



Limited Investigation of Active Feel Control Stick System (Active Stick)

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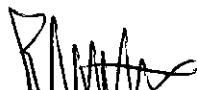
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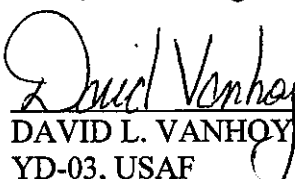

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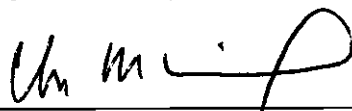

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14. ABSTRACT This report presents the results of Project Active Stick, a Limited Investigation of the Active Feel Control Stick System. The overall test objective was to perform a preliminary investigation into the potential for using an active feel control stick to perform system functions traditionally incorporated in the flight control computer design. This testing compared the open-loop response, handling qualities during operational tasks, and pilot-in-the-loop oscillation susceptibility of three g-command systems during pitch-only tasks. The three systems were programmed in the Variable Stability System of Calspan's LJ-25 Learjet In-flight Simulator which was the test bed for this program. The first g-command system contained no limit protection and was the baseline system. The second system was "F-16 like" and contained angle-of-attack and load factor limiting features built into the flight control system. The third system started with the baseline system and utilized an active feel control stick to provide limit protection and flight envelope awareness. Based on a comparison of these systems, the test team explored the active feel control stick system's potential for practical applications.					
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PREFACE

The Active Stick test team would like to thank three Calspan employees that were critical to the success of this test management project. Mr. Russ Easter, the safety pilot for all test missions, was essential in the development and implementation of the three g-command systems. From the initial stages of development to the final test flight, Mr. Easter was there to answer questions as well as provide recommendations and critical insight in all aspects of the project. Everyone on the test team learned from Mr. Easter and we are all better testers because of him.

Mr. Ryan McMahon was essential in integrating each of the flight control systems on the Learjet. His knowledge of the system and his ability to make the test team's designs work on the Learjet were essential to the smooth transition from a simulator model to aircraft implementation. His knowledge, work ethic, and dedication to this project allowed for the systems to be loaded on the aircraft in record time. Mr. McMahon was also crucial during the first few sorties, providing assistance with operating the Learjet and data collection systems.

Finally, Mr. Jay Kemper was integral in building the Active Stick model used in the simulator. He was able to take the concepts of our test team and code them into a working Active Stick model. The development of this Active Stick simulator allowed for initial testing of the flight control system and significantly reduced the integration time when the system was loaded on the Learjet. The results of his efforts directly contributed to the overall success of this test.

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EXECUTIVE SUMMARY

This test report presents the results for the Active Stick Test Management Project (TMP). The Active Stick test team from the USAF Test Pilot School (TPS) at Edwards AFB, CA performed a preliminary investigation into the potential for using an active feel control stick to perform feel system control functions traditionally incorporated in the inner loop flight control computer design.

The Active Stick TMP was conducted at the request of the U.S. Air Force Test Pilot School (TPS) in collaboration with the Calspan Corporation, Buffalo, NY. The Commandant of USAF TPS directed this program. All testing was accomplished under TPS Job Order Number MT090400. Three calibration sorties and six data sorties were flown on the LJ-25 Learjet In-flight Simulator aircraft between 16 March, 2009 and 27 March, 2009 totaling 16.3 flight hours. Additionally, three T-38 target sorties were flown totaling 3.8 flight hours. The sorties were flown in the R-2508.

This testing compared the open-loop response, handling qualities during operational tasks, and pilot-in-the-loop oscillation (PIO) susceptibility of three g-command systems during pitch-only tasks. The three systems were programmed in the Variable Stability System (VSS) of Calspan's LJ-25 Learjet In-flight Simulator the test bed for this program. The first g-command system contained no limit protection and was the baseline system. The second system was "F-16 like" and contained angle of attack (AOA) and load factor limiting features built into the flight control system. The third system started with the baseline system and utilized an active feel control stick to provide limit protection and flight envelope awareness. Based on a comparison of these systems, the test team explored the active feel control stick system's potential for practical applications. During the testing process, pilot comments were collected for different types of stick feedback methods (shaker, hard stop, soft stop, varying gradient, etc.) for future research and testing.

Active Stick demonstrated the potential to transfer limiters and safe guards from the inter-loop of the flight control system to an outer-loop active control stick system. The potential was demonstrated in the areas of load factor (g) and AOA limit protection and awareness. System A's strength was uninhibited control of aircraft performance; there was no envelope limit protection. System B, on the other hand, had load factor and AOA limiting features. The implementation made it easy to achieve optimum performance but provided no means to exceed limits or provide feedback to the pilot on aircraft envelope location. System C combined the freedom of System A along with envelope boundary awareness, protection, and tactile cues.

Future testing should be focused on improving both active stick design as well as flight test techniques to provide a more comprehensive analysis of the utility of active feel stick concepts to meet specific mission objectives throughout the entire flight envelope.

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INTRODUCTION

General

This Test Management Project (TMP) investigated the potential of using an active control stick to perform feel system control functions traditionally incorporated in the inner loop flight control computer design. This was accomplished by comparing three different g-command flight control systems (FCSs). The first objective of the Active Stick program compared the open-loop (pilot-out-of-the-loop) flying qualities of each g-command system to characterize “heart-of-the-envelope” and boundary limit responses. “Heart-of-the-envelope” was defined as the region of Learjet operation that did not approach any angle of attack (AOA), load factor, or airspeed limits. The second objective compared the pilot-in-the-loop oscillation (PIO) tendencies of each g-command system. The third objective compared the handling qualities of three g-command flight control systems during operationally representative tasks to highlight any FCS deficiencies. The final objective was a human factors evaluation of each FCS’s ability to provide feedback for aircraft flight envelope awareness.

The Active Stick TMP was conducted at the request of the U.S. Air Force Test Pilot School (TPS) in collaboration with the Calspan Corporation, Buffalo, NY. The Commandant of USAF TPS directed this program. All testing was accomplished under TPS Job Order Number MT090400. Three calibration sorties and six data sorties were flown on the LJ-25 Learjet In-flight Simulator aircraft between 16 March 2009 and 27 March 2009 totaling 16.3 flight hours. Additionally, three T-38 target sorties were flown totaling 3.8 flight hours. The sorties were flown in the R-2508.

Background

The evolution of modern aircraft created a need for power-driven aerodynamic control surfaces. These power-driven control surfaces were necessary because aerodynamic loads associated with unpowered, reversible systems became too large for pilots to overcome. Irreversible systems were developed using hydraulic actuators in order to overcome these aerodynamic forces. With the advent of an irreversible control system, the pilot could no longer feel the aerodynamic forces directly acting on the flight controls surfaces through the cockpit controls. Such “tactile feedback” is an important aid for pilot handling qualities assessment. To compensate for the lack of tactile feel in an irreversible system, an artificial means of providing force feedback was developed using an arrangement of springs, dampers, and/or bob weights. This artificial system simulated the force feedback traditionally provided by a reversible system and allowed the pilot to feel artificial forces related to calibrated airspeed and load factor. Sensing the simulated changes in airspeed or dynamic pressure on the control surfaces allowed the pilot to sense changes in flight condition as though the system were reversible.

With the development of irreversible systems also came the ability to implement stability and control augmentation systems to improve bare-airframe stability and aircraft

response. Designers advanced from merely augmenting bare airframe stability to reshaping the airplane response in an effort to further improve handling qualities. Eventually, cockpit controls were linked to the control surfaces electronically by wires and computers thus yielding the “fly-by-wire system”. The flight control systems of a fly-by-wire system are complex and difficult to design. Often incorporated in these flight control system designs are feel system characteristics designed to give the pilot some of the tactile cues that would be given by a reversible system.

The Active Stick concept was to provide the pilot the tactile feel traditionally associated with a reversible system by using a variable feel control stick. The variable control stick varied frequency, damping ratio, force gradients, preload, and friction as a function of aircraft load factor, angle of attack, and/or airspeed, which made the cockpit controls feel as though they were tied to a reversible flight control system. The variable-feel control stick was also programmed with nonlinear gradients, down-springs, and bob-weight effects, which aided in simulating the reversible feel. The Active Stick test team performed a preliminary investigation into the potential for using an active feel control stick to perform feel system functions traditionally incorporated in the inner loop flight control computer design. If the concept of Active Stick proves to be valid, it would provide designers and engineers with more options to optimize flight control system design.

Program Chronology

A joint Technical Review Board (TRB) and Safety Review Board (SRB) were conducted on 09 Feb 2009. The TRB was chaired by Ms. Mary McNeely, USAF TPS/ED. The SRB was chaired by Mr. Jason Bostjancic of AFFTC/SET.

The test project consisted of four days of simulator testing, four ground checkout and test sessions, three LJ-25 calibration sorties (5.6 hrs), six LJ-25 test sorties (10.7 hrs), and three T-38 chase sorties (3.8 hrs). All sorties were flown within the R-2508 complex at Edwards Air Force Base, California. The simulator testing occurred from 23 February to 12 March 2009. Ground tests occurred from 13 to 18 March 2008. Calibration sorties occurred from 16 to 18 March 2009. Flight testing occurred from 20 to 27 March 2009.

Test Item Description

Three versions of a g-command flight control system developed by Calspan engineers and the test team were flown on the Calspan LJ-25 Learjet In-flight Simulator. System A was a pure g-command system with no limit protection, System B was a g-command system with AOA and load factor limiting, and System C was the same as System A with an active feel control stick. The implementations of the flight control system designs are detailed in Appendix F. A comparison of these systems was used to investigate the potential for an active feel control stick to perform feel system functions traditionally incorporated in the inner loop of the flight control computer design. The

comparison was accomplished within the Calspan LJ-25 Learjet In-flight Simulator's Variable Stability System (VSS) flight envelope illustrated in figure 1.

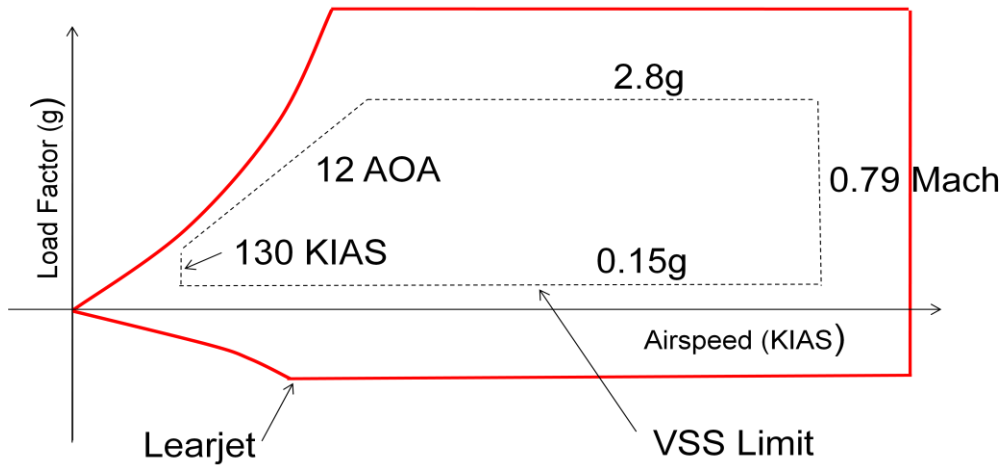


Figure 1: Learjet VSS Flight Envelope

System A (Baseline)

System A (figure 2) was a basic g-command flight control system with no limit protection. The primary feedback loop used normal acceleration with an associated pitch damper to command aircraft pitch response. This g-command system had a six pounds per inch stick force gradient (figure C-12). Stick deflection was passed through a linear pitch command gradient that resulted in a prescribed load factor. One-inch stick deflection was proportional to commanding 1 g (figure C-10). The total aft stick deflection was 2.5 inches indicating that System A was capable of commanding 3.5 g. In theory, if the deflection of the elevator achieved the load factor commanded by the pilot, then the error between the feedback loop and the commanded load factor went to zero. At steady state conditions, assuming the force on the stick remained constant, the load factor achieved remained constant as well.

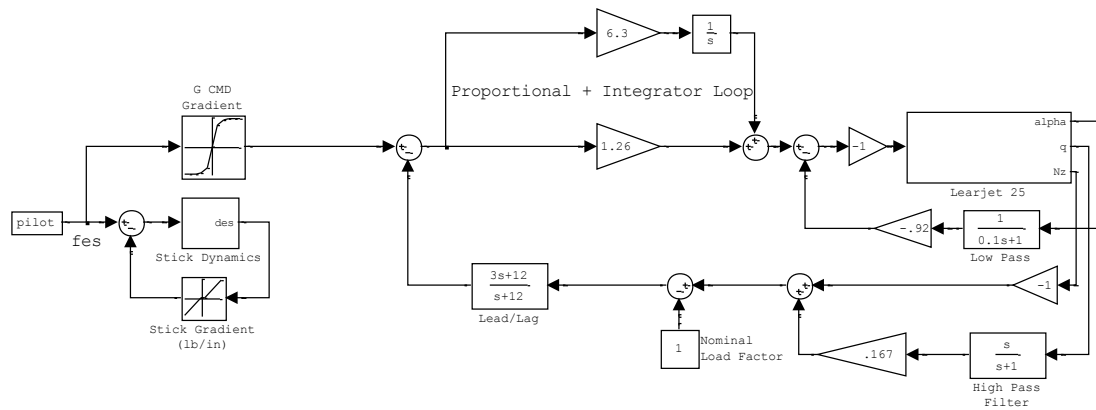


Figure 2: System A (Baseline)

System B (F-16 Like)

System B (figure 3) was a g-command system similar to system A. The stick force per inch was six pounds (figure C-12) and one-inch stick deflection was proportional to commanding 1g (figure C-10). The differences resided with AOA and load factor limiting features built into the flight control system. Load factor limiting was built into the system primarily by limiting the amount of aft stick travel to 1.7 inches such that the maximum stick deflection will not cause an over-g. At angles of attack above 9.5 degrees, the first AOA (alpha) feedback limiting feature became active and reduced the commanded load factor. The second alpha feedback limiting feature became active at 11.5 degrees. This alpha limiting feedback kept the steady state AOA below the design limit no matter how much force was applied to the stick.

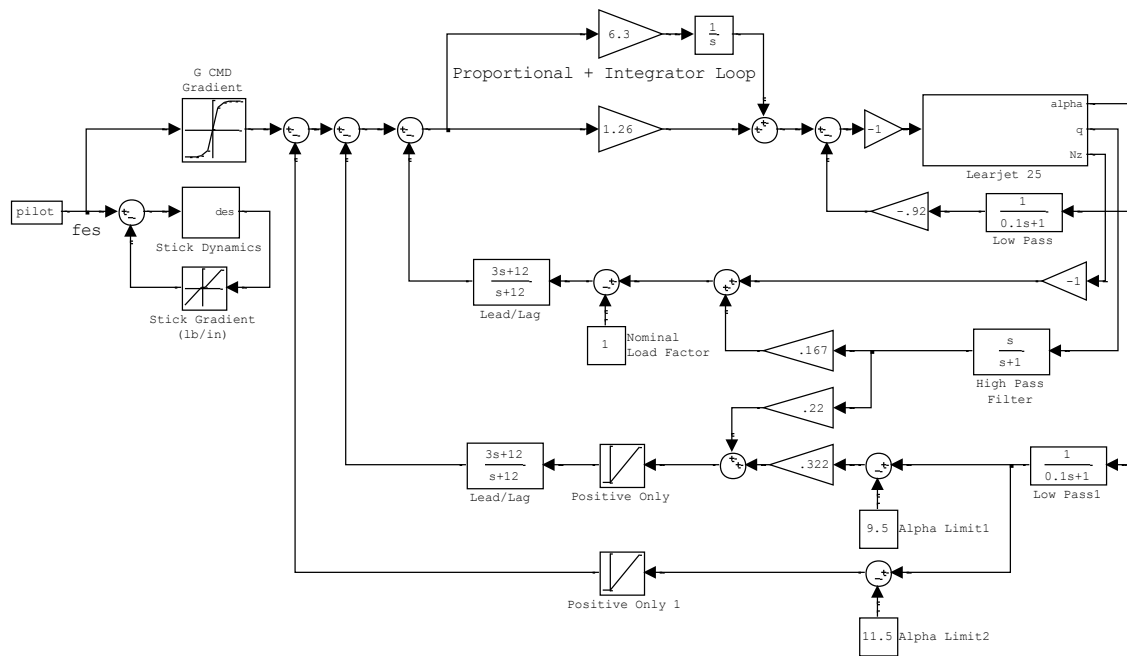


Figure 3: System B (F-16 -Like)

System C (Active Stick)

System C (figure 4) was the basic g-command flight control system (System A) with an active feel control stick to provide limit protection and flight envelope awareness. Limit protection was provided using soft stops and stick pushers to help prevent the pilot from exceeding an AOA or load factor limit. Stick shakers, variable gradients, and soft stops were used to provide flight envelope (energy) awareness to the pilot.

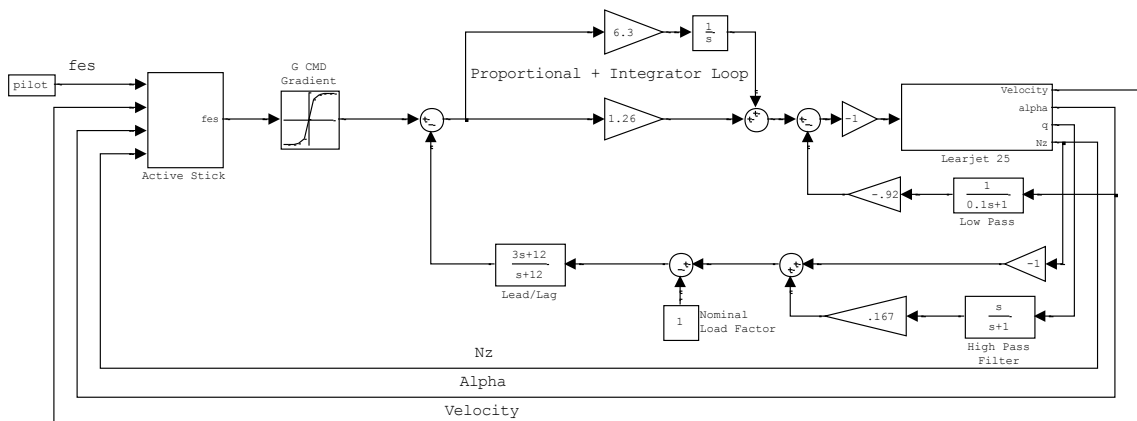


Figure 4: System C (Active Stick)

The “Active Stick” box in figure 4 had a stick force input from the pilot and three feedback variables; aircraft velocity, AOA, and load factor. These variables were used to schedule active stick functions. Active Stick functions became active at specified values or “margins” associated with each of the VSS limits of the Learjet. Figure 5 illustrates the concept of margins within the VSS flight envelope. Area “0” presented in figure 5 represents the heart-of-the-envelope.

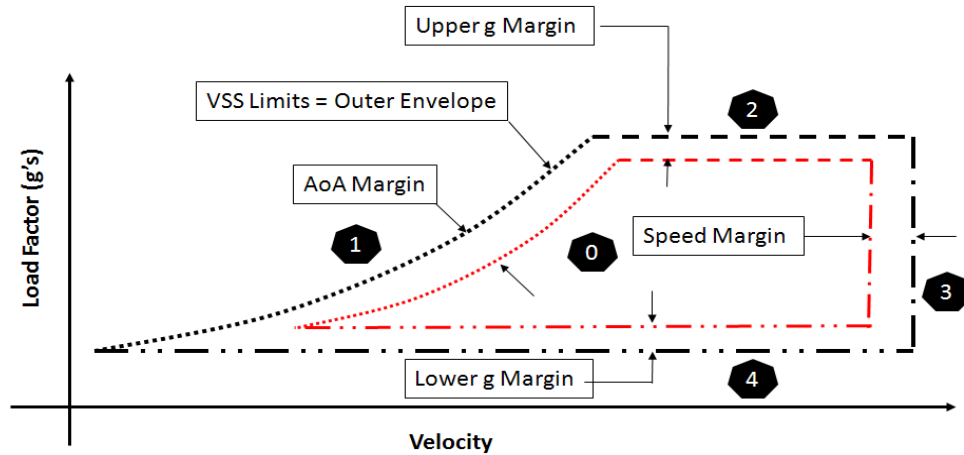


Figure 5: Example VSS Envelope Margin Depiction

Airspeed was used to activate a stick shaker at the speed margin to warn the pilot of an impending aircraft over-speed. The AOA feedback was used to activate a stick shaker and/or gradient at an AOA margin. Aircraft load factor was used to activate a stick gradient at aircraft load factor margins (upper and lower g margin).

The final System C design (figure 6) incorporated stick shakers for the AOA and airspeed limits, stick pushers for AOA protection and awareness, and soft stops for load factor limit protection and awareness. Specifically, System C consisted of the following active stick functions: an AOA protection stick pusher (with 5 lbs/degree of AOA) actuated at 9 degrees of AOA; an AOA awareness stick shaker (with 10 Hz and an amplitude of 0.1 inches) that actuated at 11 degrees AOA; an airspeed warning stick shaker (with 20 Hz and an amplitude of 0.1 inches) actuated at 320 KIAS; and g-limit protection and awareness soft stops. The first soft stop actuated at 2.4 g, with a breakout force of 4 lbs. The second soft stop actuated at 2.7 g (0.1 g less than the VSS limit), with a 10 lb breakout force.

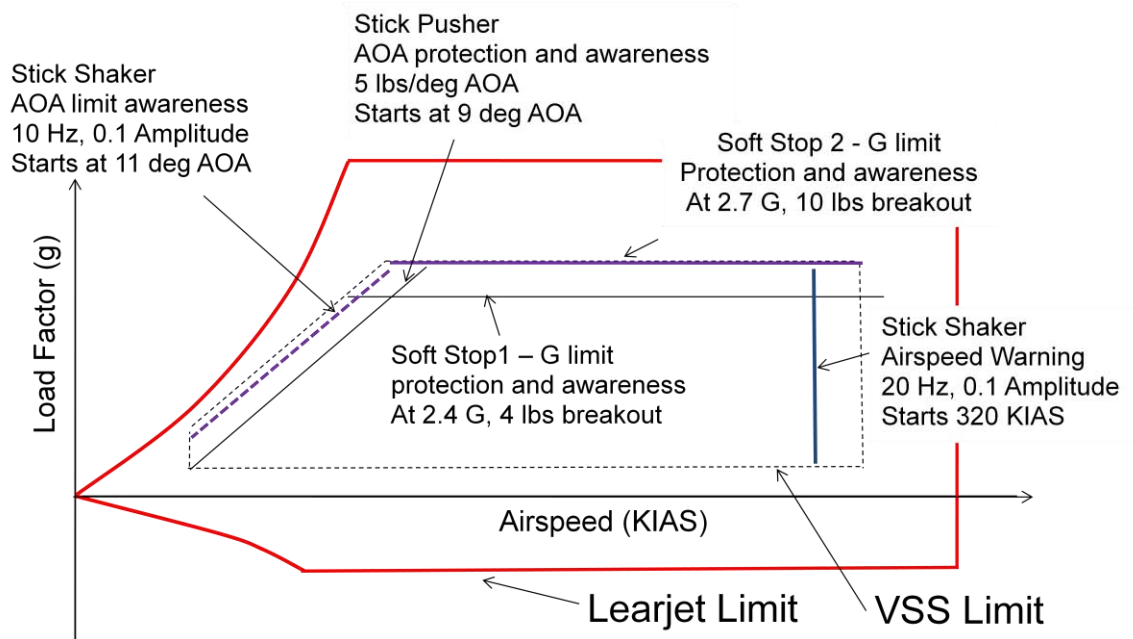


Figure 6: Active Stick Example

Research Vehicle

The Calspan LJ-25 Learjet was a modified Learjet designed to serve as a three axis in-flight simulator, where normal operations included the use of a safety pilot and an evaluation pilot. The safety pilot's controls (left seat) were standard, but the evaluation pilot's controls (right seat) were replaced with components of fly-by-wire, response feedback, variable stability, and variable control systems. The response feedback flight control system used the Learjet control surfaces to augment the stability characteristics of the basic Learjet.

The VSS was divided into two independent parts, a variable feel system and a response feedback system. The variable feel system provided the evaluation pilot with the stick and rudder pedal forces, gradients, and displacements, while the response feedback flight control system augmented the normal Learjet dynamics to represent those of the vehicle being simulated. The evaluation pilot's inputs were fed into the flight control system through the feel system, and the resulting control surface movements produced the aircraft response. The loop was closed by sensing the aircraft's motions and feeding back signals proportional to these motions, thus modifying the response to the pilot's inputs. Angle of attack vanes, sideslip vanes, rate and attitude gyros, and air data information were all used as the sensor elements. AOA, load factor, sideslip, and airspeed were displayed to the test team with cockpit gauges and instruments. The instruments provided a level of envelope awareness and protection and were referenced during all tasks for all three systems. The VSS flight control modes were as follows:

VSS MODE: For purposes of this test, three different G-command flight control systems were available to the test team for selection and testing. Existing safety trips and logic were hardwired into the Learjet and were not affected by the three implemented control systems.

EMERGENCY FLY BY WIRE (FBW) MODE: In the event the safety pilot became incapacitated or certain control cable failures occurred, the evaluation pilot was able to fly the aircraft as a normal Learjet using the FBW mode. All basic Learjet systems (gear, flaps, spoilers, brakes, etc.) were available. The handling characteristics were those of the basic aircraft with the yaw damper on. All safety trips were disabled and no feedback loops were used except rudder deflection per sideslip rate for yaw damping.

EVALUATION PILOT MANUAL DISENGAGE MODE: The evaluation pilot had the ability to electrically disengage the VSS and return control of the aircraft to the safety pilot. A disengage switch was located on the right seat center stick.

SAFETY PILOT MANUAL DISENGAGE MODE: The safety pilot had the ability to disengage the VSS by depressing any of the following: wheel master switch, glare shield disengage switch, or throttle quadrant disengage switch.

FORCE DISENGAGE MODE: A large force input by the safety pilot to the normal Learjet wheel/column allowed the VSS to disengage.

The Learjet had the capability to allow programming of the variable feel system and the response feedback flight control system through either the digital configuration control panel located on the pedestal between the pilots or from the computer in the back of the aircraft. Using the onboard computer at the test conductor's station gave flight test engineers the capability to make in-flight adjustments to the response feedback system (flight control system) and the variable feel system (control stick) without affecting the existing safety trips. Programmed test inputs (PTIs) were also initiated from the test conductor's on board computer to administer computer generated step inputs.

A Head Down Display (HDD) was used for programmed tracking tasks. The VSS Learjet discrete algorithm was used to simulate a medium to high gain pitch tracking task. The HDD tracking task allowed handling qualities evaluations and assignment of Cooper-Harper ratings (reference 1) and Pilot-in-the-Loop oscillation ratings (reference 2) without a target aircraft (reference appendix D and E, respectively). When using target aircraft for handling qualities evaluations, a culminated tracking sight was used. The collimated tracking sight had five selectable milliradian (mil) settings 12, 9, 6, 3, 0 for Workload Buildup and Handling Qualities During Tracking (HQDT) flight test techniques (FTTs).

