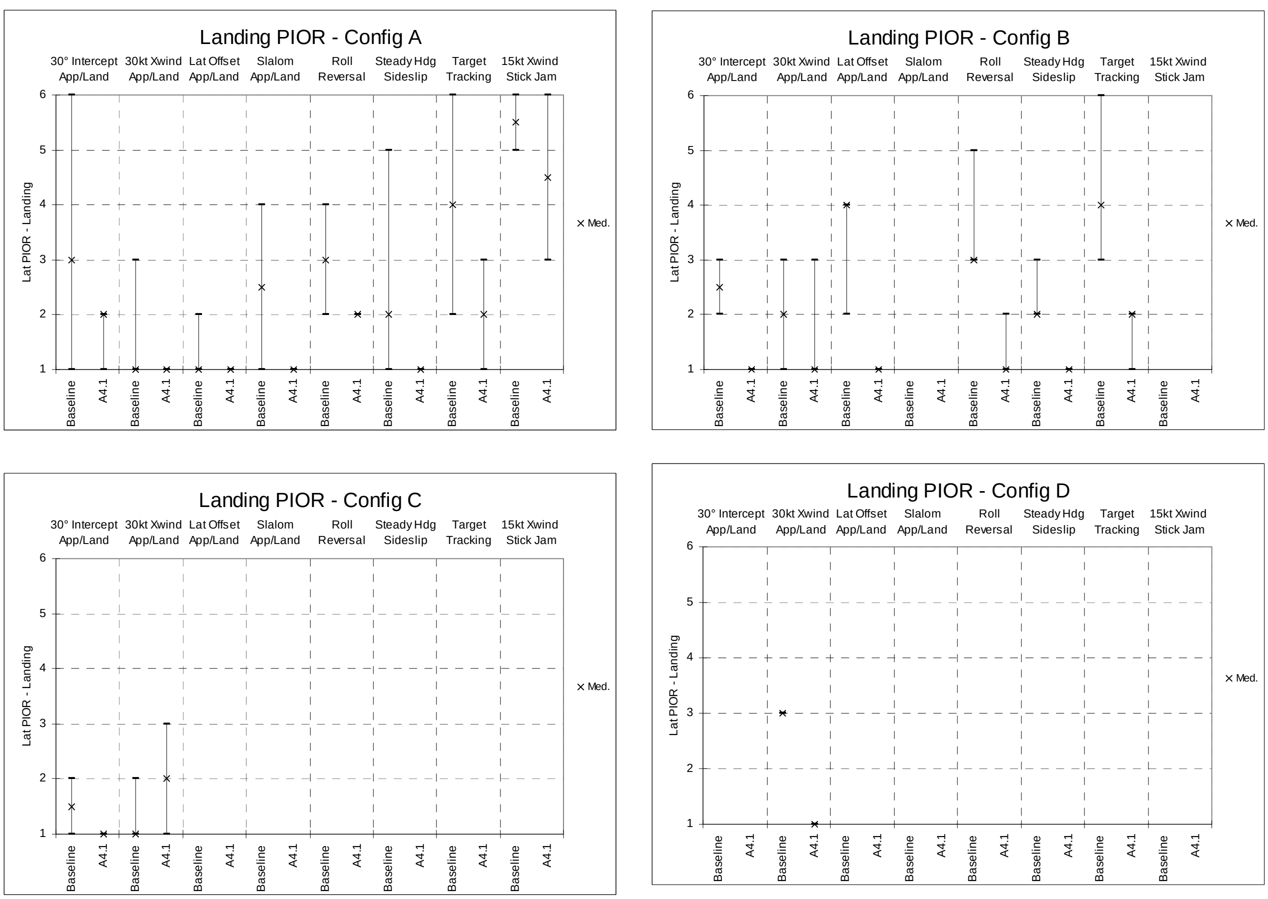

Figure 13. Pilots' PIO Ratings during Landing

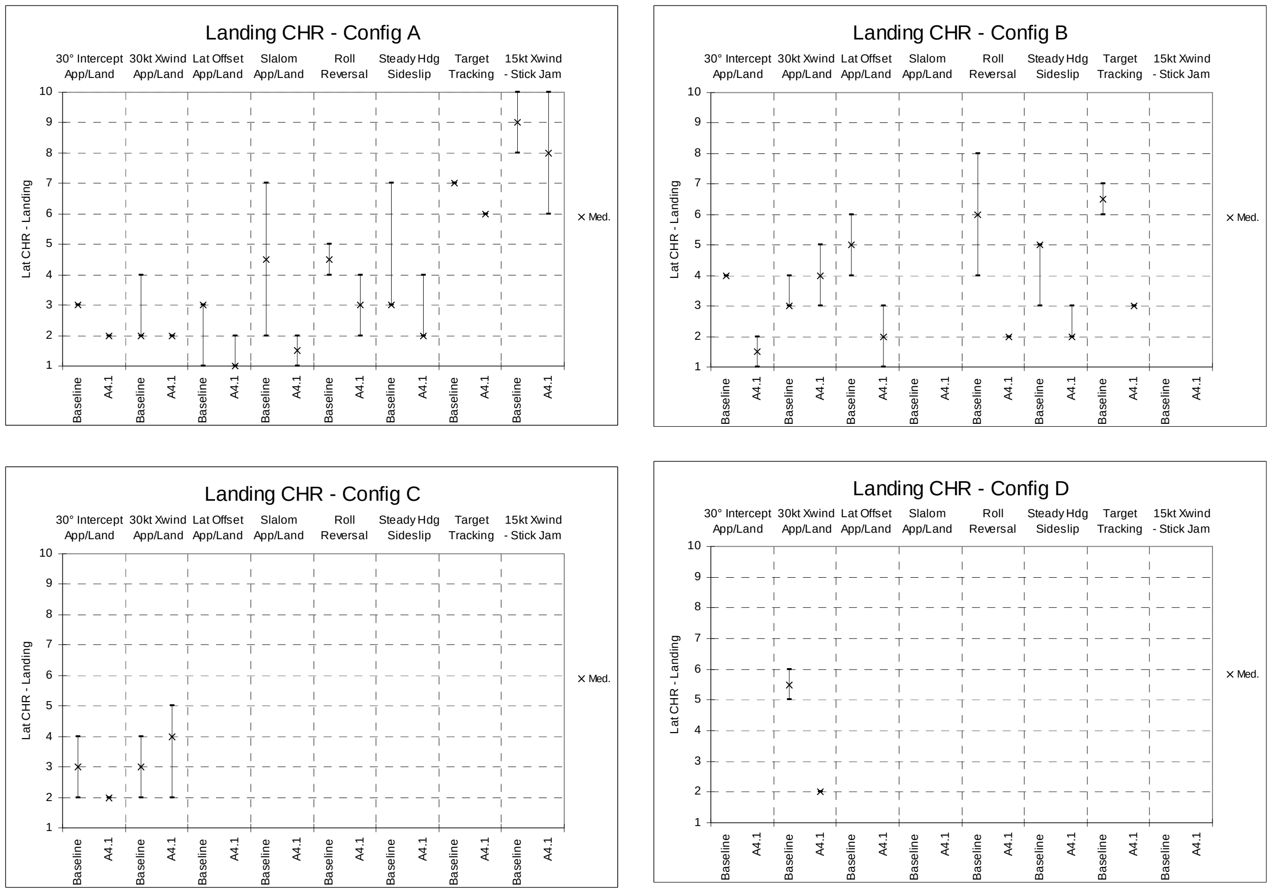

Figure 14. Pilots' PIO Ratings during Landing

As a means for further validation, the Real-time Oscillation Verifier (ROVER) software by Hoh Aeronautics, Inc. [6] was utilized as a PIO detection tool. The application uses four key parameters to identify potential PIOs, namely minimum roll rate, minimum lateral stick deflection, frequency of oscillation, and minimum phase angle between lateral stick and roll rate.