Overall Test Objective

The overall objective was to perform a preliminary investigation into the potential of using an active feel control stick system to perform system functions traditionally incorporated in the inner loop of the flight control computer design. To meet this overall objective, the following specific test objectives were accomplished:

- Objective 1: Compare the open-loop flying qualities of three g-command flight control systems during pitch-only tasks.
- Objective 2: Compare the PIO susceptibility of three g-command flight control systems.
- Objective 3: Compare the handling qualities of three g-command flight control systems during operationally representative tasks (head down display tracking task, air-to-air target tracking task, break turn maneuvers, safe escape maneuvers).
- Objective 4: Human factors evaluation of feedback for envelope awareness.

All objectives were met.

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TEST AND EVALUATION

The flying portion of this test project consisted of three LJ-25 calibration sorties (5.6 hrs), six LJ-25 test sorties (10.7 hrs), and three T-38 target sorties (3.8 hrs). All sorties were flown within the R-2515 complex at Edwards Air Force Base, California. Calibration sorties occurred from 16 to 18 March 2009. Flight testing occurred from 20 to 27 March 2009.

The first three calibration flights were used to ensure the three flight control system designs were appropriate for flight test. Special emphasis was placed on tuning each flight control system so that accurate comparisons could be made during test sorties. System A and B were tuned to ensure the proper range of stick travel and ensure the stick force per g was satisfactory. System B was also tuned to optimize the angle of attack (AOA) limiter so that boundary limit excursions (exceeding a variable stability system (VSS) boundary limit) were kept to a minimum. System C had seven versions of Active Stick (reference appendix A for all System C configurations tested) implemented for tuning and evaluation. Pilot comments were recorded to obtain initial feedback on the various Active Stick functions (shaker, hard stop, soft stop, and varying gradient – reference appendix A for pilot comments). All three systems (A, B, and C) were tuned to have similar pitch responses in the heart of the VSS envelope. Programmed test inputs (PTIs) in the longitudinal axis were used to verify open-loop pitch responses. Envelope limit assaults (manual ramps and steps) were used to verify implementation of each of the flight control systems. The head down display (HDD) symbology validation and test verification was accomplished using sample runs. Finally, the actual corner velocity location of the VSS system was verified by flying slow bleed rate turns.

Data for Active Stick TMP were collected on six test sorties. Each member of the test team flew twice. The profile order was varied between flights in order to prioritize data collection. The test team met between every sortie in order to determine the best test plan for subsequent test sorties, as well as pass along pertinent lessons learned to optimize the next sortie's execution.

Open-Loop Flying Qualities Comparison

Open-loop (pilot-out-of-the-loop) flying qualities were compared between flight control Systems A, B, and C in order to characterize key differences in the heart-of-the-envelope and at the envelope boundaries. The purpose of this comparison was to identify open-loop flying qualities differences, as well as system implementation differences between all three systems. Additionally, this provided a baseline for the test team when conducting handling qualities tasks. This objective was met by using open-loop programmed test inputs (PTIs) to evaluate the aircraft pitch response and by using manual ramps to evaluate the envelope boundary characteristics for each flight control system. These tests also served to verify system implementation characteristics met the intended design (reference appendix F).

All maneuvers were flown with entry altitudes of $15,000 \pm 200$ feet pressure altitude (PA). Three airspeeds were flown in order to characterize open loop characteristics at different portions of the aircraft envelope. V_{LO} (180 KIAS) was the low airspeed point and was used to characterize angle of attack effects; the airspeed flown for these points was within the data band of 180 ± 5 KIAS. V_{CORNER} was used to characterize the aircraft's response in the heart-of-the-envelope. The airspeed flown for these points was based on the aircraft fuel weight (i.e. aircraft gross weight) as shown in table 1.

Table 1: Corner Velocity vs. Fuel Weight

Fuel (lbs)	Corner Velocity (KIAS)
5100	235 ± 5
4100	225 ± 5
3100	215 ± 5
2100	205 ± 5

V_{HI} (300 ± 5 KIAS) was flown to characterize normal load factor (g) effects at high airspeeds.

Pitch responses for each system were investigated first. Two sets of 5 second longitudinal PTI steps were input into each system. Two different PTIs were designed to capture 1.5 g for each system at each of the three airspeeds (V_{LO} , V_{CORNER} , and V_{HI}). Both PTIs used were a 1.5 g-command (g-step) and a 4.625 lbs force command (Force-Step, which commanded 1.5 g for each system). Figure 7 illustrates where each step input was implemented into System B.

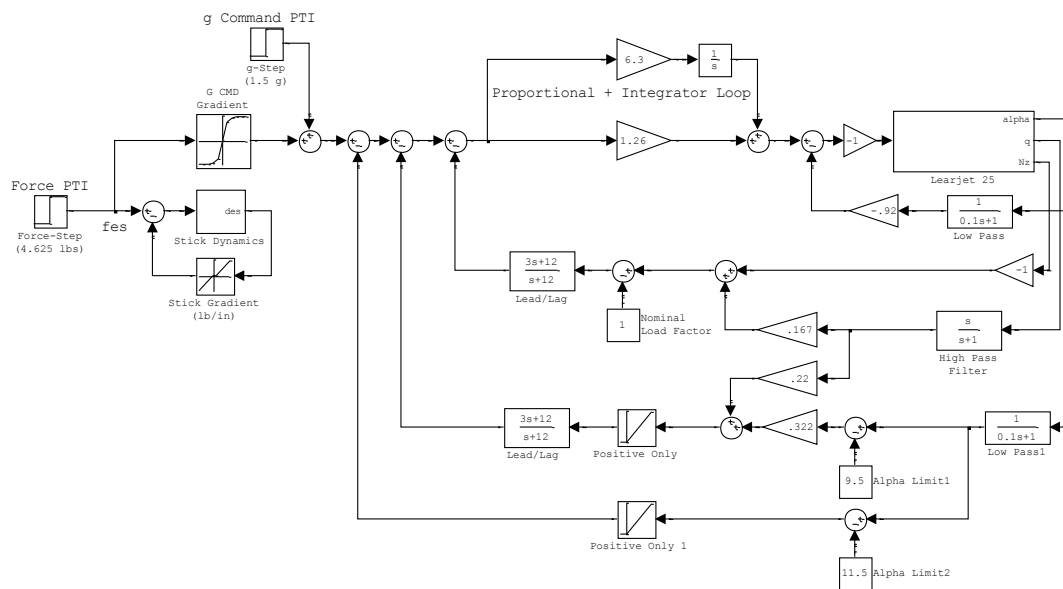


Figure 7: PTI Input Locations for System B

The step inputs for System A and C were implemented in the same positions as System B. These inputs were applied in order to compare the pitch response for each system at points of interest within the aircraft envelope. PTIs were input after trimming the aircraft at the specified conditions in straight and level flight.

Pitch responses at slow regimes of flight were investigated to characterize differences in aircraft pitch response when angle of attack was relatively high. As illustrated in figure 8 the responses for Systems A and C were nearly identical, but the response for System B had a higher peak pitch rate, lower steady state pitch rate, and high frequency oscillations (approximately 3-4 Hz). It was suspected that the high frequency oscillations were due to high feedback gains and the wash out pitch rate path through the positive only AOA feedback. Pitch rate response for the g-command step input at V_{LO} is presented in figure C-1.

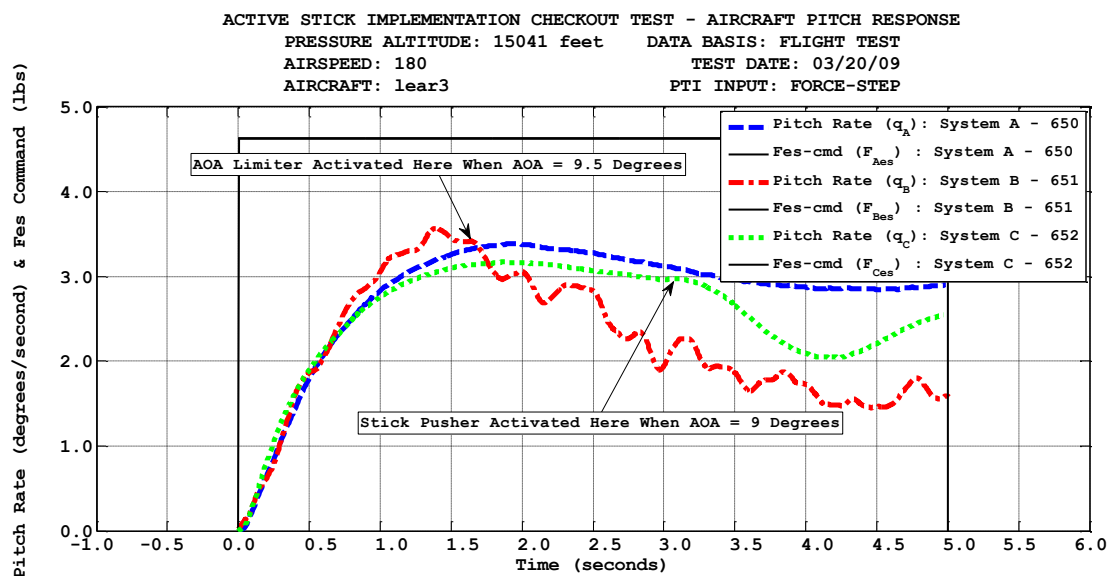


Figure 8: Pitch Rate Response to 1.5 g Commanded Force PTI at V_{LO}

The lower steady-state value of pitch rate for System B was attributed to angle of attack feedback in the control loop which limited pitch rate, while Systems A and C had no angle of attack feedback or limiting. System C's stick pusher became active at 3.25 seconds and began pushing back on the stick resulting in a decrease in AOA even though the commanded step was holding a constant 4.625 lbs. Systems A and C were capable of achieving higher steady state pitch rates than System B, but Systems A and C could also exceed system angle of attack limits.

Pitch rate response plots illustrate amplified pitch effects that are not always felt or seen during flight, which was the case during this test. The aircrew noticed no apparent difference in pitch response for each system. The pitch angle response plots provided in figures 9 and C-2 illustrate why this occurred. Pitch angle responses were

nearly identical; the maximum pitch angle differences after 5 seconds from the 1.5 g commanded input was 2.7 degrees.

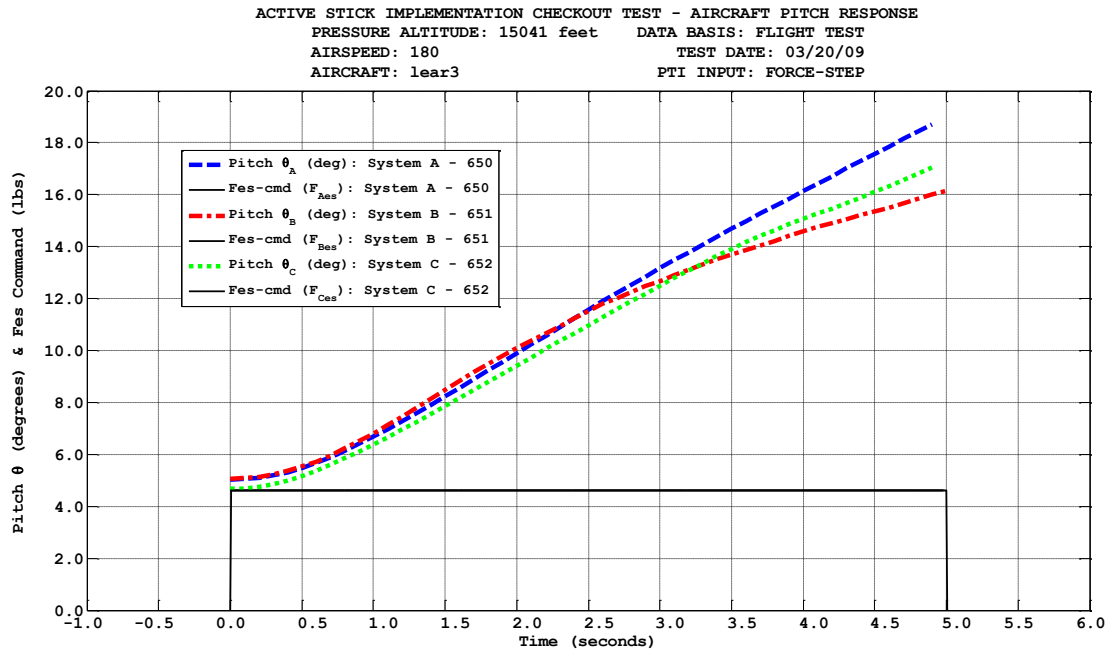


Figure 9: Pitch Angle Response to 1.5 g Commanded Force PTI at V_{LO}

As illustrated in figures 10 and C-3, there were no apparent differences between the inputs or the aircraft responses for any system at V_{CORNER} . The oscillations in pitch rate for System B were attributed to high gain feedback and the wash out pitch rate through the positive only AOA feedback.

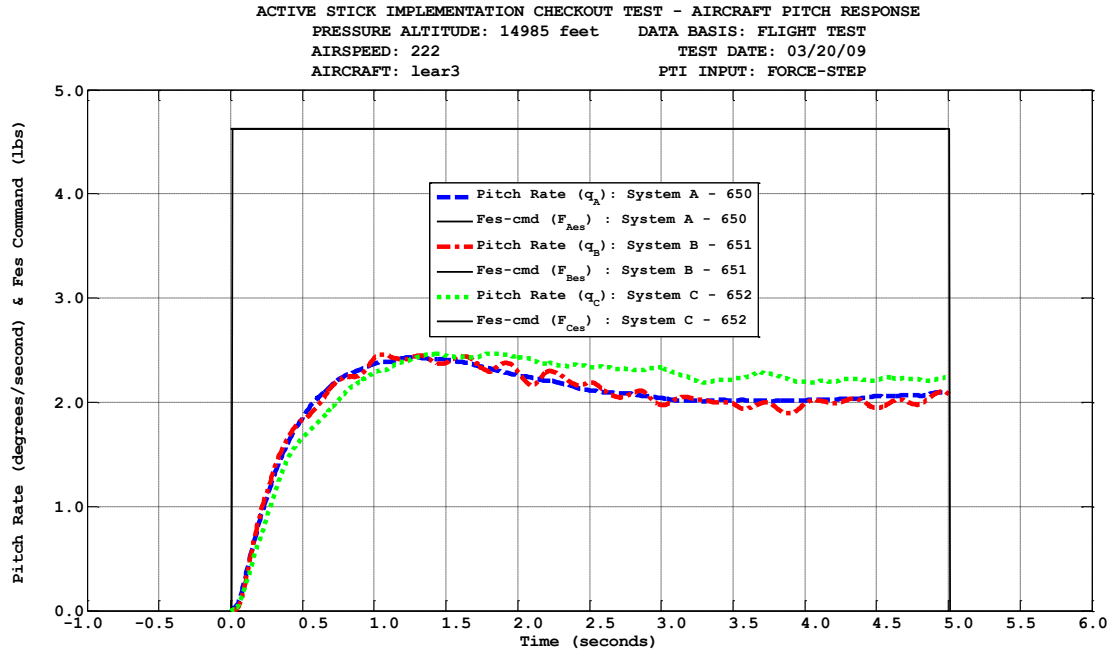


Figure 10: Pitch Rate Response to 1.5 g Commanded Force PTI at V_{CORNER}

Pitch response at V_{CORNER} was captured and is presented in figures 11 and C-4.

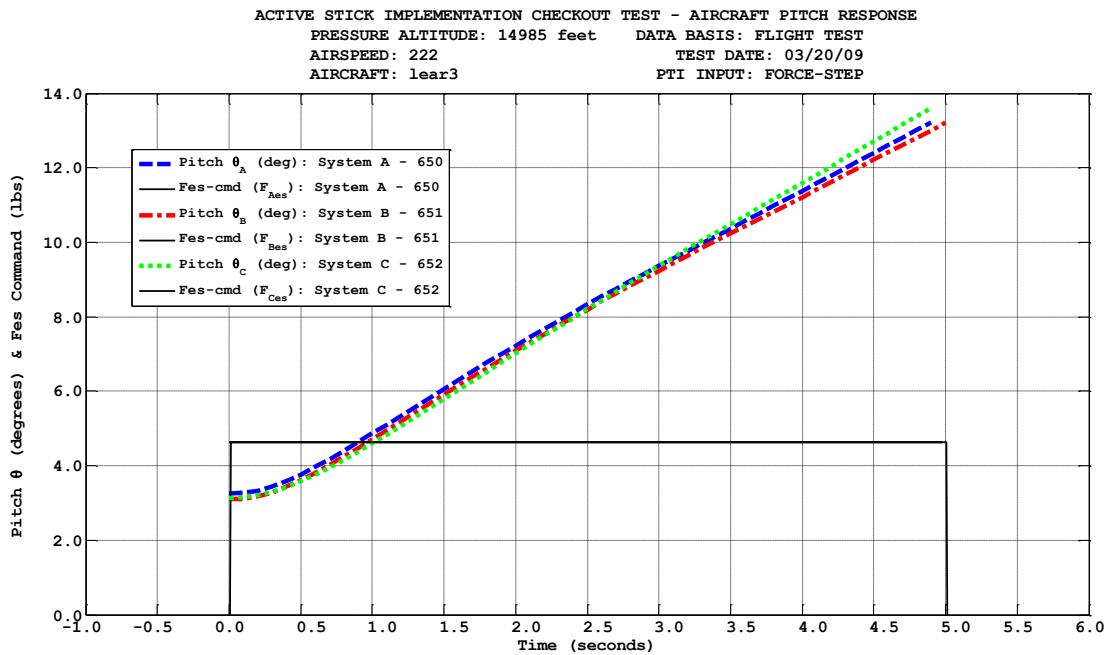


Figure 11: Pitch Angle Response to 1.5 g Commanded Force PTI at V_{CORNER}

The pitch response at faster regimes of flight was investigated to characterize differences in aircraft pitch response when AOA was relatively low. As illustrated in figures 12 and C-5 respectively, the steady-state pitch rate response to the PTI g-command and force command inputs for Systems A and C were nearly identical at approximately 1.5 degrees per second. The responses for System B oscillated around the steady state values of System A and C for the g-step input. Once again, the pitch rate oscillations were attributed to high feedback gains and wash out pitch rate through the positive only AOA feedback. Pitch rate response from the force-step input provided a less oscillatory pitch rate response than the g-step. For all three systems, the steady state pitch rate was reached more quickly at V_{HI} than at V_{LO} .

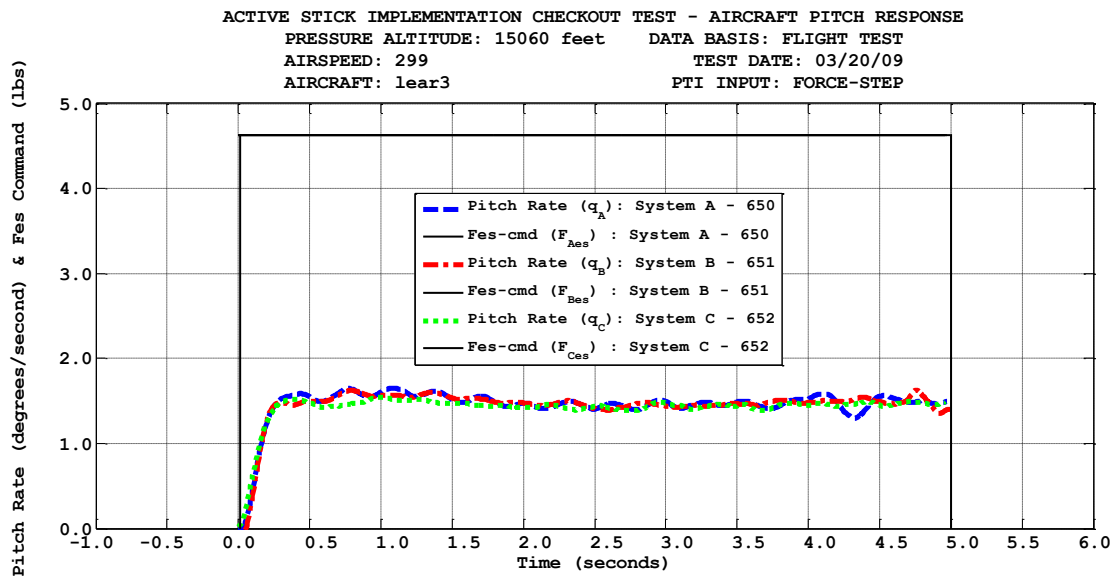


Figure 12: Pitch Rate Response to 1.5 g Commanded Force PTI at V_{HI}

The aircrew noticed no difference in aircraft pitch response at V_{HI} . These results were as expected and are presented in figures 13 and C-6.

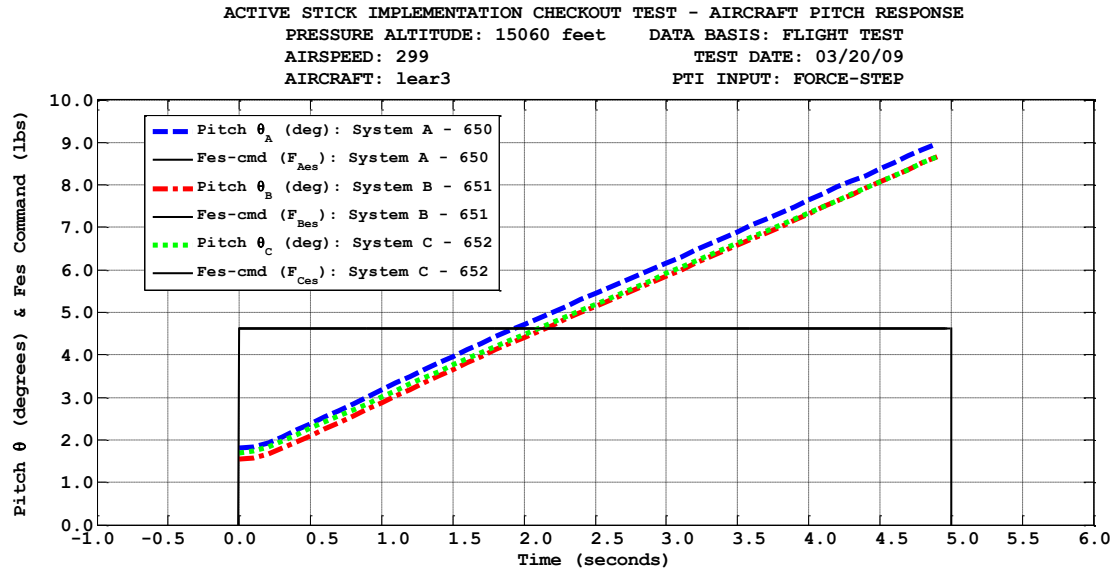


Figure 13: Pitch Angle Response to 1.5 g Commanded Force PTI at V_{HI}

Manual ramp inputs were used to evaluate heart-of-the-envelope and envelope boundary characteristics for all three systems at the aircraft AOA and load factor boundaries: V_{LO} and V_{HI} . This also served to verify system implementation characteristics (force gradients, breakout forces, stops, etc.) were in accordance with the intended design (reference appendix F). The maneuvers were performed by trimming on conditions in straight and level flight, then rolling into a bank to perform a level turn. At this point, a slow g-onset rate was created by pulling aft stick until the aircraft reached maximum load factor or AOA (System B) or the VSS tripped (Systems A and C) while staying in the altitude and airspeed data band. The important parameters noted during the maneuvers were stick forces (F_{es}), stick displacements (δ_{es}), load factor (g), and angle of attack (α). The manual ramps also provided key insight into the specific differences of each FCS implementation as defined in the test item description.

Manual ramps at slow regimes of flight were investigated to characterize differences in stick and flight control system attributes as well as to verify VSS system trip limits at the aircraft AOA envelope boundary. VSS system trips occurred between 12-13 degrees AOA. Each systems' stick force was essentially the same until reaching approximately 9 degrees angle of attack. At this point small increases in stick force continued to produce large changes in angle of attack for System A as illustrated in figure 14. System B characteristics were comprised of angle of attack limiting such that increases in stick force resulted in a maximum of 11.8 degrees of angle of attack. System C stick force increased beginning at 9 degrees AOA due to the stick pusher. In addition, the stick shaker became active at 11 degrees AOA as shown in figure C-7. System A continued to command a load factor at the low airspeed, which caused the aircraft to continue an increase in AOA at the peak stick force until the system tripped in AOA. The same characteristic was found in System C, but at a higher stick force due to the stick

pusher and resulted in a system trip. This characteristic was not present in System B due to the AOA feedback.

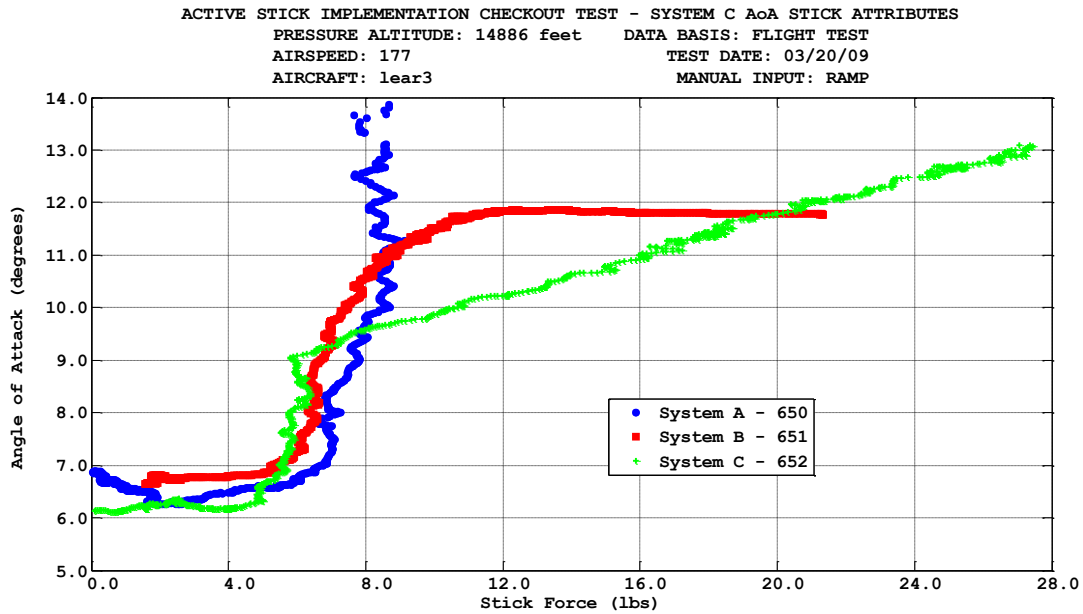


Figure 14: Flight Control System Stick Attributes at V_{LO}

Manual ramp assaults on the load factor boundary of the aircraft envelope provided significant insight into the differences of each FCS and each stick implementation. The VSS limit trips occurred at 3.1 g's. Each system was designed to have the same feel in the heart of the aircraft envelope; this was evidenced by plotting stick force as a function of g for each system. Figure 15 illustrates flight test results for stick force per g; ground test results for stick force per g-commanded are illustrated in figure C-8.

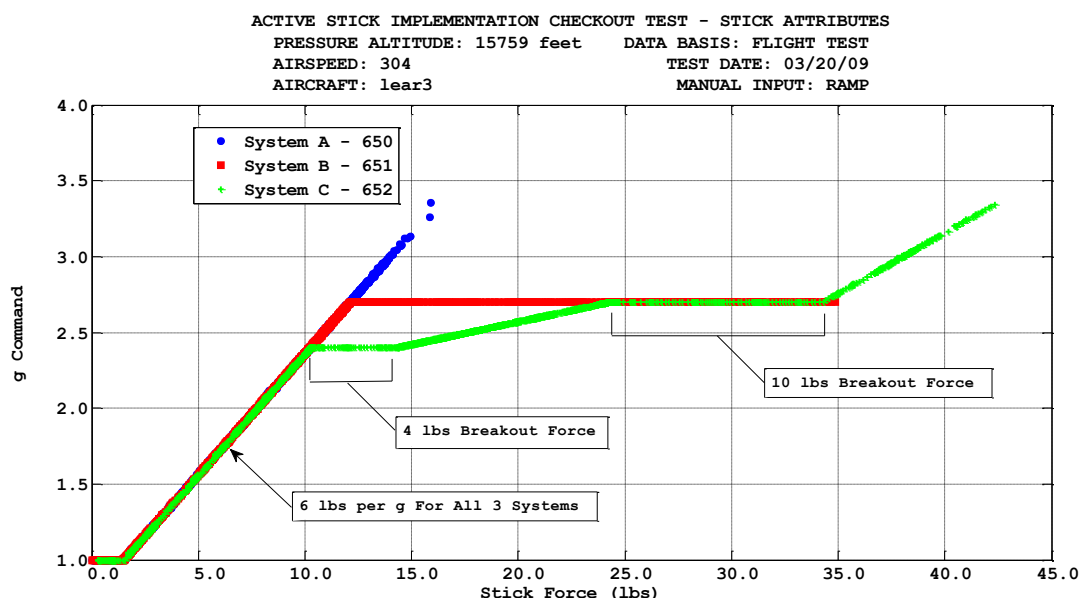


Figure 15: Stick Force (F_{es}) vs. Load Factor

The figure above illustrates the stick force characteristics as a function of aircraft load factor for each system tested as described in the test item description. Stick displacement as a function of load factor and load factor commanded for flight test and ground test are illustrated in figures C-9 and C-10, respectively. Stick displacement as function of stick force for flight and ground test are illustrated in figures C-11 and C-12, respectively. These figures show that the slopes, gradients, and soft stops were the same for both ground and flight test.

System A allowed stick displacements which commanded up to 3.1 g before the VSS tripped off. System B stick displacement was limited to 1.7 inches (2.7 g). Both System A and System B had the same gradients for stick force per g as well as stick displacement per g (1 inch per g). System C, on the other hand, was designed to provide envelope awareness as well as protection. The stick force and displacement gradient was the same as System A and B up to 2.4 g. At 2.4 g, the system required 15 pounds of additional force (4 pounds of which was breakout force) to achieve 2.7 g (2.7 g representing optimum load factor performance). Upon obtaining 2.7 g, a 10 pounds breakout force was present to help keep the aircraft on 2.7 g (optimum performance target), but this force could be overcome in order to obtain higher g if desired. The slope became 12 pounds per g (twice the slope of the initial heart-of-the-envelope force gradient) beyond 2.7 g as an envelope protection measure.

Overall, the open-loop flying qualities of all three systems were as expected, however there were slight differences at the low airspeed points for System B. There was a higher peak pitch rate, lower steady-state pitch rate response, and oscillations in the steady-state response. The differences were not apparent to the evaluator pilot during the flight, therefore the test team determined the objectives could still be met with System B

as implemented. Additionally, the manual pitch ramps verified the implementation of the design of all three flight control systems. Systems A, B, and C exhibited nearly identical feel and performance characteristics in the heart-of-the-envelope (1 to 2.4 g and 2 to 9 degrees AOA). As expected, at the envelope boundaries each system exhibited differences based on their respective design characteristics.

Comparison of Handling Qualities During Operational Tasks

The third objective involved a comparison of the three g-commanded flight control systems during operationally representative tasks. The primary data collected during each task were Cooper-Harper ratings and pilot comments. Four operational tasks were chosen for the test. They were a Head Down Display (HDD) Target Tracking task, an Air-to-Air Target Tracking task, a Break Turn maneuver, and finally a Safe Escape maneuver. Each task was designed to investigate the aircraft handling qualities, investigate the system's ability to provide envelope protection, and to assess the pilot's awareness of approaching boundaries. For each task the desired and adequate performance was defined in such a way that the pilot was required to quickly achieve and maintain a condition near the aircraft limits. By forcing the pilot to fly near the boundaries to achieve the required performance, it was expected that a quantitative measure of the flight control systems ability to provide envelope protection and awareness would be evident in the Cooper-Harper ratings. For all tasks, if the VSS system tripped off due to AOA or load factor boundary excursions a Cooper-Harper rating of 10 was assigned.

Head Down Display Target Tracking Task

The first operationally representative task was the Head Down Display (HDD) Target Tracking task. For each of the three g-commanded flight control systems the task was performed at three different airspeeds and by all three project test pilots. During the task the Learjet safety pilot modulated the throttles to maintain airspeed conditions while the project test pilot focused on the tracking task. The first airspeed was at V_{LO} (180 KIAS) and was designed to assault the AOA boundary. The second airspeed was at the calculated corner velocity (V_{CORNER}) based on the aircraft weight at the start of the task and was designed to assault the AOA and load factor boundaries simultaneously. The final airspeed was at V_{HI} (300 KIAS) and was designed to assault the load factor boundary. The VSS Learjet had three different HDD tracking algorithms available; discrete, high frequency sum of sines, and low frequency sum of sines. During the calibration sorties the test team determined that the "discrete" HDD tracking task would provide the best data based on the test objectives because it challenged the envelope boundaries better than the other two algorithms. Therefore the discrete HDD task was the only tracking algorithm used during the test. The tasks were performed for 60 seconds and were the same for each of the three systems. The specific task involved tracking a small dot with a flight path marker on the head down display by maintaining the dot within the flight path marker circle. An example of the HDD screen is presented in figure 16.

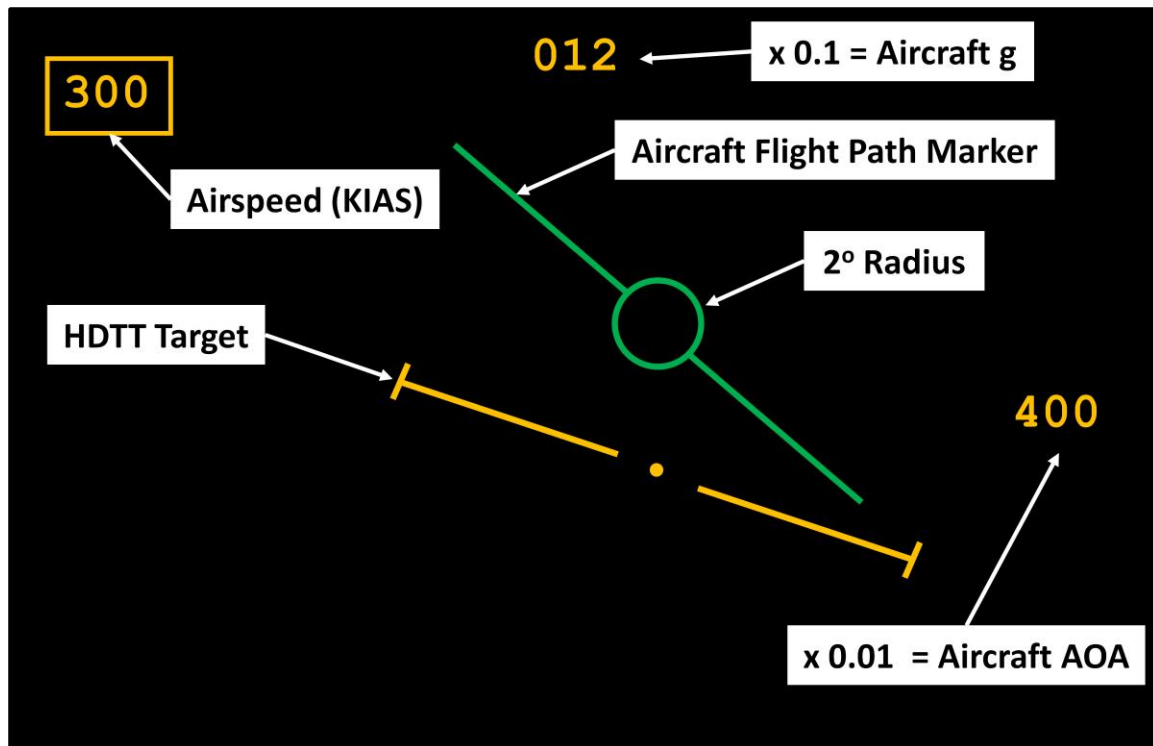


Figure 16: HDD Tracking Task Display

Desired performance was defined as maintaining the dot within the circle 90 percent of the time and adequate performance was defined as maintaining the dot within the circle 70 percent of the time. The discrete algorithm involved rapid displacements of the dot forcing the pilot to aggressively attempt to capture the dot within the circle and served to assault the appropriate boundaries based on the airspeed. All HDD tracking tasks were performed at a pressure altitude of 15,000 feet with a data band of 5,000 feet.

Figure 17 illustrates the number of system trips compared to the total number of HDD maneuvers for each of the three systems.

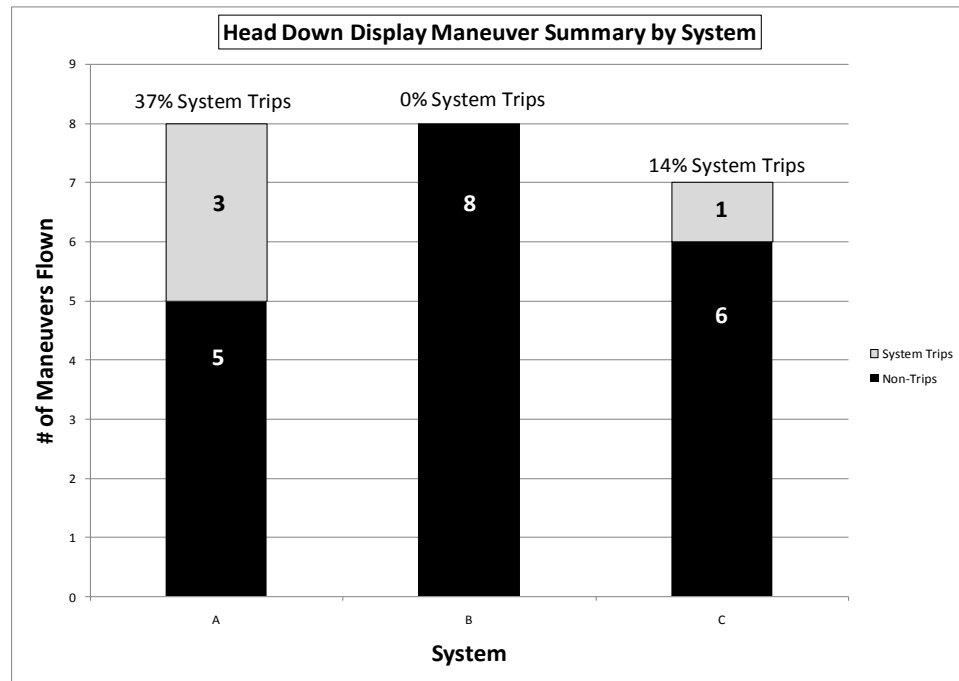


Figure 17: HDD Maneuver Summary by System

System A tripped 37 percent of the time while System C tripped 14 percent of the time. System B had no trips. All three of the System A trips were at V_{LO} . The System C trip was at V_{HI} . The data indicates that system B had the best boundary protection. System C provided some protection but could still be tripped. A combination of the tactile feel of System C and pilot compensation in the form of cockpit gauge crosscheck was required to prevent System C boundary excursions. System A provided the least boundary protection and required more pilot compensation with cockpit gauge scan than System C.

Figure 18 illustrates the Cooper-Harper ratings for the HDD maneuvers for each of the three systems.

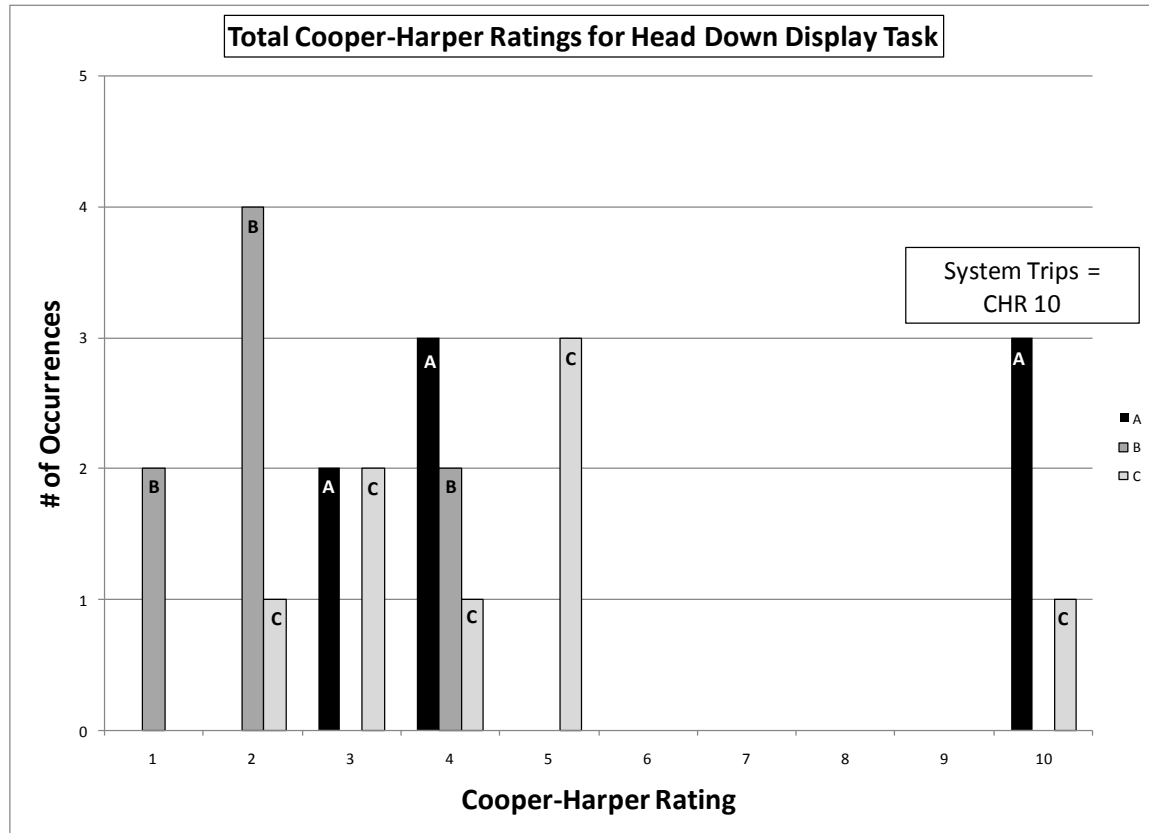


Figure 18: Total Cooper-Harper Ratings for HDD Task

System B ratings were consistently better than the other systems. The ratings for System A and System C were similar. The test team expected System C to have better ratings than system A. These data were not expected by the test team and were not entirely consistent with the results from the other FTTs. Figures C-13 and C-14 illustrate the Cooper-Harper ratings broken down by V_{LO} and V_{CORNER} , respectively and do not explain why overall ratings for System C are worse than System A. The source of this task's unexpected results was apparent at high airspeeds. Figure 19 illustrates the Cooper-Harper ratings for the HDD maneuver at V_{HI} .

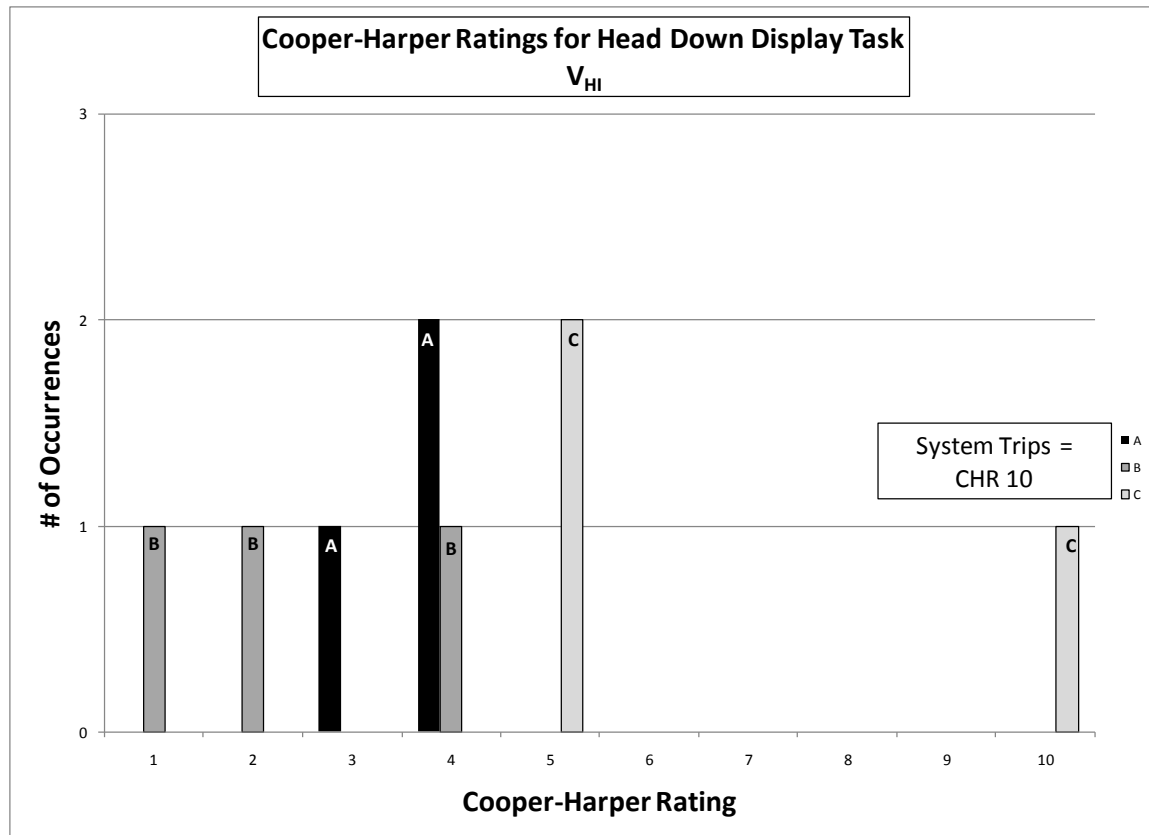


Figure 19: Cooper-Harper Ratings for Head Down Display Task (V_{HI})

These data show System A with better ratings than System C. The HDD task incorporated discrete jumps of the tracking dot in both positive and negative directions. The implementation of the Active Stick functions in System C had design deficiencies at less than 1 g. There was little focus placed on the aircraft envelope at less than 1 g during the Active Stick design of System C. This was due to limiting the test's scope to positive boundary protection and awareness. The evaluator pilots commented that System C's design required more force to achieve less than 1 g conditions than the other two systems. It was likely that System C's higher force for pitch down transitions adversely affected performance. At less than 1 g, System A had a well-implemented stick force per load factor. System A's better ratings were attributed to better performance following discrete negative jumps. Based on these data, it was clear that boundary protection and awareness at less than 1 g warranted further investigation. Future active stick designs could include AOA, load factor, airspeed tactile feedback, and protection that encompass the entire flight envelope including operation at less than 1 g. Implementation of force gradients, soft stops, and stick shakers at less than 1 g are all design features that could be used to optimize flight control system design. **Expand future active feel control stick investigations to include flight regimes less than 1 g. (R1)¹**

¹ Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

Air-to-Air Target Tracking Maneuver

The second operationally representative task was the Air-to-Air Target Tracking task. For each of the three g-commanded flight control systems the task was performed at three different airspeeds and by all three evaluation pilots. The first airspeed was at V_{LO} (180 KIAS) and was designed to assault the AOA boundary. The second airspeed was at the calculated corner velocity (V_{CORNER}) based on the aircraft weight at the start of the task and was designed to assault the AOA and load factor boundary simultaneously. The final airspeed was at V_{HI} (300 KIAS) and was designed to assault the load factor boundary. A T-38 was utilized as a target for the task. Set up for the task involved the Learjet established approximately 1500 feet in trail of the target. Based on the test airspeed the target aircraft entered a turn targeting a specific load factor. For the V_{LO} , V_{CORNER} , and V_{HI} test points the T-38 entered a 1.7 g, a 2.0 g, and a 2.4 g turn respectively. Once the turn was established the evaluator pilot reestablished tracking on the target at the desired trail distance. The task was initiated when the evaluator pilot relaxed load factor to establish lag pursuit on the target aircraft and then attempted to recapture for fine tracking.

There were two separate tasks performed during the recapture. The first task involved a gross acquisition where the number of overshoots was observed during the recapture. The second task involved determining the fine tracking capability once acquisition had been established. For the first task, desired performance was defined as one overshoot during gross acquisition and adequate performance was defined as two overshoots. For the second task, desired performance was achieving fine tracking with the collimated tracking sight fixed within a circle encompassing the canopy of the T-38 while adequate performance was achieving fine tracking within a circle encompassing the entire T-38 (figure 20). All Air-to-Air tracking tasks were performed at a pressure altitude of 15,000 feet with a data band of 5,000 feet. The T-38 target aircraft flew at the test airspeed within a tolerance of ± 10 knots and at the planned load factor within a tolerance of ± 0.2 g.

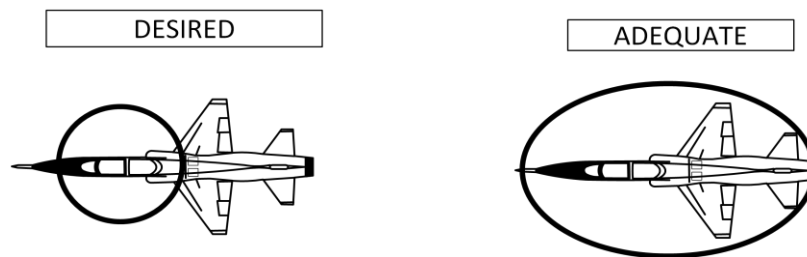


Figure 20: Fine Tracking Performance Criteria

Figures 21 and 22 illustrate the number of system trips compared to the total number of Air-to-Air gross acquisition and Air-to-Air fine tracking maneuvers for each of the three systems, respectively.

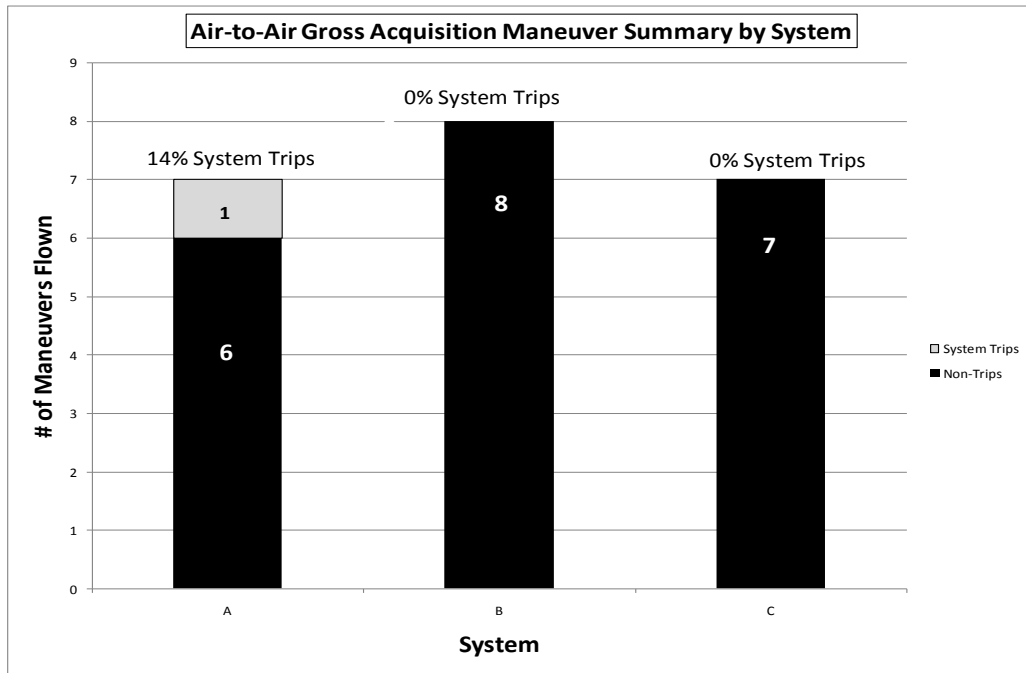


Figure 21: Air-to-Air Gross Acquisition Maneuver Summary by System

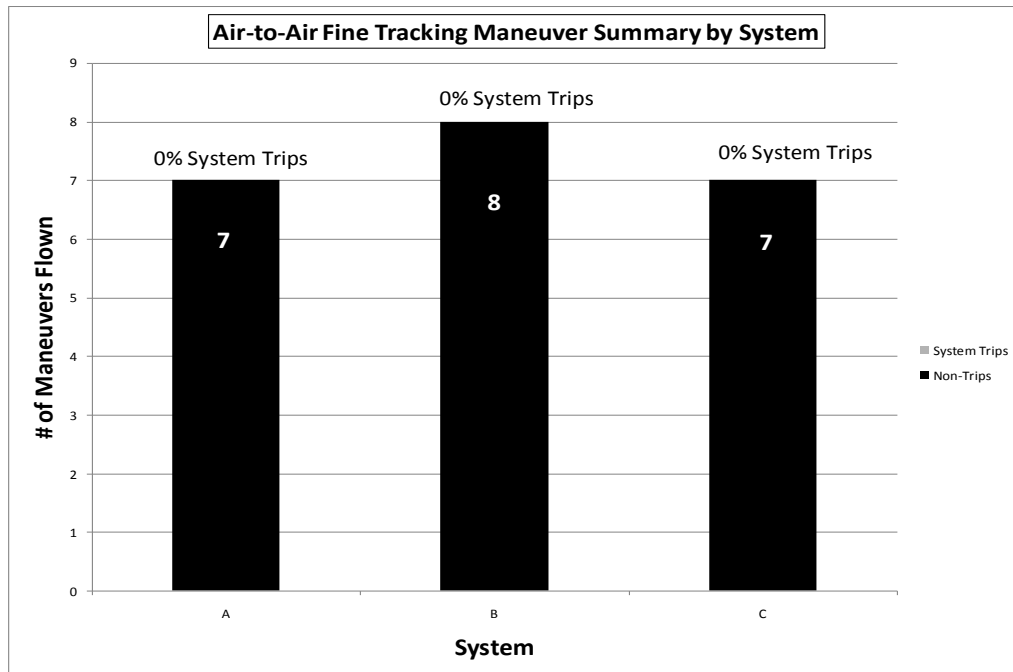


Figure 22: Air-to-Air Fine Tracking System Trip Summary

During the recapture of the Air-to-Air gross acquisition task, the load factor and AOA were elevated such that the active stick functions of system C were activated; however the load factor and AOA generally were not elevated to the boundary limits such that system trips were prevalent. There was only one system trip where a boundary excursion occurred with System A during a gross acquisition task at V_{HI} . This trip was due to a load factor boundary excursion and was an indication of the lack of protection associated with System A. For Air-to-Air fine tracking, the tasks were essentially performed in the heart-of-the-envelope where the active stick functions of System C were not activated and the limit boundaries were not approached. There were no system trips during the Air-to-Air fine tracking tasks. While the tasks did not challenge the very edge of the limit boundaries, data were collected about the tracking handling qualities of each system. It was expected that the Copper-Harper ratings for each of the three systems would be similar due the fact that the tasks were mostly performed in the heart-of-the-envelope.