The application was firstly validated against ten C-17 flight events during approach and landing, including several incidents of roll PIO. The resulting thresholds for the software's internal key parameters that identify PIOs were subsequently set as follows.

1. Minimum roll rate = 12 deg/sec peak-to-peak.
2. Minimum lateral stick deflection = 4.5 inches peak-to-peak (one-half roll stick).
3. Frequency of oscillation = 1 through 8 rad/sec.
4. Minimum phase angle between lateral stick and roll rate = 75 degrees.

It should be noted that, in other studies, HAI has found that the minimum roll rate threshold should be increased to accommodate the ground simulator environment. In their NASA F-18 research, HAI found that by doubling the minimum roll rate threshold to 24 deg/sec, some of ROVER's nuisance trips were eliminated. No such efforts were undertaken to optimize either this threshold, or the other three thresholds, for the Jackson ground simulator data. However, and due to the high sample rate of the simulation data, ROVER was used with its filter option activated. With no filtering, the high-frequency noise was found to mask the lower-frequency response. The filter allowed the frequency range of interest to be better identified (by filtering the higher frequencies out).

More than 100 ROVER runs were executed and a representative sample for each flight card, with both baseline and the modified control laws, was selected. The results are summarized in Table 1, which lists the names of the source data files, flight cards and loading configurations, and whether a PIO was noted by either the Pilot or ROVER, for each one of the two control laws evaluated. The numerical values for the PIO flag range from 1 to 4, where a value of 4 signifies PIO and a value of 3.5 signifies potential PIO. The last two columns of the referenced table list the PIO state as identified by both the Pilot and ROVER.

Although the ROVER results did not always match the pilots' opinions of PIO, which, incidentally, is not unexpected, the general results do show a good agreement between ROVER and the pilots. In cases where the pilot identified PIO but ROVER did not (such as ROVER Case 14), a closer look of the data was warranted in order to identify any real PIOs or just the perception of a PIO by the pilot. ROVER was set to detect PIO, and not tendencies for PIO, so such instances of disagreements may bare some significance. Also, it may well be that the pilot had noticed small-amplitude PIOs which may have gone undetected by ROVER, considering that the tool was tuned using the larger-amplitude, incident PIOs (peak-to-peak roll stick of 4.5"). However, more emphasis was placed on the statistical trend of the ROVER results, rather than individual cases, particularly in view of the fact that ROVER was not tuned for ground simulation data.