Figures 23 and 24 illustrate the Cooper-Harper ratings for the Air-to-Air gross acquisition and Air-to-Air fine tracking maneuvers for each of the three systems, respectively.

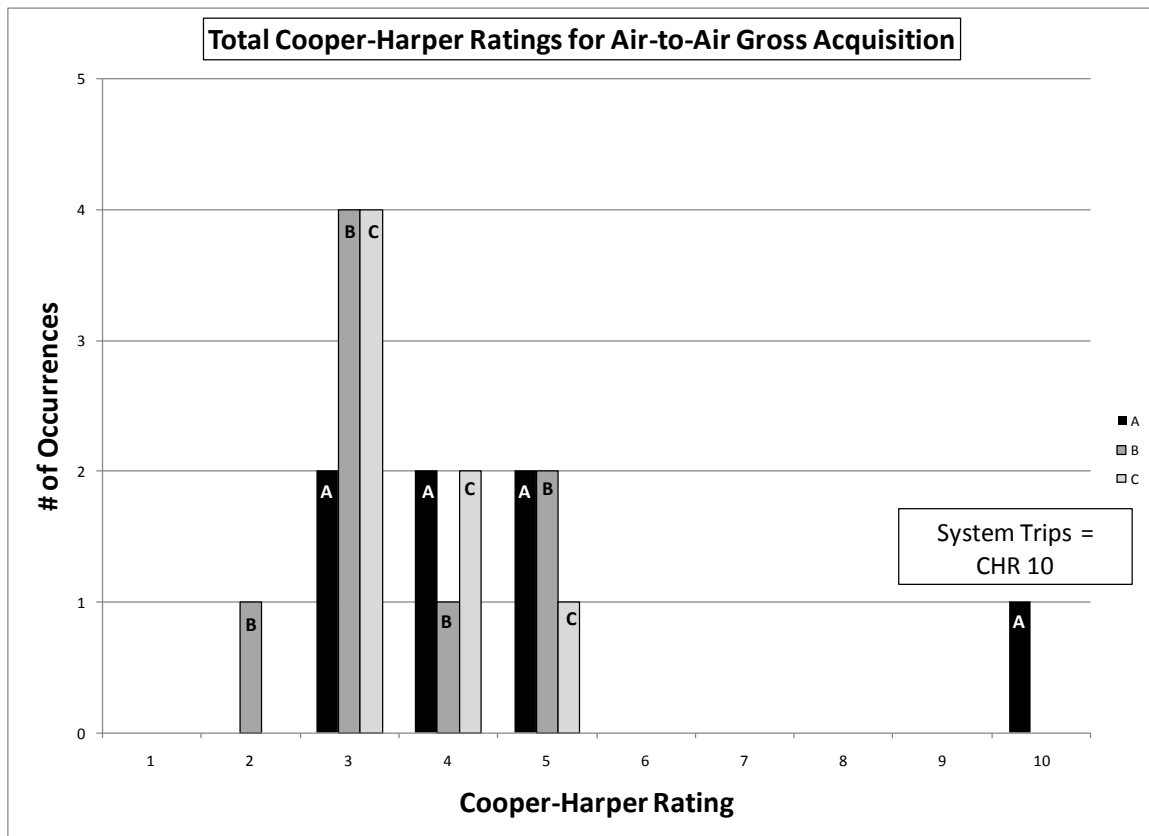


Figure 23: Total Cooper-Harper Ratings for Air-to-Air Gross Acquisition

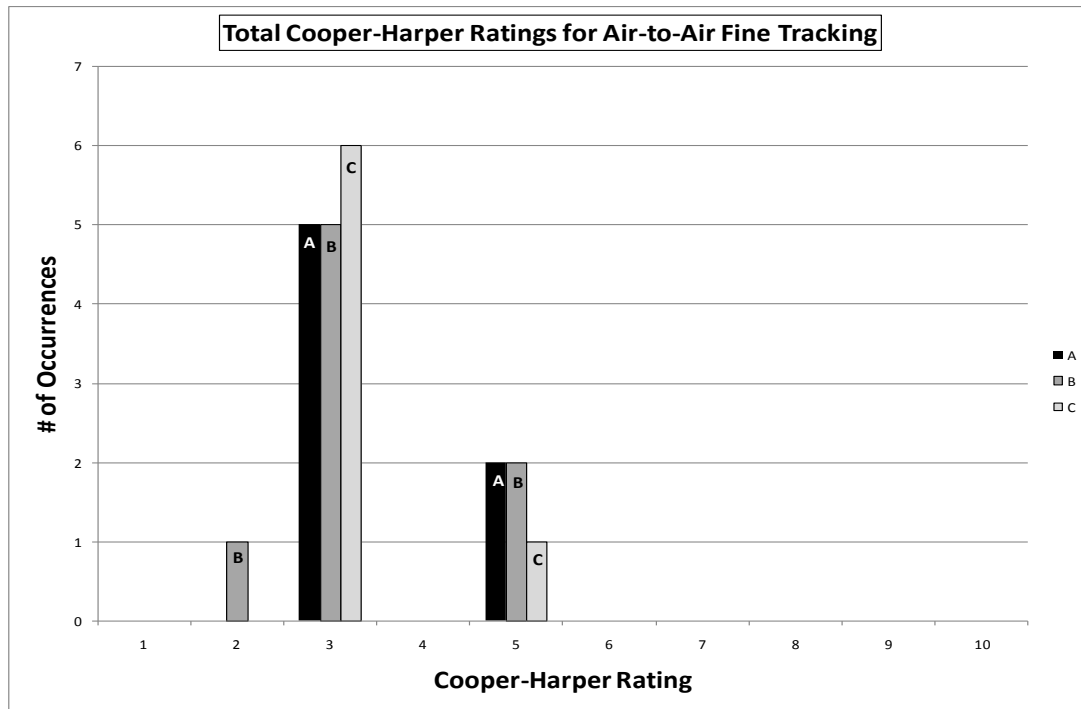


Figure 24: Total Cooper-Harper Ratings for Air-to-Air Fine Tracking

The Cooper-Harper ratings for the Air-to-Air gross acquisition and fine tracking tasks were similar for all three systems. Based on the similar ratings, it did not appear that System C's force gradients and stick shaker features had adverse handling quality effects during the gross acquisition tasks. For the fine tracking task, the ratings were similar and were expected as the task was essentially performed in the heart-of-the-envelope. As previously stated, the fine tracking task was not effective in characterizing the handling qualities of System C; however the task did verify that all three systems exhibited similar tracking handling qualities in the heart-of-the-envelope.

Break Turn Maneuver

The third operationally representative task was the Break Turn maneuver. For each of the three g-commanded flight control systems the task was performed at three different airspeeds and by two of the project test pilots. The first airspeed was at V_{LO} (180 KIAS) and was designed to assault the AOA boundary. The second airspeed was at the calculated corner velocity (V_{CORNER}) based on the aircraft weight at the start of the task and was designed to assault the AOA and load factor boundary simultaneously. The final airspeed was at V_{HI} (300 KIAS) and was designed to assault the load factor boundary. A T-38 was utilized as a target for the task. Set up for the task involved the Learjet established approximately one nautical mile in trail of the target. Based on the test airspeed the target aircraft entered a turn targeting a specific load factor following a "fight's on" call from the evaluator pilot. For the V_{LO} , V_{CORNER} , and V_{HI} test points the

T-38 entered a 1.7 g, a 2.0 g, and a 2.4 g turn respectively. After the T-38 target entered the turn the Learjet evaluator pilot continued wings level until line-of-sight rate of the T-38 significantly increased. The Learjet evaluator pilot then entered a maximum performance turn to capture the target with the collimated tracking sight.

Desired performance was defined as achieving and maintaining the target maximum AOA or load factor for 90 percent of the time and adequate performance was for 70 percent of the time. All Break Turn maneuvers were performed at a pressure altitude of 15,000 feet with a data band of 5,000 feet. The T-38 target aircraft flew at the test airspeed within a tolerance of ± 10 knots and at the planned load factor within a tolerance of ± 0.2 g.

Figure 25 illustrates the number of system trips compared to the total number of Break Turn maneuvers for each of the three systems.

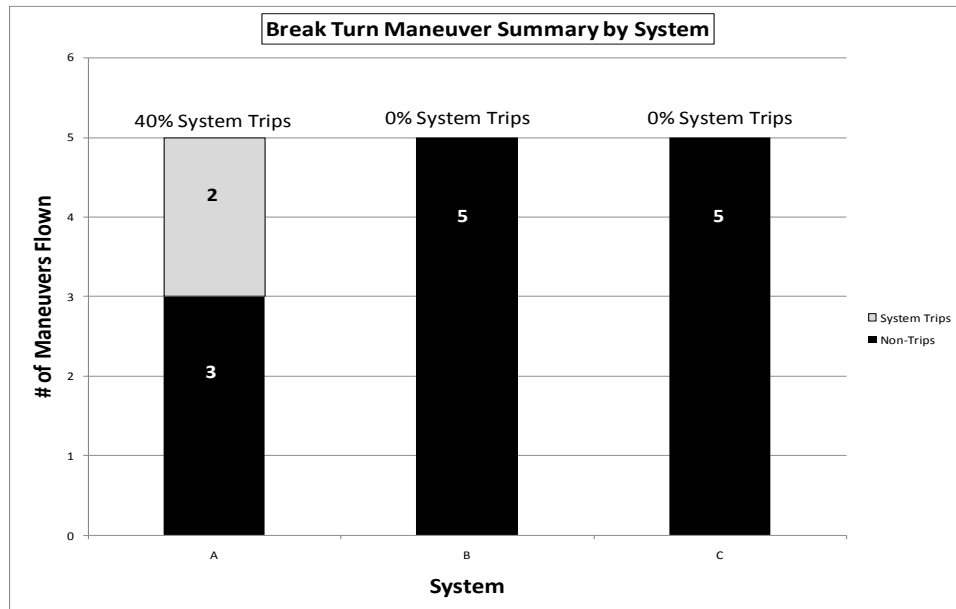


Figure 25: Break Turn System Trip Summary

System A tripped 40 percent of the time while no system trips occurred with System B and C. The data indicates that Systems B and C provided better boundary limit protect than System A.

Figure 26 illustrates the Cooper-Harper ratings for the Break Turn maneuver for each of the three systems.

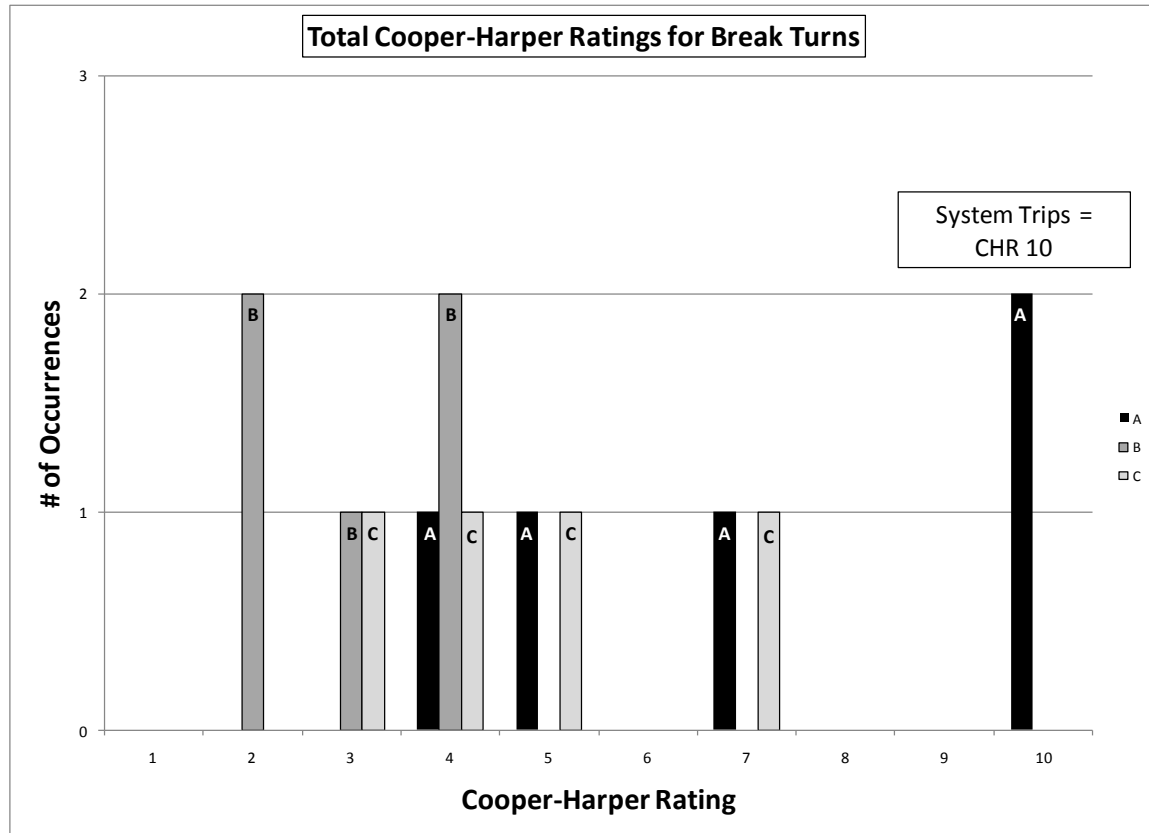


Figure 26: Total Cooper-Harper Ratings for Break Turns

System B ratings were better than System A and System C ratings. System A ratings were worse than System C ratings primarily due to the System A trips. The boundary limit protection of System B essentially allowed the pilot to input aggressive full aft stick inputs with little concern for boundary excursions. With System B the pilot's entire attention could be focused on the target during the break turn. Referencing the cockpit load factor and AOA gauge was not required while flying with System B. The result was lower pilot workload and compensation to perform the task. While flying with System A, the cockpit load factor and AOA gauge had to be referenced to avoid system trips. In addition System A provided minimal awareness to envelope boundaries. During approaches to the load factor boundary the pilot had the "seat of the pants" feel of increasing load factor, however during AOA boundary approaches the pilot had no awareness without referencing a cockpit gauge. The result was much higher workload and compensation to accomplish the task. The two CHR 10 assignments for System A were due to system trips at V_{LO} and V_{HI} where no boundary protection existed. The single CHR seven assignment for System A occurred at V_{CORNER} where adequate performance was not achieved. Based on pilot comments, workload and compensation while flying

with System C was lower than System A but higher than System B. System C provided noticeably better boundary awareness and protection than System A. There were no system trips for the Break Turn maneuver with System C; however there was one case where adequate performance was not achieved at V_{LO} and a Cooper-Harper rating of seven was assigned. The lack of performance in this case was due to the AOA pusher function where the pilot did not adequately compensate for the awareness feature. The protection and awareness features of System C lowered the workload and compensation compared to System A, however System C did not lower the workload and compensation to the levels of System B. The data clearly indicates System B provided the best boundary protection and task performance and System C provided better boundary protection, awareness, and task performance than System A.

Safe Escape Maneuvers

The fourth operationally representative task was the Safe Escape maneuver. For each of the three g-commanded flight control systems the task was performed at three different airspeeds and by all three project test pilots. The first airspeed was at V_{LO} (180 KIAS) and was designed to assault the AOA boundary. The second airspeed was at the calculated corner velocity (V_{CORNER}) based on the aircraft weight at the start of the task and was designed to assault the AOA and load factor boundaries simultaneously. The final airspeed was at V_{HI} (250 KIAS) and was designed to assault the load factor boundary. Setup altitude and airspeed varied such that the maneuver could be initiated from a 20 degree nose low dive at the desired altitude and airspeed. When the desired release conditions were achieved, the maneuver was initiated with a maximum performance pull to place the waterline symbol on the head down display 20 degrees nose high. At the V_{HI} airspeed, desired performance was to achieve a load factor of $2.7\text{ g} \pm 0.2\text{ g}$ within 3 seconds and maintain that load factor with $\pm 0.1\text{ g}$ until reaching 20 degree nose high with the waterline symbol. At the V_{HI} airspeed, adequate performance was to achieve a load factor of $2.7\text{ g} \pm 0.2\text{ g}$ within 4 seconds and maintain that load factor with $\pm 0.2\text{ g}$ until reaching 20 degree nose high with the waterline symbol. At the V_{CORNER} airspeed the desired and adequate criteria remained the same and the evaluator pilot planned on pulling to the maximum available load factor even though it may not have been available due to airspeed bleeding below the corner velocity. At the V_{LO} airspeed, desired performance was to achieve a AOA of $11.5^\circ \pm 1\text{ degrees}$ within 3 seconds and maintain that AOA within $\pm 0.5\text{ degrees}$ until reaching 20 degrees nose high with the waterline symbol. At the V_{LO} airspeed, adequate performance was to achieve a AOA of $11.5\text{ degrees} \pm 1\text{ degree}$ within 4 seconds and maintain that AOA within $\pm 1\text{ degrees}$ until reaching 20° nose high with the waterline symbol.

Figure 27 illustrates the number of system trips compared to the total number of Safe Escape maneuvers for each of the three systems.

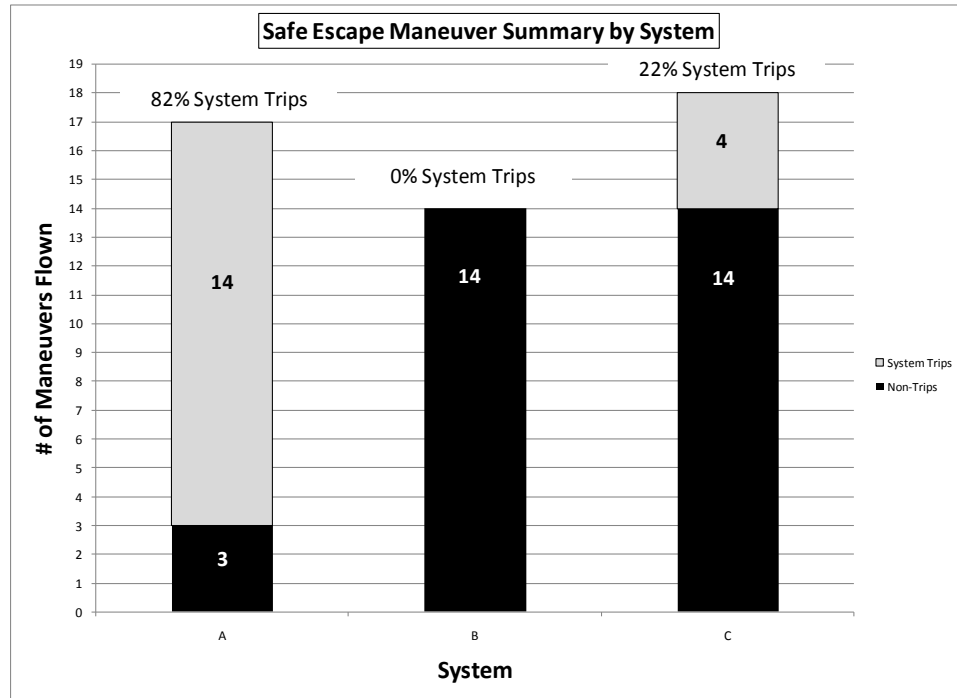


Figure 27: Safe Escape Maneuver Summary of System Trips

System A tripped 82 percent of the time while System C tripped 22 percent of the time. There were no limit trips with system B. The data clearly indicates that System B provided the best limit protection. System C provided considerably better limit protection than System A. System A provided little limit protection.

Figure 28 illustrates the Cooper-Harper ratings for the Safe Escape maneuvers for each of the three systems.

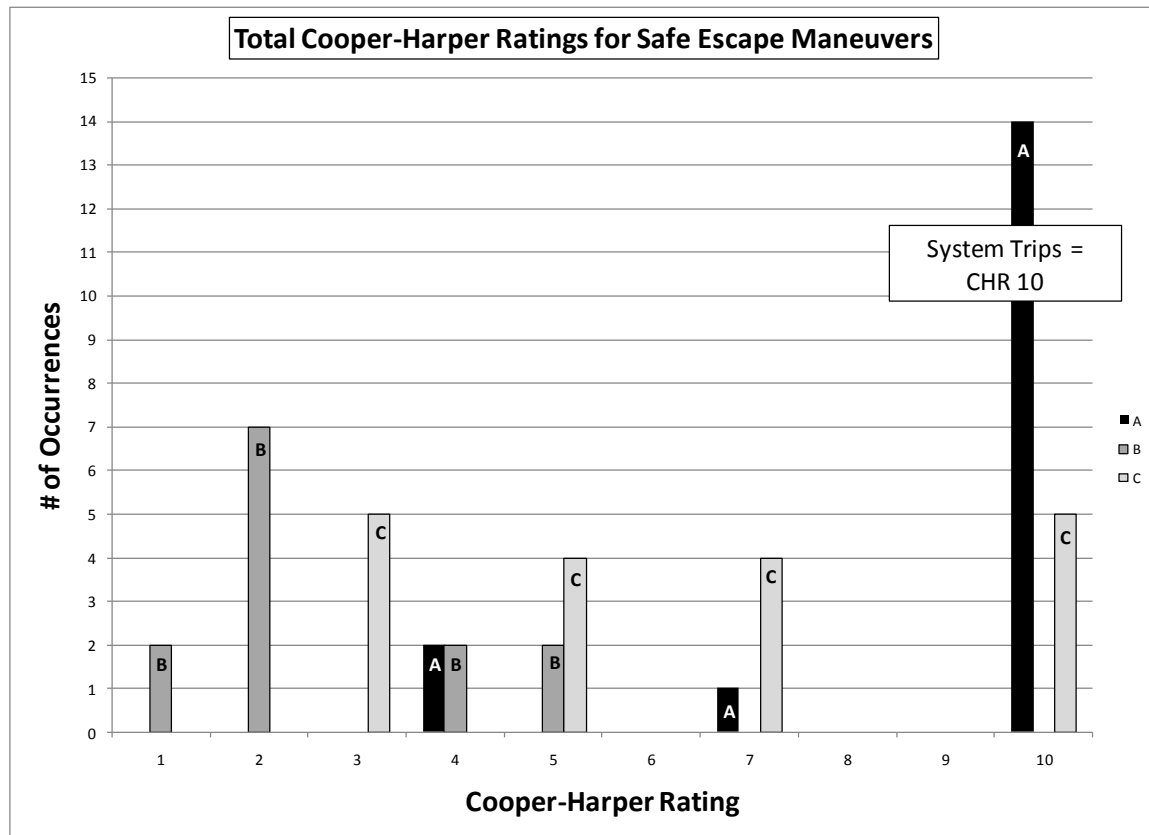


Figure 28: Total Cooper-Harper Ratings for Safe Escape Maneuvers

System B ratings were better than System A ratings and System C ratings fell between the other two systems. The boundary limit protection of System B essentially allowed the pilot to input aggressive full aft stick inputs with little concern for boundary excursions. Referencing the cockpit g and AOA gauge was not required while flying with System B. The result was lower pilot workload and compensation to perform the task. While flying with System A the cockpit and load factor and AOA gauge had to be referenced to avoid system trips. In addition System A provided minimal awareness to envelope boundaries. During approaches to the load factor boundary the pilot had the “seat of the pants” feel of increasing load factor, however during AOA boundary approaches the pilot had no awareness without referencing a cockpit gauge. The result was much higher workload and compensation to accomplish the task. Based on pilot comments, workload and compensation while flying with System C was lower than System A but higher than System B. System C provided better boundary awareness and protection than System A; however there were clearly cases where System C did not

provide adequate protection and achieve desired performance. There were four instances where a Cooper-Harper rating of seven was assigned to System C. This rating was attributed to the stick pusher limiting the pilot's ability to achieve and maintain the AOA in the required time for adequate performance. During aggressive pulls, the 2.4 g soft stop could easily be pulled through to a limit trip without the evaluator pilot having complete awareness of the approaching boundary. The data clearly indicates System B provided the best boundary protection and task performance and System C provided better boundary protection, awareness, and task performance than System A.

Pilot-in-the-Loop Oscillation Susceptibility Comparison

The primary objective was to identify and compare differences in the PIO susceptibility of each flight control system. This PIO susceptibility investigation was performed in order to determine if implementation issues associated with phase lag, rate limiting, and non-linear stick force gradient adversely affected handling qualities in each of the three flight control systems.

A Workload Buildup (WLB) FTT (reference 3) was used to investigate the PIO susceptibility of the three systems. This WLB FTT involved a T-38 target. This FTT was flown at three different airspeeds: V_{LO} (180 KIAS), V_{CORNER} (205-235 KIAS, weight dependent), and V_{HI} (300 KIAS). Set up for the task involved the Learjet established approximately 1500 feet in trail of the target. Based on the test airspeed the target aircraft entered a turn targeting a specific load factor. For the V_{LO} , V_{CORNER} , and V_{HI} test points the T-38 entered a 1.7 g, a 2.0 g, and a 2.4 g turn respectively. The task was initiated when the evaluator pilot reduced load factor to establish lag pursuit of the target aircraft, and then aggressively captured the T-38 fuselage within the boundaries of the collimated tracking sight. The WLB FTT was used to assess PIO susceptibility by remaining within the boundaries of the collimated tracking sight as they were incrementally decreased. To the maximum extent possible, the boundaries were treated as life threatening. Upper and lower boundaries of the collimated tracking sight began with a 12 mil separation, and decreased to 9 mils, 6 mils, 3 mils, and zero mils. Zero error tracking was attempted upon reaching zero mils. Figure 29 illustrates the Total Workload Buildup PIO ratings.

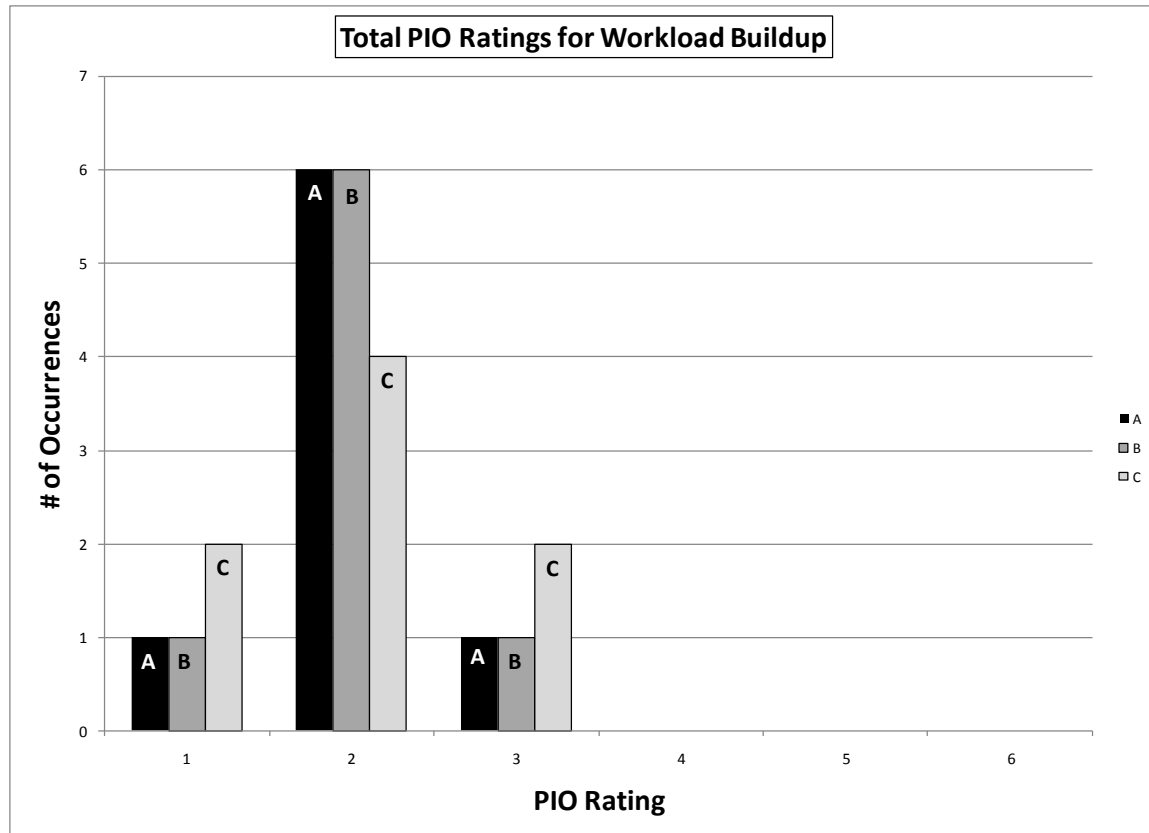


Figure 29: Total PIO Ratings for Workload Buildup

The PIO ratings of the three systems were similar. No PIOs were experienced during the Workload Buildup FTTs. The majority of the PIO ratings were two, indicating that undesirable motions tended to occur for all three systems. In addition, all systems demonstrated undesirable motions that were easily induced – PIO rating of three. During a tracking task with a fixed sight, any roll motion repositioned the aim point in pitch, creating a pendulum effect. The farther away from the target, the larger the error created by this effect. Based on pilot comments, the pendulum effect was noted for all three systems. The PIO rating of three for all systems was likely due to the pendulum effect and not necessarily due to flight control system attributes. The pendulum effect may be reduced in two ways: a constantly computed gun sight may be implemented, or the collimated gun sight may be re-positioned on the roll axis. **Account for pendulum effect in test planning and test execution in order to completely isolate flight control system PIO susceptibility attributes. (R2)**

PIO susceptibility at boundary limits was revealed during the operationally representative maneuvers. The procedures, methods, and conditions for each of these FTTs are described in The Comparison of Handling Qualities During Operationally Representative Tasks subsection of this report. Figure 30 illustrates a summary of PIO ratings for all operationally representative tasks.

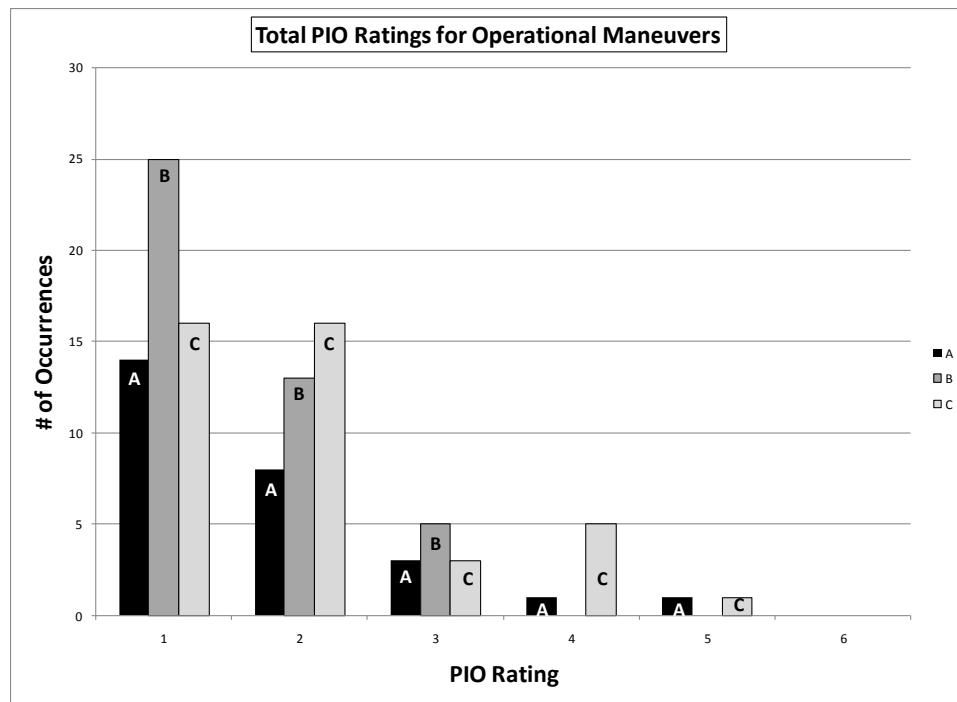


Figure 30: Total PIO Ratings for Operational Maneuvers

The Head Down Display (HDD) tracking task and Air-to-Air tracking tasks had PIO ratings of three or less. Pilot comments associated with these maneuvers were similar to those obtained during the Workload Buildup testing. The majority of the PIO ratings for the Safe Escape and Break Turn maneuvers were also three or less. However, some PIO ratings for the Safe Escape and Break Turn maneuvers were greater than three.

A PIO rating of four was given six times: one for System A and five for System C. For System A, the task was a Safe Escape maneuver at V_{LO} . The pilot tightened control inputs while focusing on the AOA gauge. This resulted in bounded overshoots near the AOA envelope boundary. For System C, all five PIO ratings of four occurred at V_{LO} and V_{CORNER} where AOA assaults were prevalent. The PIO susceptibility was likely due to the functionality of the stick pusher as the aircraft approached the AOA boundary. Based on pilot comments, these nonlinear changes were difficult to predict and most likely resulted in bounded oscillations near the AOA limit. A PIO rating of five was assigned twice: once for System A and once for System C. Both ratings were assigned during Safe Escape maneuvers at the V_{LO} condition. For System A, pilot comments indicated that using the AOA gauge for zero error tracking resulted in a divergent PIO. This was attributed to AOA gauge lag. System C's rating was associated with the stick pusher implementation near the AOA limit. Overall, System C proved to be susceptible to PIOs when AOA limits were approached and the Active Stick pusher was triggered. Redesigning AOA protection features such as eliminating or changing the location and magnitude of the stick pusher may reduce the PIO susceptibility.

At the low airspeeds, the WLB FTT painted a limited picture of each system's PIO susceptibility due to performance limitations of the target aircraft. The operational FTTs exposed more useful PIO data. The T-38 target aircraft could not maintain an AOA that challenged the AOA boundaries of System C due to lift limits at low airspeeds while in a turn. Data from the operationally representative tasks indicated that the active stick features of System C at high AOA were susceptible to PIO. For future investigations of the PIO susceptibility of active stick functions at high AOA, a target that can perform at a higher AOA at lower airspeeds should be used. Likewise, the target aircraft would also need to be able to perform at the required load factor at the higher speeds. **Use a target aircraft with more compatible performance characteristics for future testing. (R3)**

Human Factors Evaluation of Feedback for Envelope Awareness

Pilot ratings of aircraft envelope awareness were collected using a human factors questionnaire. The human factors questionnaire compared System A to System B, System B to System A, System B to System C, System C to System B, System A to System C and System C to System A. In each comparison, aircraft parameters (AOA, load factor, airspeed) were used to determine which system provided better flight envelope awareness. The five-point comparison rating scale illustrated in table 2 was used to quantify and qualify pilot opinions about each flight control system.

Table 2: Five Point Comparison Rating Scale

Response Value	Response Alternative
1	Much Worse
2	Worse
3	About Equal
4	Better
5	Much Better

Pilot comments were also recorded to provide insight about system performance and envelope awareness feedback. Aircraft Envelope Awareness questionnaires and pilot comments were used for this analysis. The results of all five point comparisons for AOA are illustrated in figure 31. The five point comparison for load factor showed similar results and is displayed in figure C-15. The airspeed comparison was omitted since there were no noticeable differences between the comparisons.

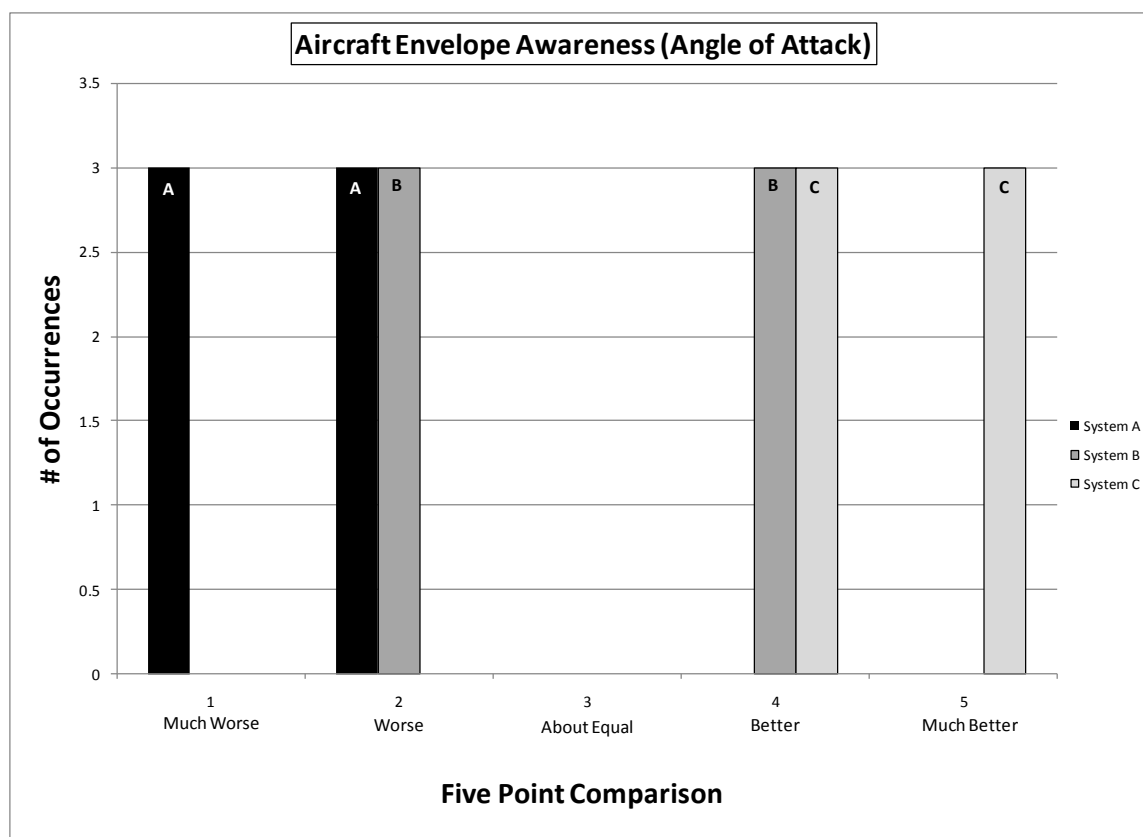


Figure 31: Aircraft Envelope Awareness (Angle of Attack)

The purpose of this comparison was to determine if one system could provide better aircraft envelope awareness than the other systems. More specifically, the objective was to evaluate what type of feedback worked best for determining aircraft envelope awareness pertaining to AOA, load factor, and airspeed. Evaluator pilots completed the Aircraft Envelope Awareness questionnaires after their last test flight. Pilot comments for each system are summarized below.

The only feedback provided by System A was stick force (increased load factor required increased stick force). The evaluator pilot could not tell exactly what load factor was commanded without referencing the g-meter. During load factor assaults, the evaluator pilot compensated for this lack of load factor feedback by referencing the g-meter to prevent a VSS system trip. Similarly, the aircraft AOA was determined by referencing the AOA indicator as there was no way to determine AOA based on stick feel alone. When maneuvering at, or close to corner velocity, both the AOA and g-meter had to be cross-checked simultaneously, significantly increasing pilot workload.

System B provided some envelope awareness associated with the full aft stop. With a full aft stick input, the evaluator pilot knew that the aircraft was either at the load factor limit (2.7 g) or at the AOA limit (11.8 degrees AOA). It was possible for the evaluator pilot to determine the approximate transition from a load factor boundary to an

AOA boundary based on the feel of the load factor. A decrease in load factor indicated that the aircraft had passed below corner velocity and had transitioned to the lift limit boundary (AOA). This “seat-of-the-pants” feel was helpful but not foolproof in determining exact aircraft envelope location. The evaluator pilot still utilized the g-meter and AOA gauge to determine flight envelope location.

System C had “layered” features approaching both AOA and load factor limits (load factor - two soft stops; AOA - stick pusher combined with a stick shaker). For load factor limits, the first soft stop provided intermediate boundary awareness and the pilot knew that a 2.4g load factor was commanded. When more force was applied beyond the first soft stop, the evaluator pilot knew that a load factor above 2.4 was commanded but the exact load factor could not be determined without referencing the g-meter. This indicated that the second soft stop was not noticeable enough to the pilot. It was difficult to determine a distinct line between 2.7 g and exceeding a VSS limit. The stick shaker (active at 11 degrees AOA) provided adequate flight envelope awareness at corner velocity and below. The stick pusher activated at 9.0 degrees AOA and helped provide protection as well as envelope awareness at airspeeds below corner velocity. However, the stick pusher contributed to PIO tendencies at low airspeeds. At corner velocity, the combined stick shaker, pusher, and forces provided good pilot feedback for aircraft envelope awareness. The feedback provided by System C allowed the pilot to determine when approaching an AOA or load factor boundary without necessarily looking at the AOA and/or g-meters. However, since System C did not have full limit protection, the AOA and g-meters were crosschecked to prevent the pilot from exceeding VSS limits. The overall crosscheck was expedited based on System C feedback system design, because the feedback from the stick told the pilot exactly what gauge to look at. System C showed that active stick functionality can improve a pilot’s boundary awareness and can also provide some limit protection. The design of System C for the Active Stick project, however, was not perfect. There were instances where limits were exceeded during tasks and there were also issues with PIO at low airspeeds due to the stick pusher. Redesigning AOA protection features such as eliminating or changing the location and magnitude of the stick pusher may reduce PIO susceptibility while still providing sufficient awareness and limit protection for the pilot. Likewise, changing the quantity, location, and magnitude of the force gradients for load factor awareness may provide the correct amount of awareness while also improving protection from a load factor limit.

Based on the pilot comments and the five-point comparison scale results, System C provided the best envelope awareness to the pilot. Even though System C provided the best envelope awareness to the pilot, System C still had more VSS limit excursions than System B. Figure 32 illustrates the number of FTT maneuvers flown for each system and the number of VSS limit excursions per system.

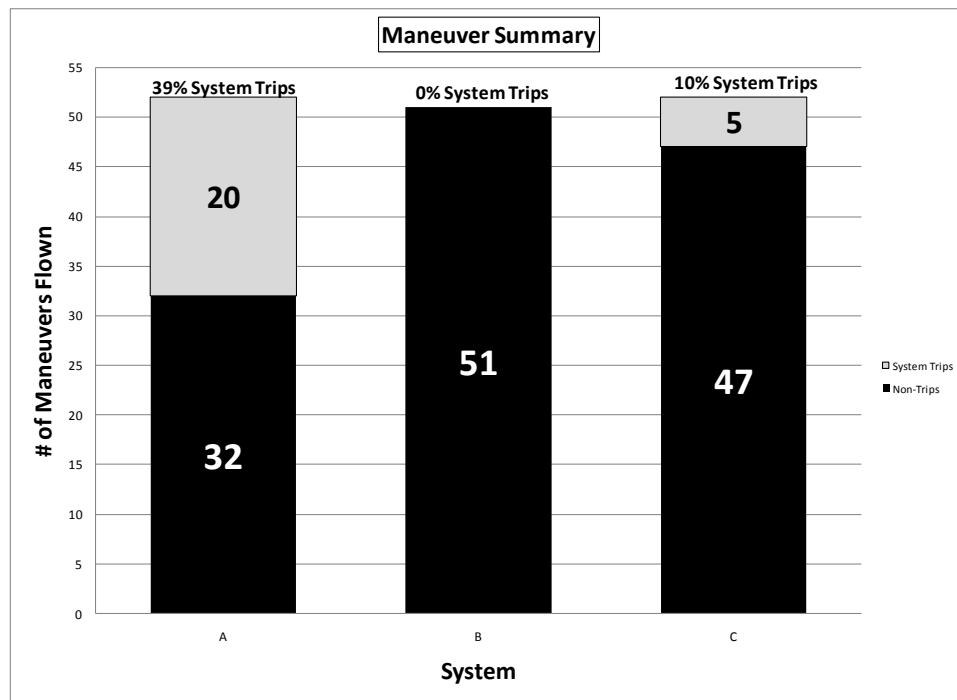


Figure 32: Total Number of System Trips

The number of VSS limit excursions was tracked to compare each systems' performance during the flight test techniques. The fact that five VSS trips occurred with System C, while zero VSS trips occurred with System B, shows that even though System C provided the best envelope awareness, the ability of a human pilot to provide protection from aircraft limits was not as good as the limit protection designed directly into the flight control system (System B). However, there was a significant decrease in the number of limit excursions for System C when compared to System A indicating that there is potential for active stick functions to be incorporated into flight control systems. The combination of an active stick feedback and the limit protection provided by the flight control system may lead to decreased workload when attempting to max perform an aircraft by providing aircraft limit protection and essential flight envelope awareness.

Envelope awareness associated with airspeed was not directly tested since the individual FTTs did not include a large, continuous change in airspeed (i.e. start a maneuver fast and end up slow or vice versa). Instead, three airspeeds were tested as individual data points (V_{LO} , V_{CORNER} , and V_{HI}). Testing at these discrete airspeeds did not provide insight into energy awareness while transitioning within the aircraft envelope. Nor did the discrete airspeed tests provide insight into how transitioning between boundaries affects the system's ability to provide adequate envelope protection. An FTT that included airspeed changes might have highlighted additional strengths and weaknesses of the system design. Specifically, envelope boundary transition via airspeed changes could affect handling qualities and task performance as a result of stick feel changes. **Explore the effects of airspeed transitions across envelope boundaries. (R4)**

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CONCLUSIONS AND RECOMMENDATIONS

Active Stick demonstrated the potential to transfer limiters and safe guards from the inner-loop of the flight control system to an outer-loop active control stick system. The potential was demonstrated in the areas of load factor and angle of attack limit protection and awareness. System A's strength was uninhibited control of aircraft performance; there was no envelope limit protection. System B, on the other hand, had load factor and AOA limiting features. The implementation made it easy to achieve optimum performance but provided no means to exceed limits or provide feedback to the pilot on envelope location. System C combined the freedom of System A along with envelope boundary awareness protection and tactile cues.

The overall objective was to perform a preliminary investigation into the potential of using an active feel control stick system to perform system functions traditionally incorporated in the inner loop of the flight control computer design. This investigation was accomplished by evaluating four specific objectives. All objectives were met.

The first objective was to compare the open-loop flying qualities of each system during pitch only tasks to characterize key differences in both the heart of the envelope and the envelope boundaries. Systems A, B, and C exhibited nearly identical feel and performance characteristics in the heart-of-the-envelope. As expected, at the envelope boundaries each system exhibited differences based on their respective design characteristics.

The next objective was to compare the handling qualities of each FCS during operationally representative tasks. The following maneuvers were performed to accomplish this objective: head down display (HDD) tracking, air-to-air target tracking, safe escape maneuvers, and break turns. Data from the break turns and safe escape maneuvers clearly showed that System B provided the best boundary protection and task performance and System C provided better boundary protection, awareness, and task performance than System A. The air-to-air tracking tasks were essentially performed in the heart-of-the-envelope and resulted in similar ratings for all three systems. The test team did not optimize the flight control systems for flight regimes lower than 1 g. The impact of this was realized during the HDD tasks where Cooper-Harper Ratings were adversely affected by the undesirable stick forces in the system designs. Future active stick designs could include angle of attack (AOA), load factor, airspeed tactile feedback, and protection that encompass the entire flight envelope including operation below 1 g. **Expand future active feel control stick investigations to include flight regimes less than 1 g. (R1, page 24)**

Another objective was to compare the pilot-in-the-loop oscillation (PIO) susceptibility of each flight control system (FCS). The Workload Buildup (WLB) flight test technique (FTT) was used to evaluate the PIO susceptibility of each FCS, but more useful PIO data were collected during the operationally representative tasks. The reason for this was that the WLB FTT, as designed, was not adequate in identifying PIO

susceptibility at low airspeeds (high AOA) due to performance limitations of the target aircraft. As a result, the data from the WLB task indicated that there was no PIO susceptibility and PIO ratings for all systems were similar. On the other hand, the operational tasks tested the envelope boundaries, including the high AOA boundary, where System C's stick pusher was active. This revealed System C's PIO susceptibility at high AOA. For future investigations of the PIO susceptibility of active stick functions at high AOA, a target that can perform at a higher AOA at lower airspeeds could be used. Likewise, the target aircraft would also need to be able to perform at the required load factor at higher speeds. **Use a target aircraft with more compatible performance characteristics for future testing. (R3, page 38)** In addition, the pendulum effect of the fixed gun sight caused undesirable lateral-directional motions that were reflected in the PIO ratings for WLB tasks for all airspeeds. Therefore, the associated PIO ratings did not isolate the PIO susceptibility in the longitudinal axis, which was the axis of interest. **Account for pendulum effect in test planning and test execution in order to completely isolate flight control system PIO susceptibility attributes. (R2, page 36)**

The final objective was to perform a human factors evaluation on envelope awareness feedback for each FCS. This evaluation proved that active stick features can improve a pilot's boundary awareness and can also provide some limit protection. The design of System C for the Active Stick project, however, was not perfect. There were instances where limits were exceeded during tasks and there were also issues with PIOs at low airspeeds due to the stick pusher. Redesigning AOA protection features such as eliminating or changing the location and magnitude of the stick pusher may reduce PIO susceptibility while still providing sufficient awareness and limit protection for the pilot. Likewise, changing the quantity, location, and magnitude of the force gradients for load factor awareness may provide the correct amount of awareness while also improving protection from a load factor limit. Testing was conducted at discrete airspeeds and did not provide insight into the pilot's energy awareness of the aircraft while transitioning within the aircraft envelope. Nor did the discrete airspeed tests provide insight into how transitioning between boundaries affects the system's ability to provide adequate envelope protection. A flight test technique that included airspeed changes might have highlighted additional strengths and weaknesses of the system design. Specifically, envelope boundary transition via airspeed changes could affect handling qualities and task performance as a result of stick feel changes. **Explore the effects of airspeed transitions across envelope boundaries. (R4, page 41)**

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2. *Flying Qualities of Piloted Aircraft*, MIL-STD-1797B, 15 February 2006.
3. Gray, William. *A Generalized Handling Qualities Flight Test Technique Utilizing Boundary Avoidance Tracking*. American Institute of Aeronautics and Astronautics, 2008.

APPENDIX A – CALIBRATION SORTIES

Stick Force per g Evaluation

	<u>Calibration Sortie #1</u>
System A (4 Lbs/g)	--Slightly sensitive (light) stick force per g --Good pitch rate command --Good control harmony (roll and pitch about equal)
System A (8Lbs/g)	--Slightly heavy stick force --Slightly heavier in pitch than in roll --Step input, system tripped at 2.2g --Ramp input, system tripped at 2.8g
System A (12 Lbs/g)	--Too much stick force --Too heavy for Active Stick TMP to use in order to asses Active Stick's ability to protect the pilot from limits
System B (4 Lbs/g)	--Not Flown
System B (8Lbs/g)	--Feels same as System A (8 Lbs/g) --Good g-onset rate
System B (12 Lbs/g)	--Not Flown

System C Stick force gradients were 6.25 lbs/g up to the first break point. This felt reasonable and was a good compromise between the 4 lbs/g and 8 lbs/g versions of System A and B. All stick force gradients in system A and B were set to 6 lbs/g prior to the second calibration sortie. System C's initial gradient up the first soft stop was also set to 6 lbs/g.

System C Configurations Flown During Calibration Sorties

<u>System C 1</u> Reversible Soft Stop 1 -- 4 Lbs (breakout) --2.4g Soft Stop 2 --10 Lbs (breakout) --2.7g AOA Shaker --Constant Frequency (10 Hz) --Constant Amplitude (0.1) --11.0° (Start AOA) AOA Pusher --9.0° (Start AOA) --5 Lbs/°AOA	<u>System C 6</u> Irreversible Soft Stop 1 -- 4 Lbs (breakout) --2.4g Soft Stop 2 --10 Lbs (breakout) --2.7g AOA Shaker --Constant Frequency (10 Hz) --Constant Amplitude (0.1) --11.0° (Start AOA) AOA Pusher --9.0° (Start AOA) --5 Lbs/°AOA
---	---

System C1 and C6 were the same system except C1 had a programmed gradient as a function of airspeed making it act as though it were reversible.

<u>System C 2</u> Reversible Soft Stop 1 -- 15 Lbs (breakout) --2.6g Soft Stop 2 --5 Lbs (breakout) --2.7g AOA Shaker --Constant Frequency (10 Hz) --Constant Amplitude (0.1) --9.0° (Start AOA) AOA Pusher --11.0° (Start AOA) --15 Lbs/°AOA	<u>System C 3</u> Irreversible Soft Stop 1 -- 15 Lbs (breakout) --2.6g Soft Stop 2 --5 Lbs (breakout) --2.7g AOA Shaker --Constant Frequency (10 Hz) --Constant Amplitude (0.1) --9.0° (Start AOA) AOA Pusher --11.0° (Start AOA) --15 Lbs/°AOA
--	--

System C2 and C3 were the same system except C2 had a programmed gradient as a function of airspeed making it act as though it were reversible.

<u>System C 4</u> Reversible Soft Stop 1 -- 38 Lbs (breakout) --2.7g AOA Shaker --Constant Frequency (10 Hz) --Constant Amplitude (0.1) --11.6° (Start AOA) AOA Pusher --11.0° (Start AOA) --20 Lbs/°AOA	<u>System C 5</u> Irreversible Soft Stop 1 -- 38 Lbs (breakout) --2.7g AOA Shaker --Constant Frequency (10 Hz) --Constant Amplitude (0.1) --11.6° (Start AOA) AOA Pusher --11.0° (Start AOA) --20 Lbs/°AOA
--	--

System C4 and C5 were the same system except C4 had a programmed gradient as a function of airspeed making it act as though it were reversible.

System C 7

Reversible
Soft Stop 1
-- 38 Lbs (breakout)
--2.7g
AOA Shaker
--Start Frequency (10 Hz)
--End Frequency (5 Hz)
-- Start Amplitude (0.05)
--End Amplitude (0.1)
--Start AOA (9.0 deg)
--End AOA (11.0 deg)

System C7 investigated an AOA shaker that changed frequency and amplitude over a range of AOA.