ROVER Case #	Data File	Date	Time	Flt Card #	Maneuver	Pilot #	CLAW	ROVER PIO Flag	ROVER-Noted PIO?	Pilot-Noted PIO?
1	82A5	21-Jul	18:05	2A	Intercept	3	Base	3	N	Y
2	82A3	21-Jul	18:55	2A		3	A4.1	2	N	Y
3	82B1	22-Jul	19:15	2B		2	Base	2	N	N
4	82B0	22-Jul	19:01	2B		2	A4.1	2	N	N
5	82C2	23-Jul	18:40	2C		3	Base	4	Y	N
6	92C3	23-Jul	18:48	2C		3	A4.1	2	N	N
7	83AI	21-Jul	21:29	3A	Xwind	2	Base	2	N	N
8	83AJ	21-Jul	21:36	3A		2	A4.1	2	N	N
9	83BC	22-Jul	17:47	3B		2	Base	3	N	N
10	83B7	22-Jul	17:17	3B		2	A4.1	2	N	N
11	83BF	22-Jul	22:49	3B		3	Base	3.5	Y	Y
12	83BK	22-Jul	23:05	3B		3	A4.1	3.5	Y	Y
13	83C2	19-Jul	19:23	3C		1	Base	2	N	N
14	83C5	19-Jul	20:49	3C		1	A4.1	2	N	Y
15	83CE	23-Jul	18:06	3C		3	Base	2	N	N
16	83CH	23-Jul	18:25	3C		3	A4.1	2	N	N
17	83D7	23-Jul	20:52	3D		2	Base	3	N	Y
18	83D8	23-Jul	21:00	3D		2	A4.1	3	N	N
19	84A8	21-Jul	17:34	4A	Offset	3	Base	3.5	Y	Y
20	84AA	21-Jul	18:47	4A		3	A4.1	3	N	N
21	84BF	22-Jul	23:43	4B		3	Base	4	Y	Y
22	84BG	22-Jul	23:54	4B		3	A4.1	2	N	N
23	85A2	23-Jul	19:43	5A	Slalom	3	Base	3	N	Y
24	85A4	23-Jul	19:56	5A		3	A4.1	2	N	N
25	86AC	20-Jul	21:13	6A	Reversal	3	Base	4	Y	Y
26	86AF	20-Jul	21:46	6A		3	A4.1	4	Y	N
27	86B1	18-Jul	13:00	6B		1	Base	4	Y	Y
28	86B3	19-Jul	17:10	6B		1	A4.1	3	N	N
29	87A0	18-Jul	13:40	7A	SHSS	1	Base	4	Y	N
30	87A2	19-Jul	17:22	7A		1	A4.1	2	N	N
31	87B7	22-Jul	21:11	7B		3	Base	3	N	N
32	87B9	22-Jul	21:28	7B		3	A4.1	2	N	N
33	88A6	20-Jul	18:19	8A	Tracking	2	Base	3	N	Y
34	88A5	20-Jul	18:08	8A		2	A4.1	4	Y	Y
35	88A8	20-Jul	23:22	8A		3	Base	4	Y	Y
36	88A9	20-Jul	23:37	8A		3	A4.1	2	N	N
37	88B3	20-Jul	19:47	8B		2	Base	4	Y	Y
38	88B2	20-Jul	19:40	8B		2	A4.1	2	N	N

Table 1. Sample of ROVER Results

The agreement between ROVER and the pilots regarding PIO is further illustrated in Figure 15, which shows the total number of cases that were identified as PIO-prone or not PIO-prone, through each means. As shown, there were 8 baseline cases in which the pilot noted no PIO, while there were 10 baseline cases in which ROVER noted no PIO (a difference of 2). Similarly, there were 15 modified control law cases in which the pilot noted no PIO, while there were 16 cases in which ROVER noted no PIO, for a difference of 1.