Pilot Comments on Active Stick Functions

Active Stick Function	Envelope Protection	Envelope Awareness	Miscellaneous Comments
Soft/Hard Stop Location (g value) Magnitude	--2 nd soft stop in the 2.6g (15 Lbs) 2.7g (5 Lbs) was easy to pull through (hard to identify) --2 nd soft stop 2.7g (10 Lbs) was noticeable and provided some protection --Simulated hard stop (38 Lb breakout at 2.7g) works well in protecting against g-limit...gives similar results to system B --Soft stop with high force provides good protection (feels like hard stop) you can still pull past and over g with a very high force if necessary in extremis.	--Ramp input noticed 2.4g and 2.7g soft stop --Step input, did not notice 2.4g (4 Lbs) soft stop --Soft stop at 2.4g with a change in gradient followed by soft stop at 2.7g with much higher gradient (C6) provided the best awareness. The increased resistance past 2.4 provided feedback that you were approaching the limit but the force was not so high that you could not pull to command 2.7g	-C6 best system for awareness and protection.
Stick Shaker Location (AOA value) Frequency Amplitude	--AOA shaker only (9°- 11° variable freq/mag) provides little warning during a step input --Changing freq/mag during a ramp input provides some protection but better energy awareness --Shaker at 11.6° AOA provides almost no envelope protection --Shaker alone provides almost no protection especially with a rapid assault	--Constant AOA shaker at 11° provides good information on optimum performance (11.6° AOA is better performance) --9° constant shaker provides sufficient warning during ramp inputs but could be distracting during fine tracking tasks --AOA shaker only (9°- 11° variable freq/mag) provides good energy awareness but 2 nd breakpoint should be moved to 11.6°) -Liked the shaker for awareness with a high freq and low amplitude when activated at max perform AOA	--Same as calibration...did not care for the shaker over a range of AOA...see calibration comments for reasons. In general shaker not real good for protection. Shaker good for awareness.
Stick Pusher Force Onset Rate Location	-- 9° AOA pusher (5 Lb/g) is a nice ramp up and noticeable in a step and ramp input (increased stick force may cause issues with fine tracking) --11° stick pusher (20 lbs/AOA) needs to start earlier in step inputs --11° stick pusher (20 lbs/AOA) will cause PIO's with fine tracking close near AOA limit -Pusher started early (C6) with lower force gradient was ideal. Pusher with high force starting at 11° caused PIO	--11° AOA pusher (20 lbs/AOA) provides good envelope awareness with slow inputs, but is inadequate for AOA assaults --Ideal shaker for awareness was high freq low amplitude which started close to max perform AOA (C6). Did not like the shaker over a range even changing freq and amp over the AOA range did not provide adequate awareness. --Pusher with lower gradient that starts early enough provides good awareness.	-Pusher started early with lower gradient coupled with shaker for awareness close to max perform AOA was ideal (C6).
Stick Displacement			--At airspeeds being worked, differences between reversible and irreversible system were not that noticeable -- No objections to stick displacement
Stick Gradient			--No objections to gradient

APPENDIX B – ACRONYM LIST

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
AFFTC	Air Force Flight Test Center	--
AOA	Angle of Attack	--
CHR	Cooper-Harper Rating	--
F_{es}	Stick Force	pounds
FCS	Flight Control System	--
FTT	Flight Test Technique	--
HDD	Head Down Display	--
HQDT	Handling Qualities During Tracking	--
PA	Pressure Altitude	feet
PIO	Pilot-in-the-Loop Oscillation	--
PIOR	Pilot-in-the-Loop Oscillation Rating	--
PTI	Programmed Test Input	--
SRB	Safety Review Board	--
TMP	Test Management Project	--
TPS	Test Pilot School	--
TRB	Technical Review Board	--
VSS	Variable Stability System	--
WLB	Workload Buildup	--
g	Load Factor	g 's
mil	Milliradian	milliradian
n_z	Load Factor	g 's
α	Angle of Attack	degrees
δ_{es}	Stick Displacements	inches

APPENDIX C – FULL PAGE PLOTS

ACTIVE STICK - AIRCRAFT PITCH RESPONSE TO PROGRAMMED TEST INPUT
PRESSURE ALTITUDE: 15089 feet DATA BASIS: FLIGHT TEST
AIRSPEED: 183 TEST DATE: 03/20/09
AIRCRAFT: lear3 PTI INPUT: g-STEP

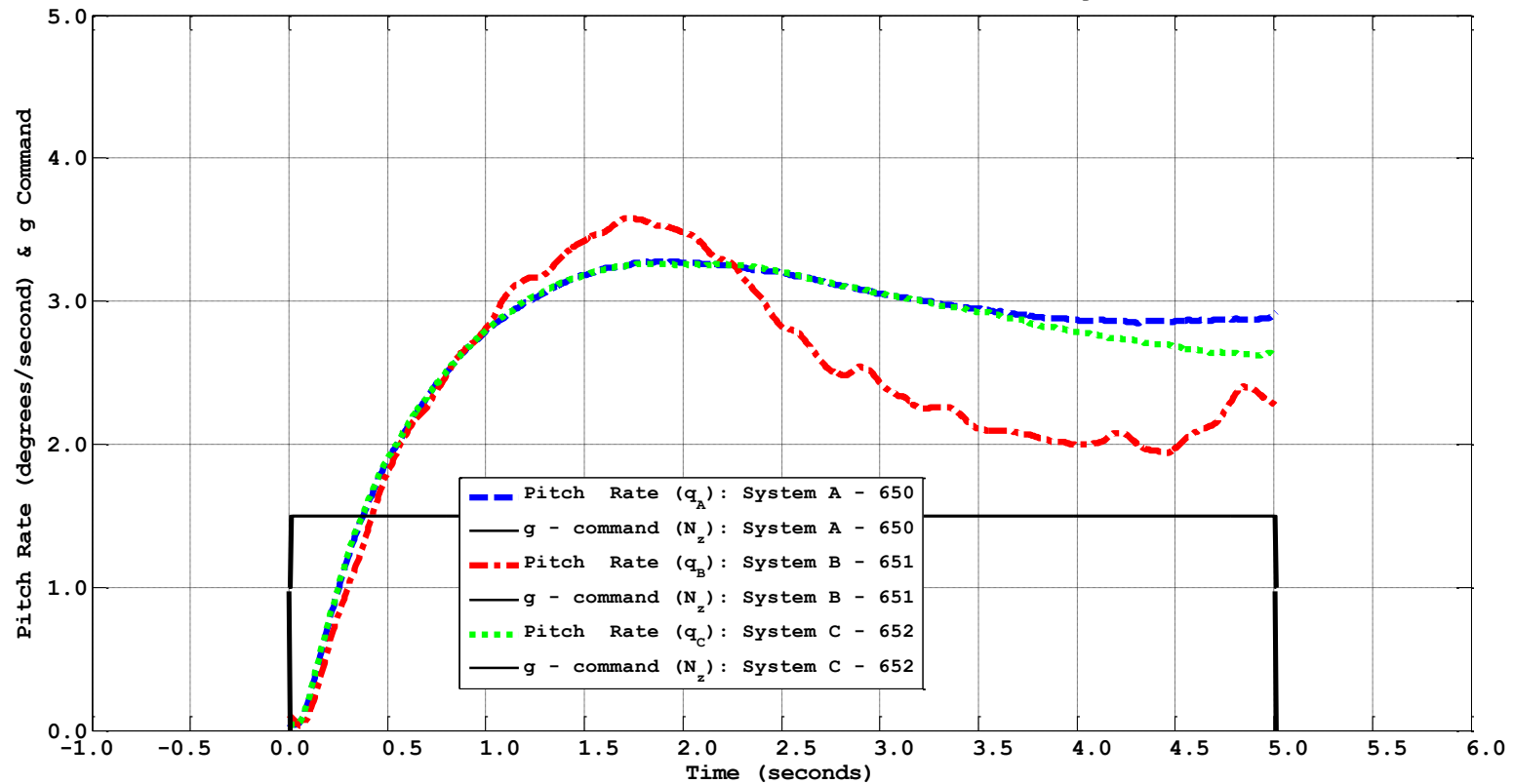


Figure C - 1: Pitch Rate Response to 1.5 g Commanded PTI at V_{LO}

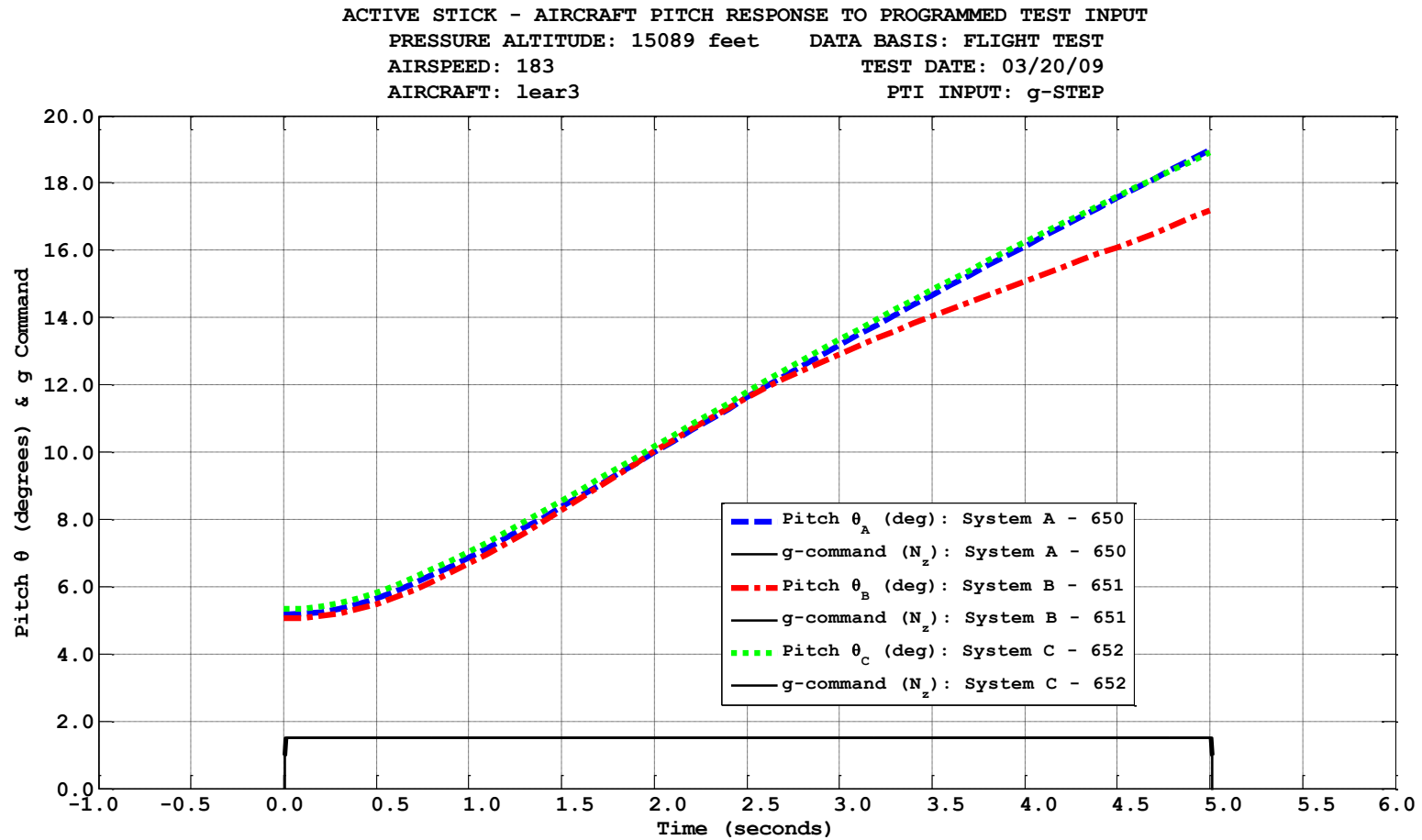


Figure C - 2: Pitch Angle Response to 1.5 g Command PTI at V_{LO}

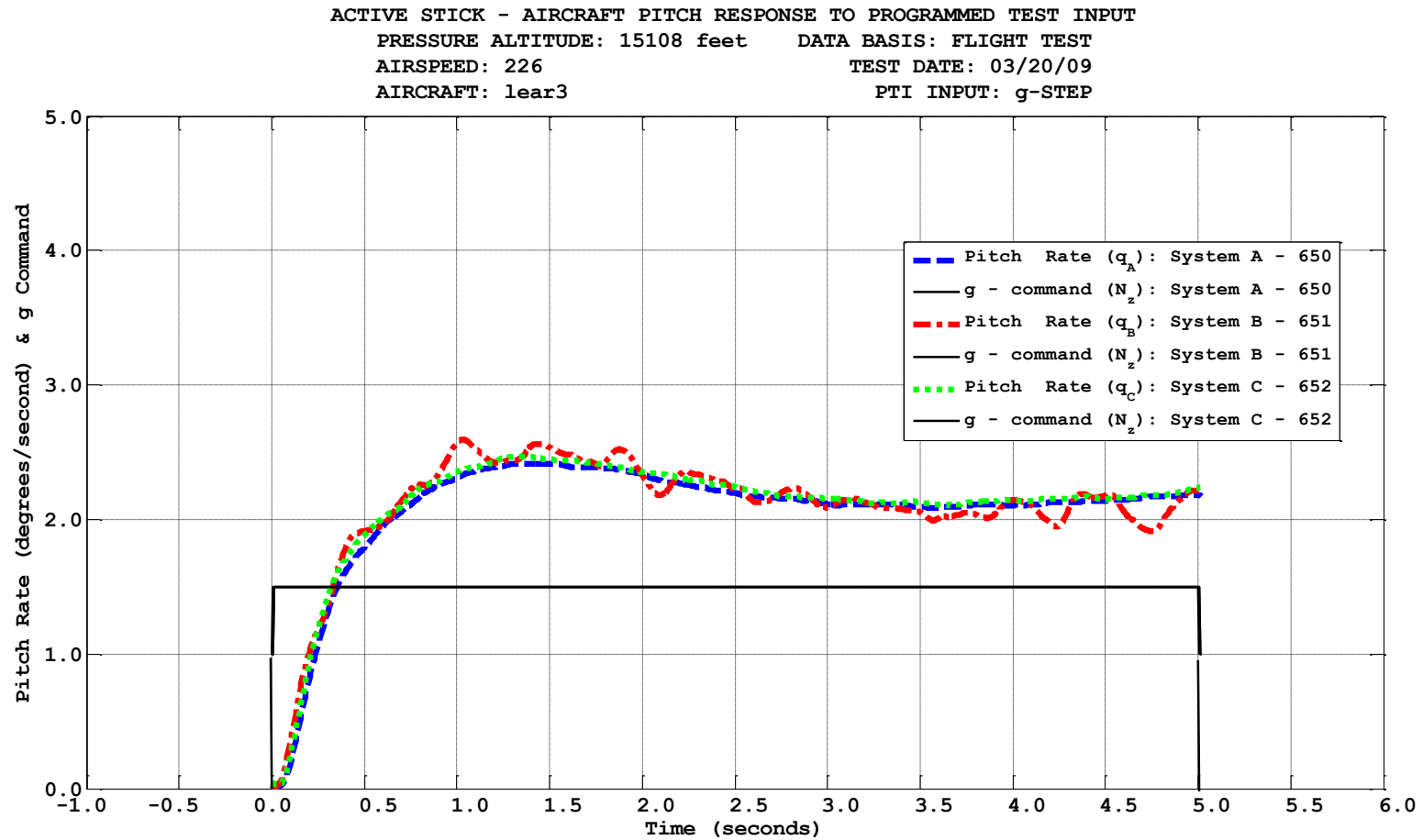


Figure C - 3: Pitch Rate Response to 1.5 g Commanded PTI at V_{CORNER}

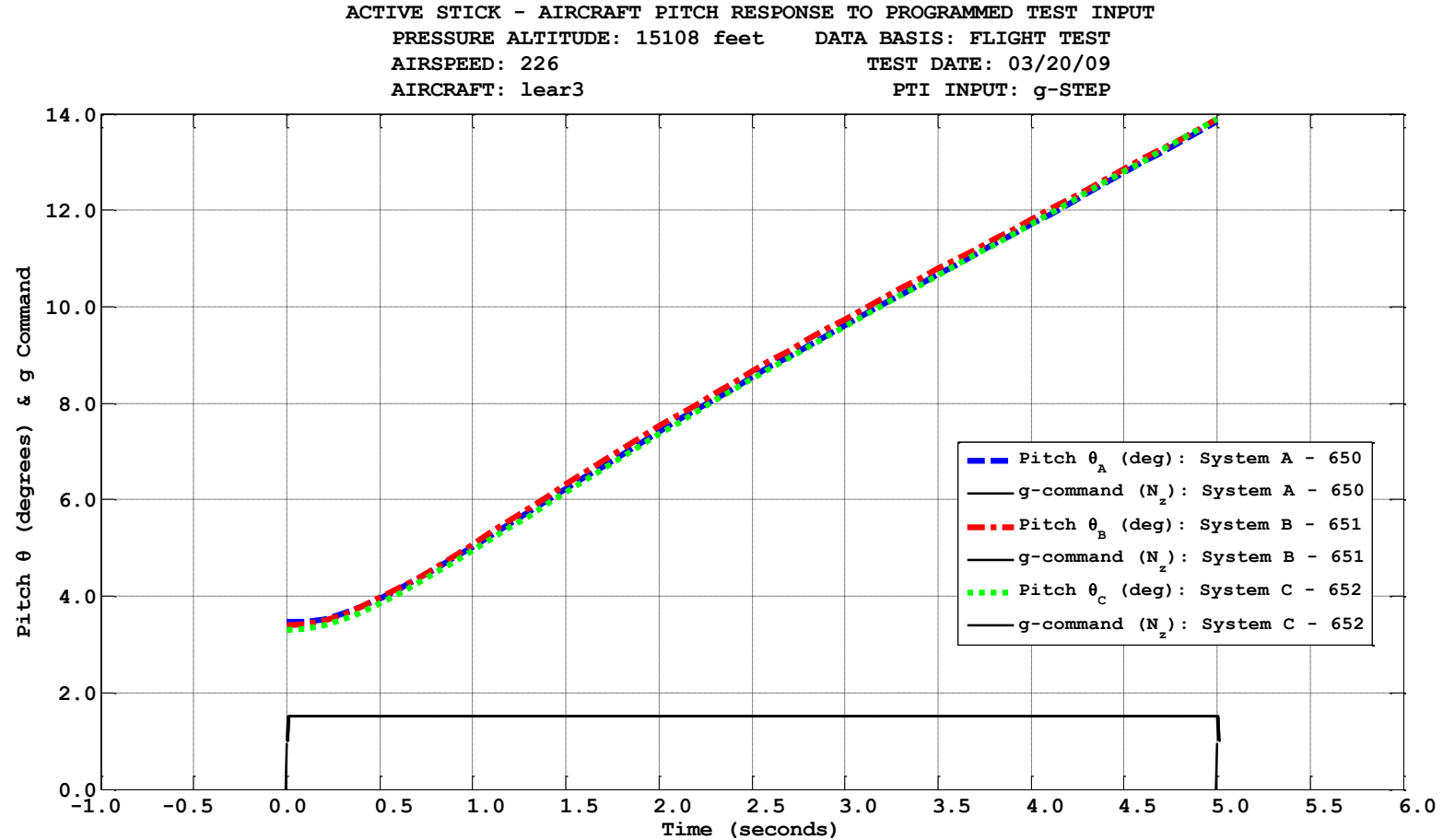


Figure C - 4: Pitch Angle Response to 1.5 g Command PTI at V_{CORNER}

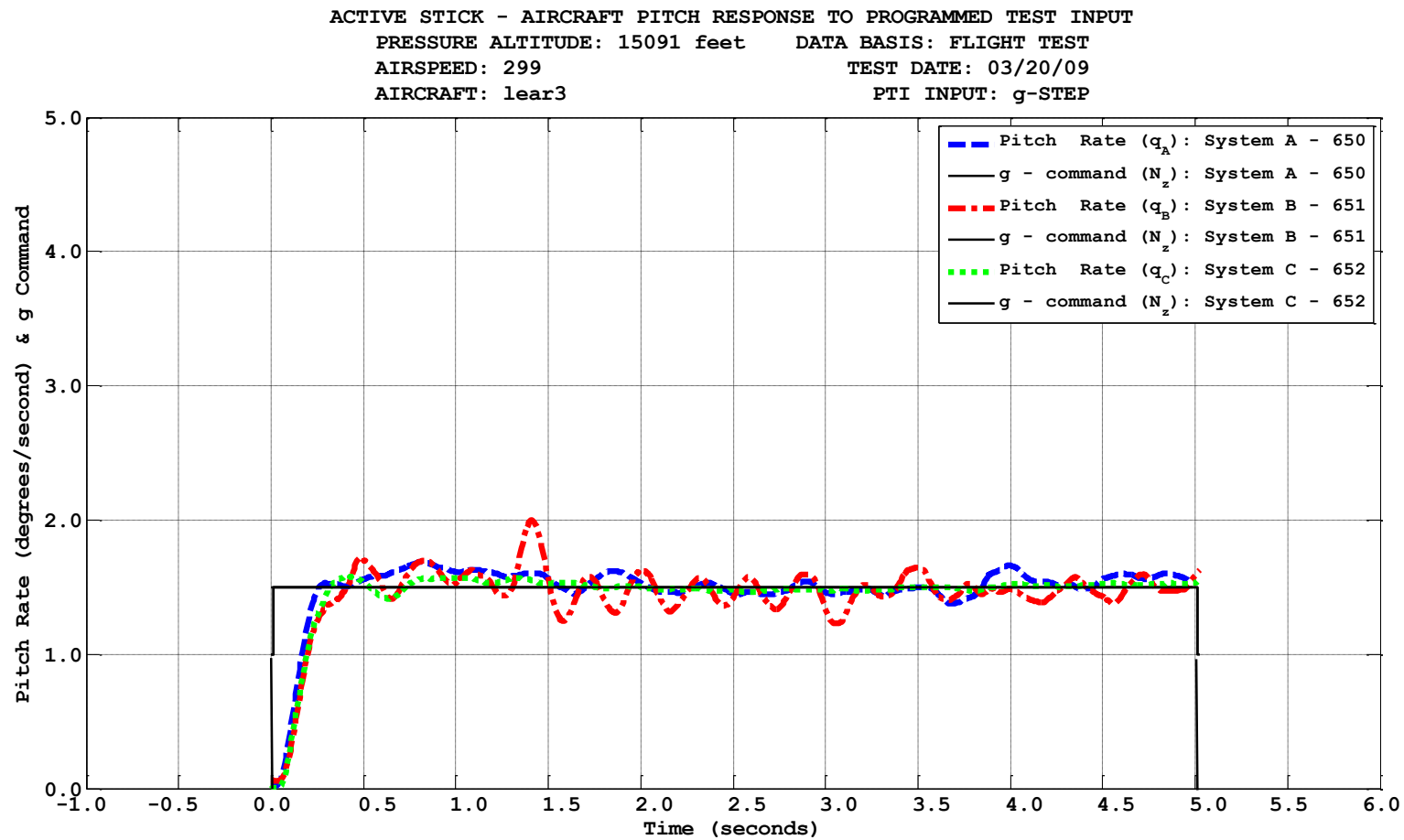


Figure C - 5: Pitch Rate Response to 1.5 g Commanded PTI at V_{HI}

ACTIVE STICK - AIRCRAFT PITCH RESPONSE TO PROGRAMMED TEST INPUT
PRESSURE ALTITUDE: 15091 feet DATA BASIS: FLIGHT TEST
AIRSPEED: 299 TEST DATE: 03/20/09
AIRCRAFT: lear3 PTI INPUT: g-STEP

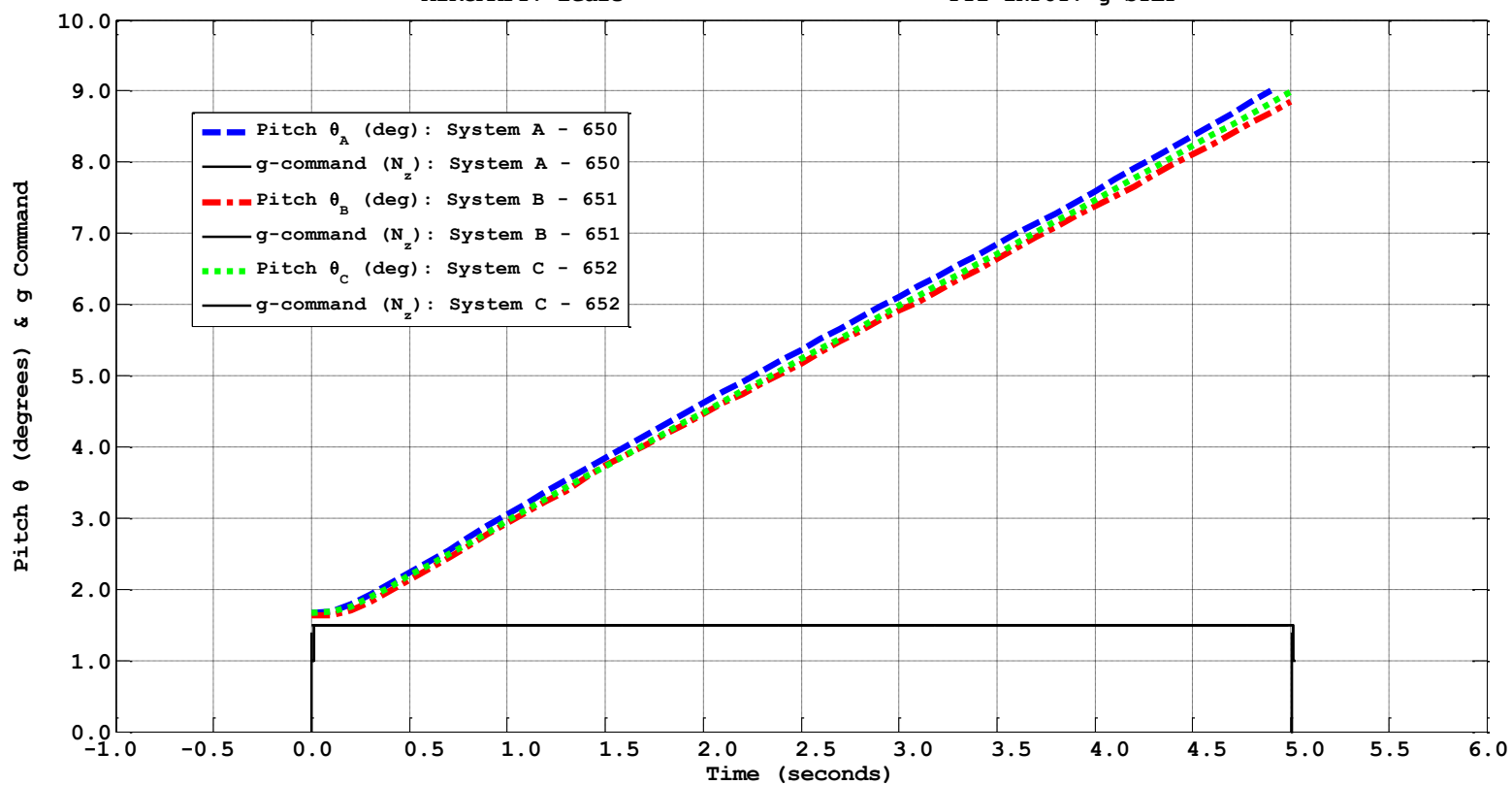


Figure C - 6: Pitch Angle Response to 1.5 g Command PTI at V_{HI}

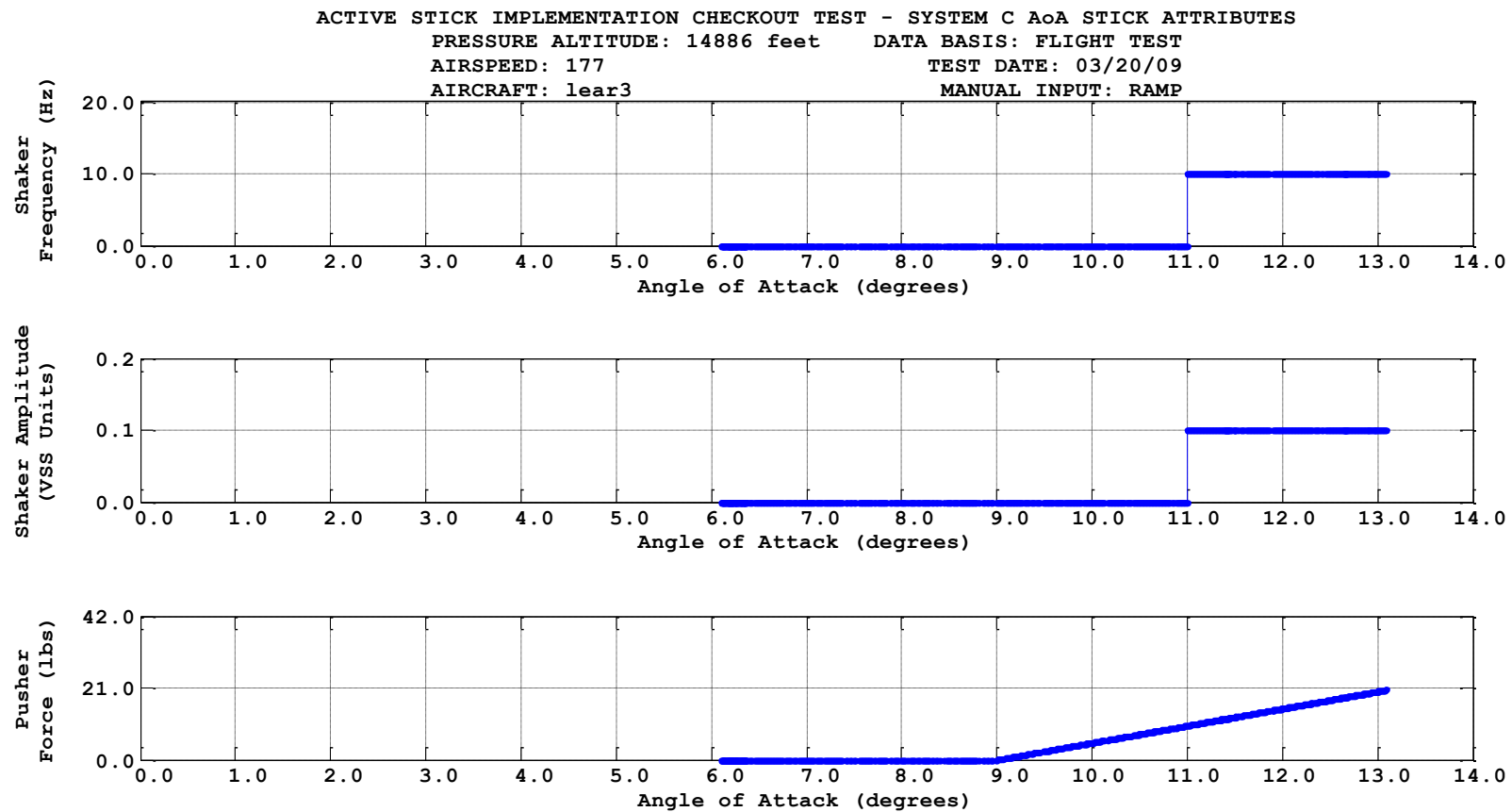


Figure C - 7: System C Angle of Attack Stick Attributes at V_{LO}

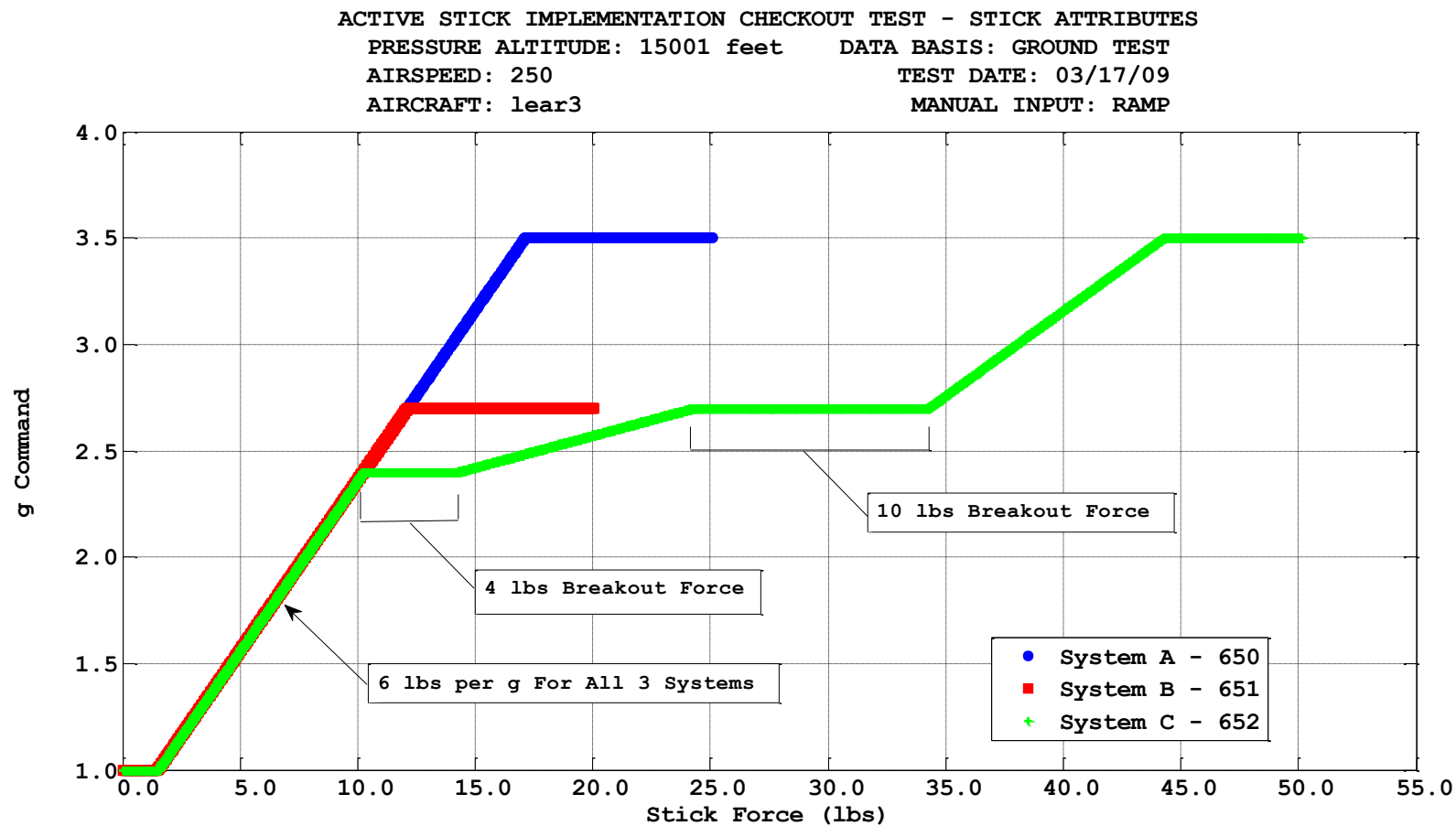


Figure C - 8: Stick Force (F_{es}) vs. Load Factor – Ground Test

ACTIVE STICK IMPLEMENTATION CHECKOUT TEST - STICK ATTRIBUTES

PRESSURE ALTITUDE: 15759 feet DATA BASIS: FLIGHT TEST

AIRSPEED: 304

TEST DATE: 03/20/09

AIRCRAFT: lear3

MANUAL INPUT: RAMP

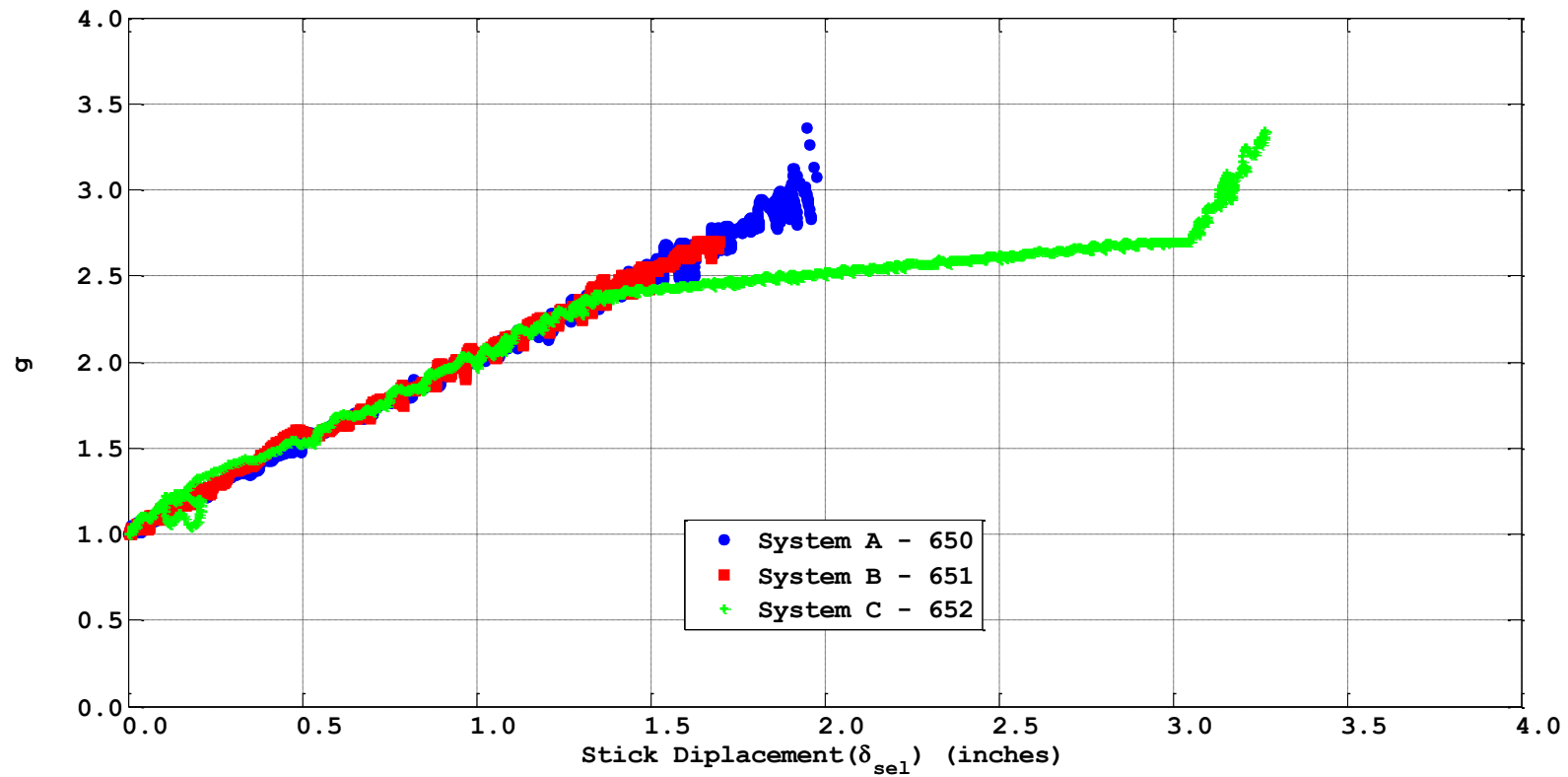


Figure C - 9: Stick Displacement vs. Load Factor – Flight Test

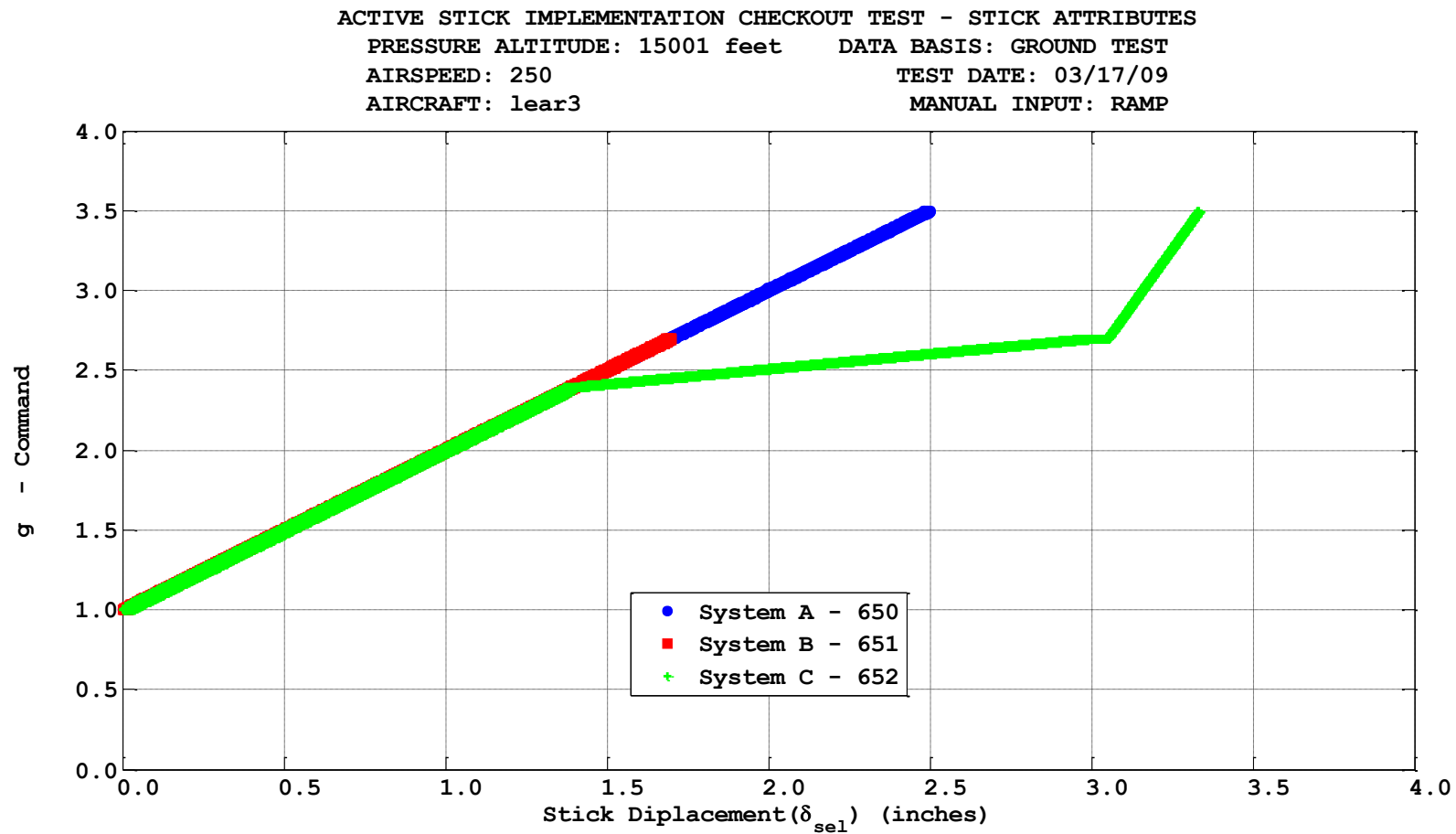


Figure C - 10: Stick Displacement vs. Commanded Load Factor – Ground Test

ACTIVE STICK IMPLEMENTATION CHECKOUT TEST - STICK ATTRIBUTES

PRESSURE ALTITUDE: 15759 feet DATA BASIS: FLIGHT TEST

AIRSPEED: 304

TEST DATE: 03/20/09

AIRCRAFT: lear3

MANUAL INPUT: RAMP

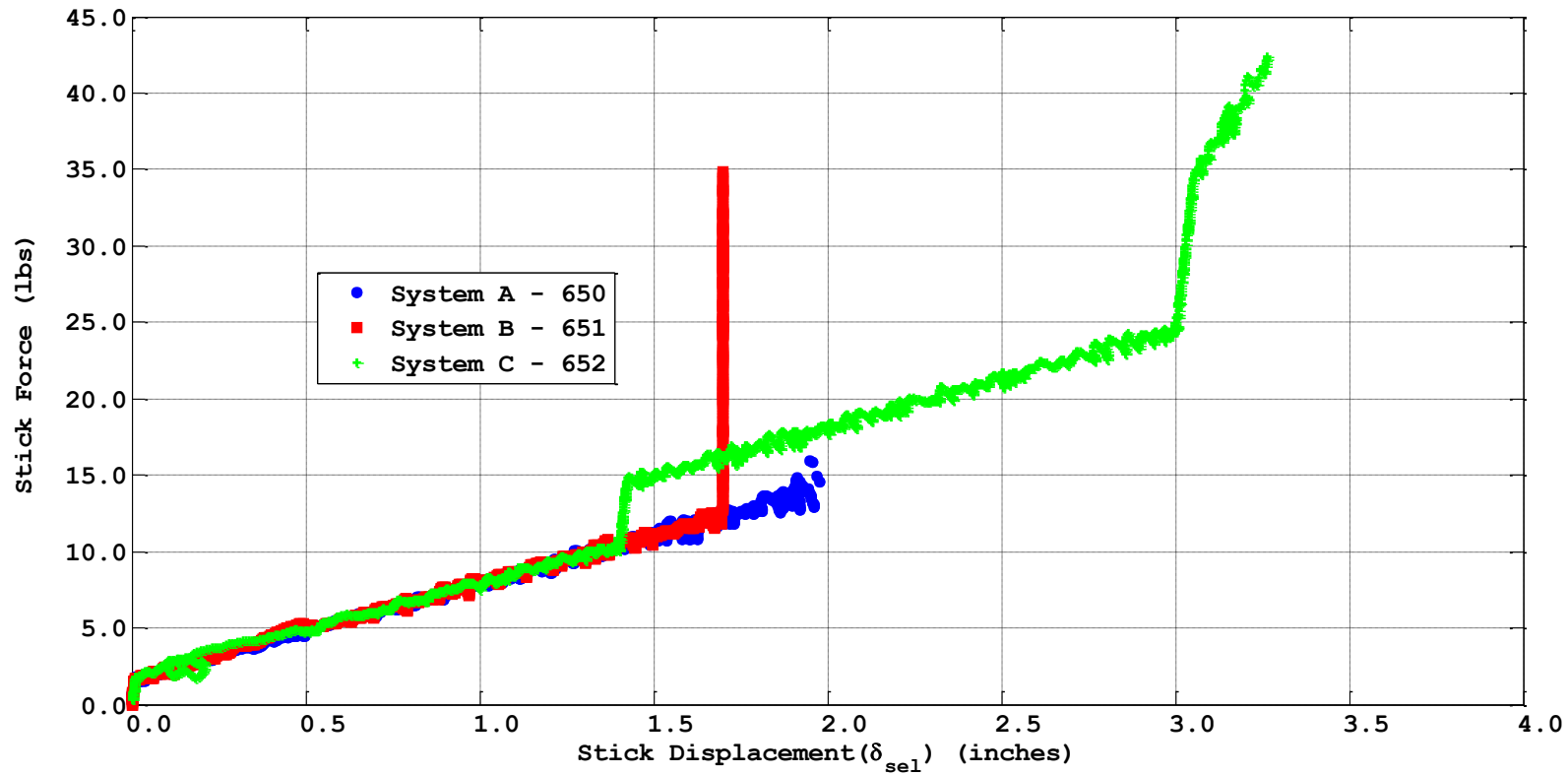


Figure C - 11: Stick Displacement vs. Stick Force – Flight Test

ACTIVE STICK IMPLEMENTATION CHECKOUT TEST - STICK ATTRIBUTES

PRESSURE ALTITUDE: 15001 feet DATA BASIS: GROUND TEST

AIRSPEED: 250

TEST DATE: 03/17/09

AIRCRAFT: lear3

MANUAL INPUT: RAMP

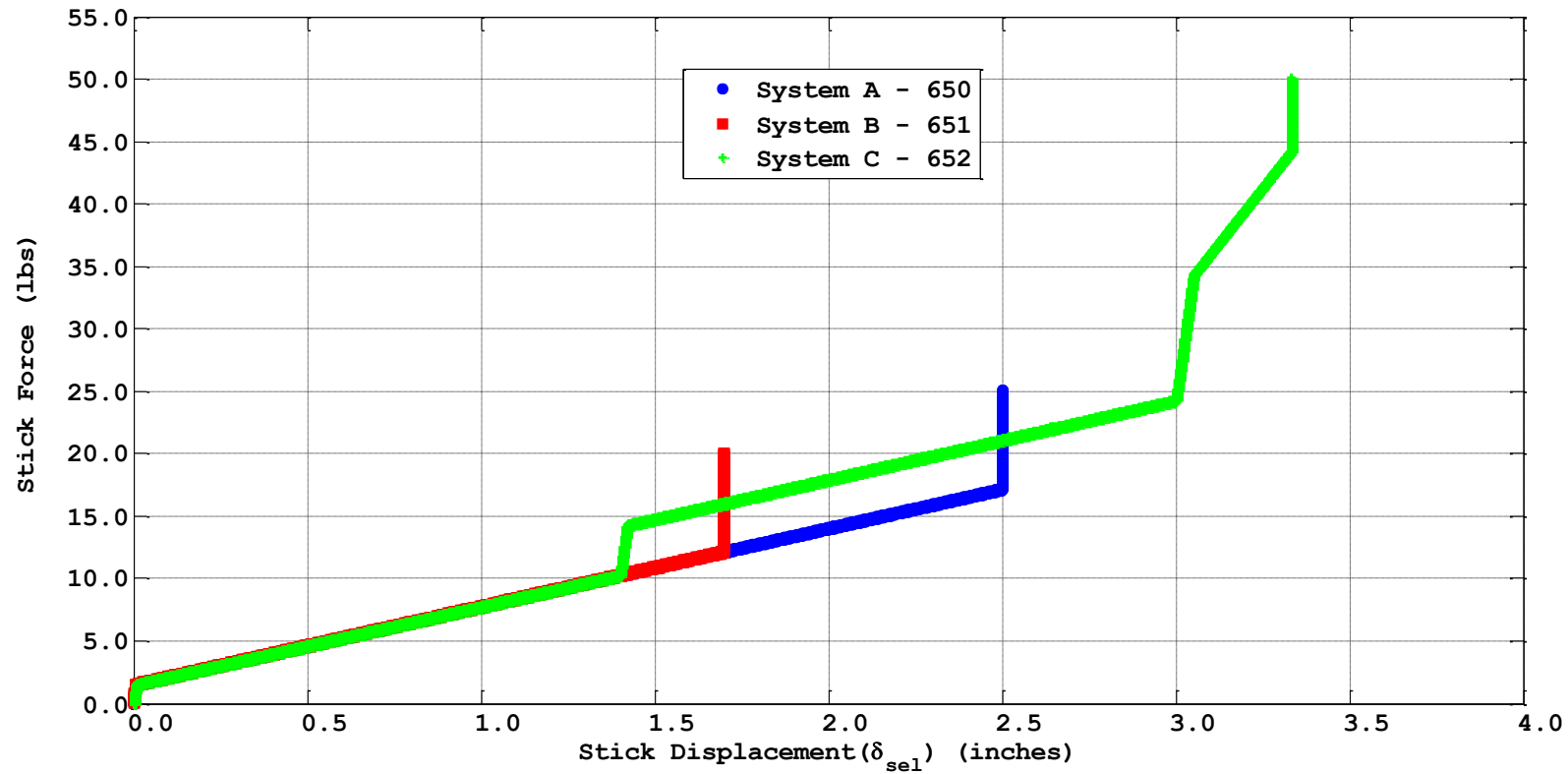


Figure C - 12: Stick Displacement vs. Stick Force – Ground Test

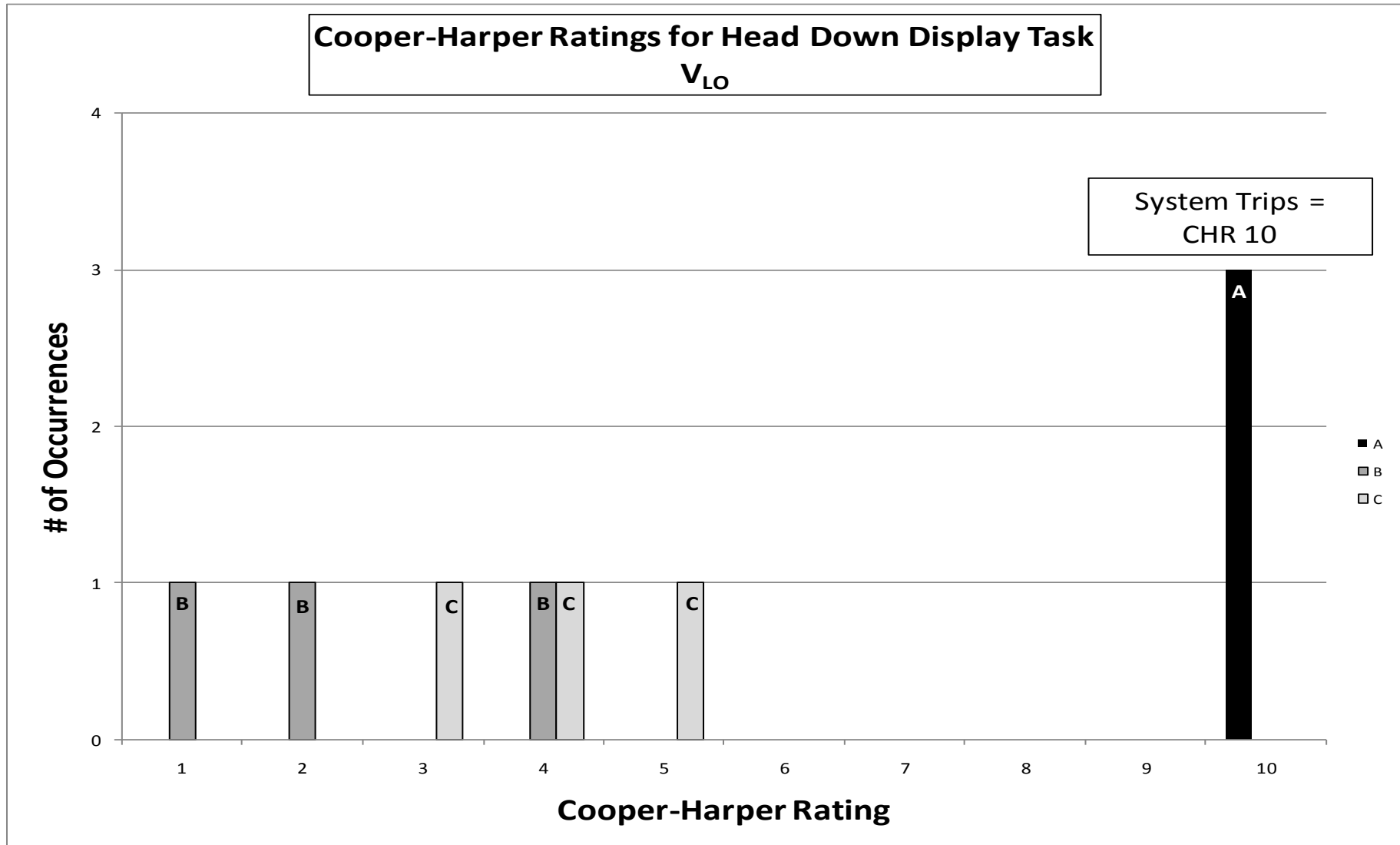


Figure C - 13: Cooper-Harper Ratings for Head Down Display Tracking Task V_{LO}

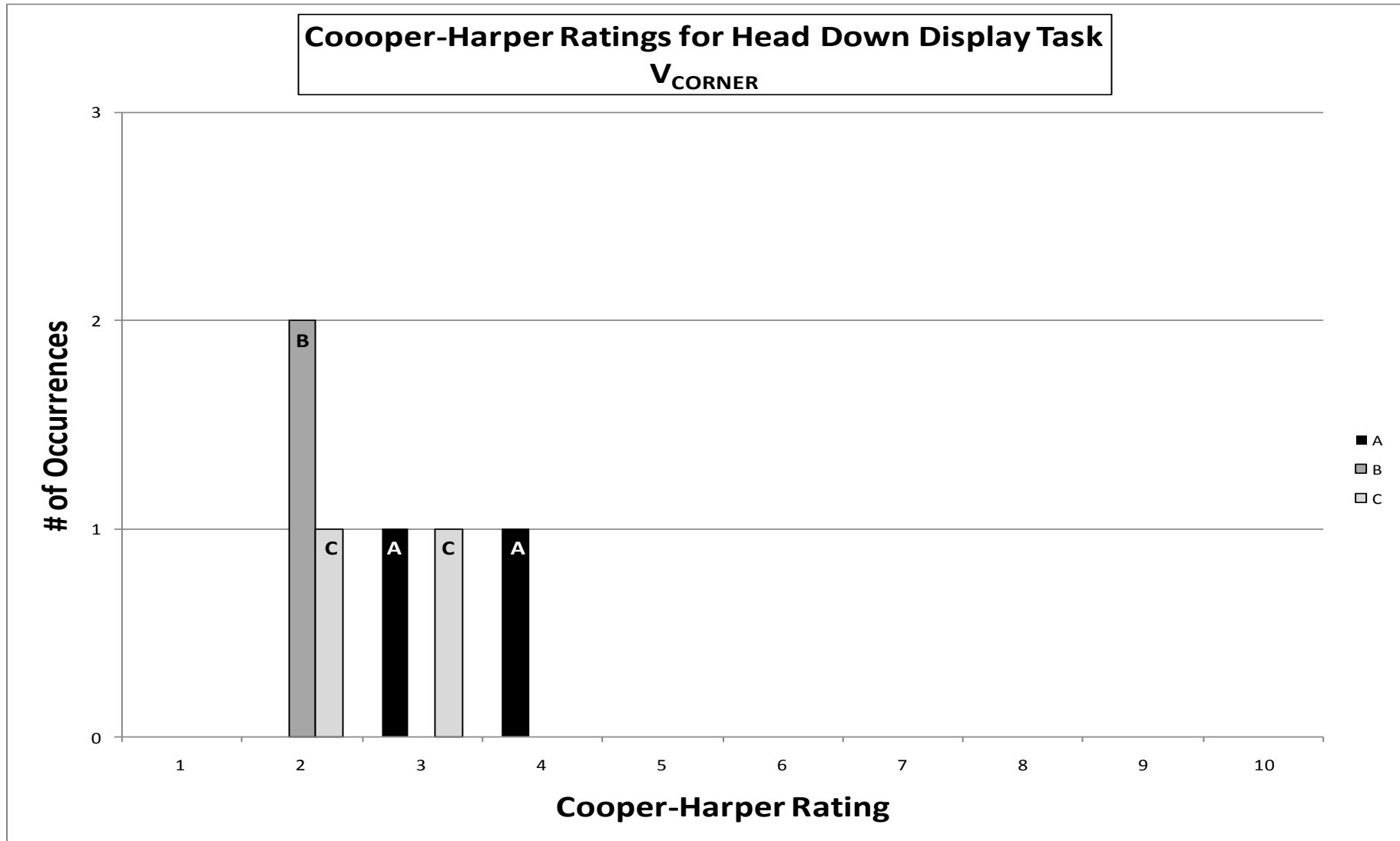


Figure C - 14: Cooper-Harper Ratings for Head Down Display Task V_{CORNER}

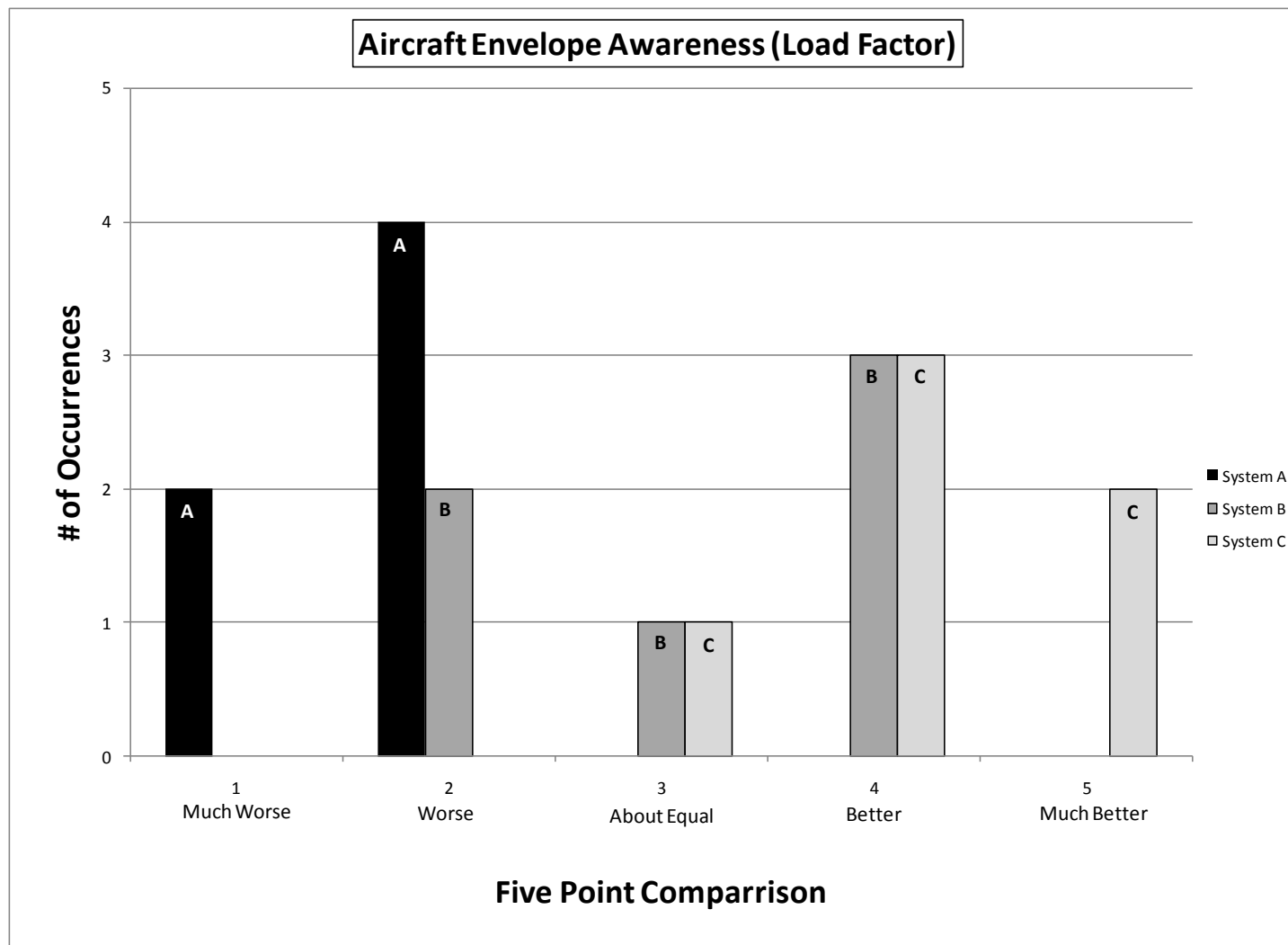


Figure C - 15: Aircraft Envelope Awareness (Load Factor)

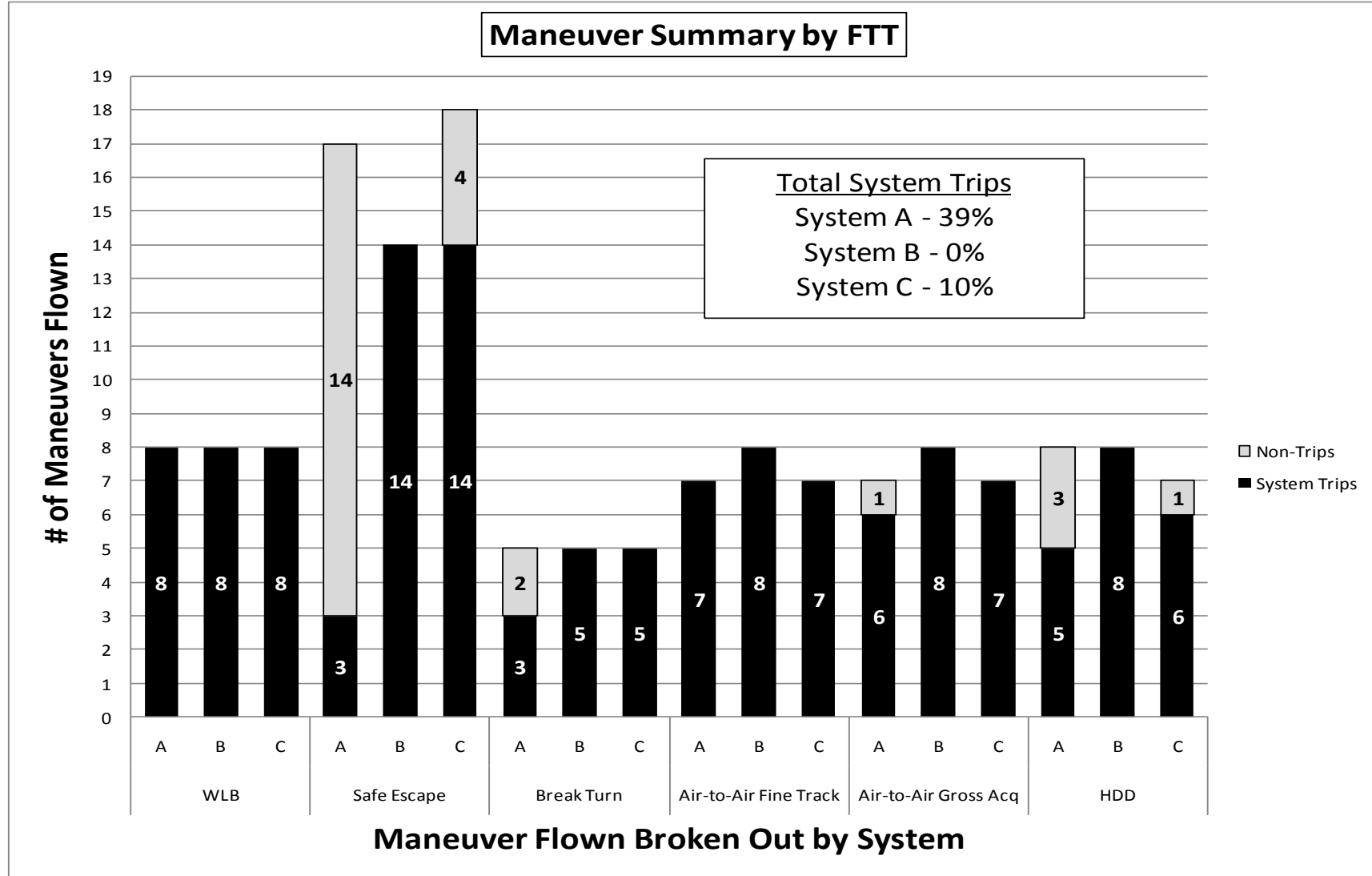


Figure C - 16: Total System Trips by FTT

APPENDIX D – COOPER-HARPER RATING SCALE

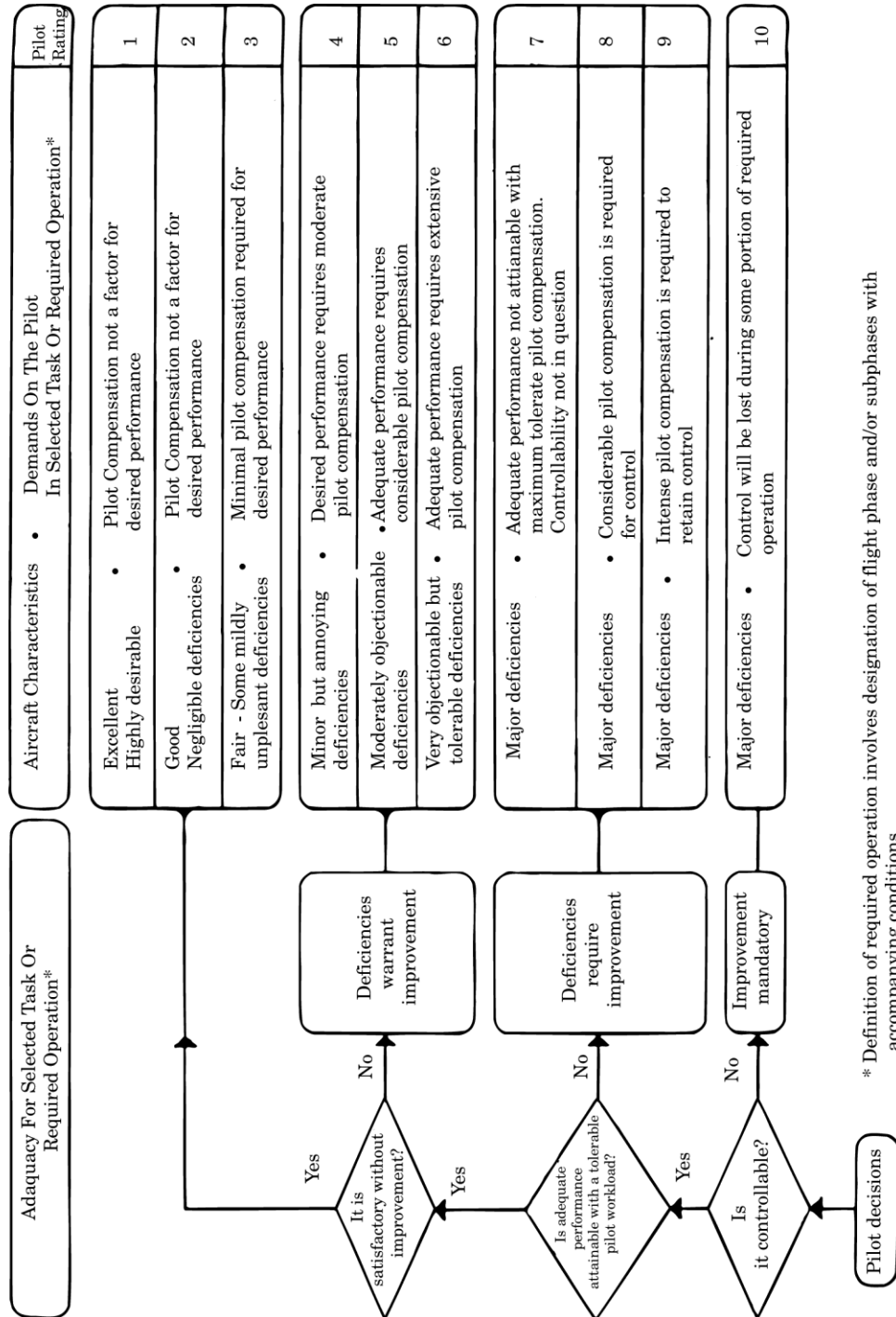


Figure D - 1: Cooper-Harper Rating Scale

APPENDIX E – PIO RATING SCALE

Did I experience PIO ?

No:

undesirable motion ?

no —————→ **1**

yes

tend to occur ? —→ **2**

easily induced ? —→ **3**

Yes:

abrupt or tight control ?

bounded ? —————→ **4**

divergent ? —————→ **5**

normal control ? —————→ **6**

Figure E - 1: PIO Rating Scale

APPENDIX F – ACTIVE STICK SIMULATOR MODEL

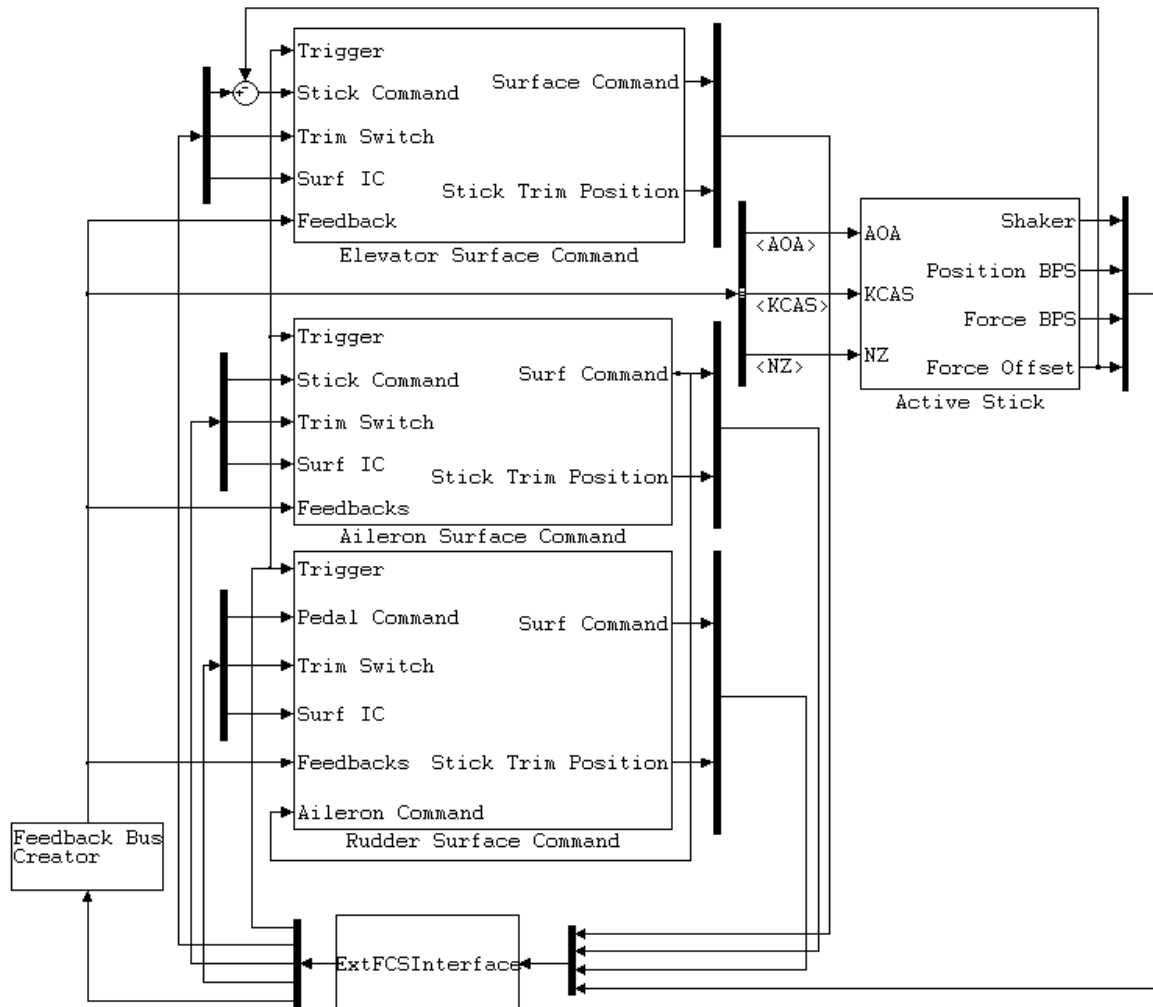


Figure F - 1: Top Level Active Stick Block Diagram

The top level simulator model shown in figure F-33 included control in the longitudinal, lateral, and directional axis. The simulator model was capable of simulating all three systems (A, B, and C). A Matlab M-file (next page) was used to define all the parameters for each system. Units used for stick deflection in the simulator were in degrees. Units used for stick deflection in the aircraft were in inches. The values in the Matlab M-file are representative of the values used in the aircraft.

```
%% This m-file defines variables for System A, B and C

%% These variables define the AOA attributes
AOA(1) = 9.0; %degrees
AOA(2) = 11.0; %degrees

%% Defines when AOA shaker starts
AOA_SHAKER = AOA(2);

%% AOA Shaker attributes
%   Can make the FREQ and AMP change with AOA if desired by giving a
start
%   value and a different end value; set values to zero to turn off
%   AOA shaker
AOA_FREQ(1) = 10; %Hz
AOA_FREQ(2) = 10; %Hz
AOA_AMP(1) = 0.1; %units depend on vehicle implementation (sim or
aircraft)
AOA_AMP(2) = 0.1; %units depend on vehicle implementation (sim or
aircraft)

%% This variable allows (system B) or denies (System A and C) AOA feedback
%   in the longitudinal flight control system
AOA_FB = 0; %Allows = (AOA_FB = 1); Denies (AOA_FB = 0)

%% These variables define the velocity shaker attributes;
%   set values to zero to turn off velocity shaker
VEL_SHAKER = 320; % Will shake at airspeeds above
VEL_FREQ = 20; %Hz
VEL_AMP = 0.1; %units depend on vehicle implementation (sim or aircraft)