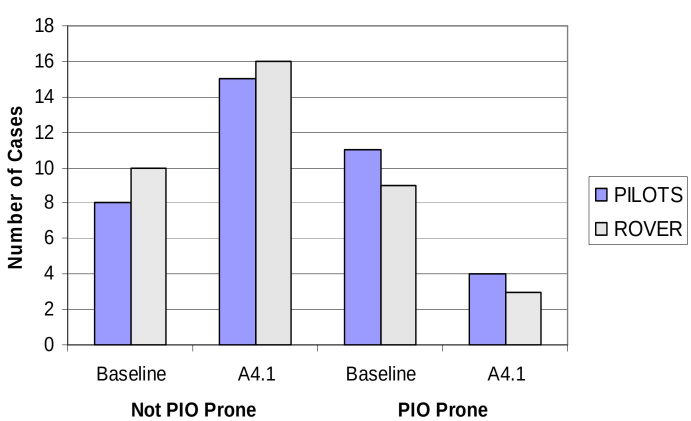

Figure 15. Comparison of ROVER versus Pilots' PIOR Results

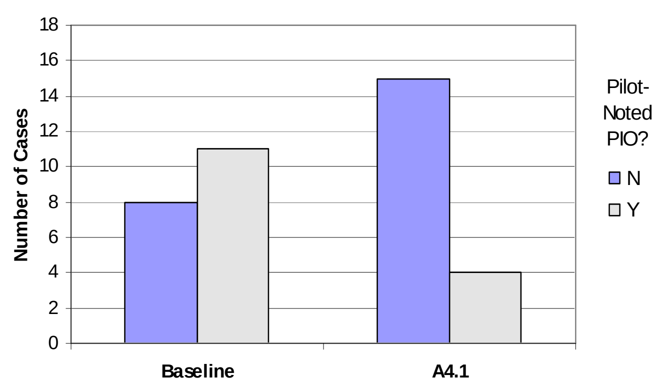

Figure 16. Pilot-Noted PIOs for Baseline and Modified Control Laws

Figure 16 and 17 illustrate the improvements due to the modified control laws, as predicted by both pilots and ROVER, respectively. Figure 16 shows that, while the baseline test cases were almost evenly divided in terms of PIO-prone versus not PIO-prone, as categorized by the pilots, the modified control law test cases showed a much more favorable divide, with considerably fewer cases noted as PIO-prone. The same trend is even more compelling when using ROVER, as shown in Figure 17. The individual ROVER flag values are also presented in Figure 18. The results clearly show the favorable trend of reduced PIOs with the new control laws.

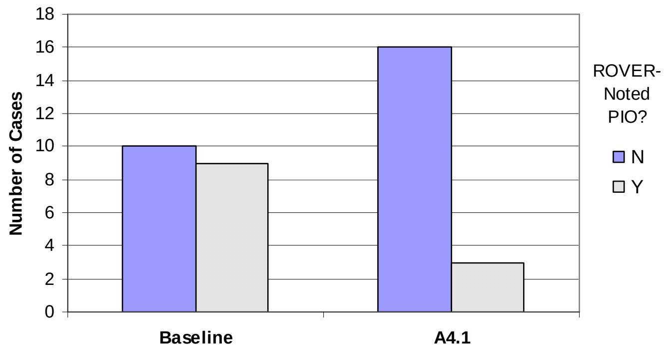

Figure 17. ROVER-Noted PIOs for Baseline and Modified Control Laws

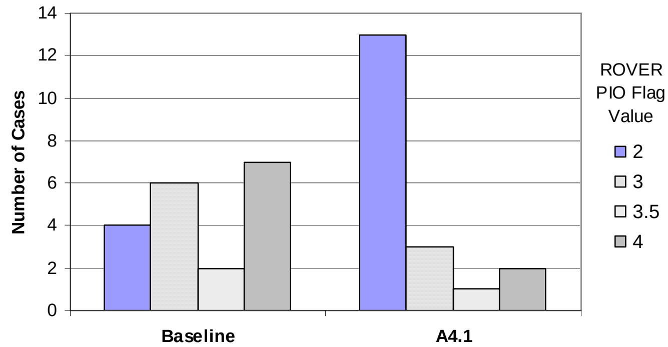

Figure 18. ROVER Flag Values for Baseline and Modified Control Laws

VI. Summary and Conclusions

The PIO improvements brought about by the modified control law were validated and quantified, both subjectively, in terms of pilot comments and ratings, and objectively, in terms of time histories and ROVER analyses. Improvements relative to the baseline control law were noted in almost all of the maneuvers and flight conditions flown, some of which reflected a PIOR incremental improvement of up to 3 points. The handling qualities that resulted from the modified control law were in most cases better than the baseline aircraft, based on both pilot assessment and offline analyses.

Based on the latest piloted simulation results and the subsequent off-line analysis, additional control law improvements are still planned beyond those described above. Significant additional improvements in phase characteristics will be derived, especially at higher frequencies and amplitudes and the adaptive gain increases necessary for severe failure modes or extreme disturbances will be evaluated by the pilots.

In closing, the following excerpt by one of the Boeing evaluation pilots who participated in the first concept-validation test is offered below.

> *"The baseline airplane is like a race car that is loose or has an oversteer condition - it is very fast, responsive, nimble - but if you press it, it is not forgiving - it breaks loose. If you have seen a race car driver going stop to stop with the steering wheel after the back end of the car starts to swing around - that is the baseline. We need an airplane that is a bit more forgiving - a race car with a slight push or understeer. (Version A4.1Control Law) is a move towards this type of balance."*

VII. Acknowledgement

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2) Shweyk, K.M. et al. “C-17 Roll PIO Non-Advocate Review Presentation,” Boeing Internal Document, Long Beach, California, April 1-2, 2003.
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