%% These variables define the "bobweight" or "pusher" attributes;
%   set values to zero to turn of "bobweight" and/or "pusher"
AOA_WARNING = AOA(1); %turns on pusher at AOA(1) value
G_WARNING = 0; %turns on bobweight at specified loadfactor
LBS_PER_AOA_OVER = 5; % Slope of pusher for AOA
LBS_PER_NZ = 0; % Slope of pusher for Nz

%% These variables define the G-command at each soft/hard stop for System
C
MIN_G_CMD = -0.75;
NEGATIVE_G_BREAK = -0.3;
POSITIVE_G_BREAK_1 = 1.4;
POSITIVE_G_BREAK_2 = 1.7;
MAX_G_CMD = 2.5;

%% These variables define the G-command at each soft/hard stop for System
B
% MIN_G_CMD = NEGATIVE_G_BREAK;
% NEGATIVE_G_BREAK = -0.65;
% POSITIVE_G_BREAK_1 = 1.7;
% POSITIVE_G_BREAK_2 = POSITIVE_G_BREAK_1;
```

```

% MAX_G_CMD = POSITIVE_G_BREAK_1;

%% These variables define the G-command at each soft/hard stop for System
A
% MIN_G_CMD = NEGATIVE_G_BREAK;
% NEGATIVE_G_BREAK = -1.5;
% POSITIVE_G_BREAK_1 = 2.5;
% POSITIVE_G_BREAK_2 = POSITIVE_G_BREAK_1;
% MAX_G_CMD = POSITIVE_G_BREAK_1;

%% These variables define the position breakpoints as a function of
%   airspeed for System C
%   -Units depend on vehicle implementation (sim or aircraft)
%   -For a reversible system, set up flag in next section and input
values
%   under the 125 and 350 KIAS column
VELOCITY_BREAKPOINTS = [ 125    250    350]; % KIAS
NEGATIVE_POSITION_2 = [ 0.0   -2,167  0.0]; % inches
NEGATIVE_POSITION_1 = [ 0.0   -1.687  0.0]; % inches
POSITIVE_POSITION_1 = [ 0.0    1.4    0.0]; % inches
POSITIVE_POSITION_2 = [ 0.0    3.0    0.0]; % inches
POSITIVE_POSITION_3 = [ 0.0    3.33   0.0]; % inches

%% These variables define the position breakpoints as a function of
%   airspeed for System B
%   -Units depend on vehicle implementation (sim or aircraft)
%   -For a reversible system, set up flag in next section and input
values
%   under the 125 and 350 KIAS column
% VELOCITY_BREAKPOINTS = [ 125    250    350]; % KIAS
% NEGATIVE_POSITION_2 = [ 0.0    0.0    0.0]; % inches
% NEGATIVE_POSITION_1 = [ 0.0   -1.67   0.0]; % inches
% POSITIVE_POSITION_1 = [ 0.0    1.7    0.0]; % inches
% POSITIVE_POSITION_2 = [ 0.0    0.0    0.0]; % inches
% POSITIVE_POSITION_3 = [ 0.0    0.0    0.0]; % inches

%% These variables define the position breakpoints as a function of
%   airspeed for System A
%   -Units depend on vehicle implementation (sim or aircraft)
%   -For a reversible system, set up flag in next section and input
values
%   under the 125 and 350 KIAS column
% VELOCITY_BREAKPOINTS = [ 125    250    350]; % KIAS
% NEGATIVE_POSITION_2 = [ 0.0    0.0    0.0]; % inches
% NEGATIVE_POSITION_1 = [ 0.0   -1.67   0.0]; % inches
% POSITIVE_POSITION_1 = [ 0.0    2.5    0.0]; % inches
% POSITIVE_POSITION_2 = [ 0.0    0.0    0.0]; % inches
% POSITIVE_POSITION_3 = [ 0.0    0.0    0.0]; % inches

%% These variables determine the reversible aspects of the system
REVERSABLE = 0; % Zero will use a non-reversible stick
REF_SPEED = 250; % Reference speed when non-reversible system is selected

```

```

%% These variables define the forces in each section of the force curve
for
%     system C.
    NEGATIVE_FORCE_2 = 10;
    NEGATIVE_FORCE_BREAKOUT_1 = 4;
    NEGATIVE_FORCE_1 = 10;
    NEUTRAL_FORCE_BREAKOUT = 1.5;
    POSITIVE_FORCE_1 = 8.75;
    POSITIVE_FORCE_BREAKOUT_1 = 4;
    POSITIVE_FORCE_2 = 10;
    POSITIVE_FORCE_BREAKOUT_2 = 10;
    POSITIVE_FORCE_3 = 10;

%% These variables define the forces in each section of the force curve
for
%     system B.
%     NEGATIVE_FORCE_2 = 10;
%     NEGATIVE_FORCE_BREAKOUT_1 = 3.375;
%     NEGATIVE_FORCE_1 = 10.625;
%     NEUTRAL_FORCE_BREAKOUT = 1.5;
%     POSITIVE_FORCE_1 = 10.625;
%     POSITIVE_FORCE_BREAKOUT_1 = 3.375;
%     POSITIVE_FORCE_2 = 10;
%     POSITIVE_FORCE_BREAKOUT_2 = 10;
%     POSITIVE_FORCE_3 = 10;

%% These variables define the forces in each section of the force curve
for
%     system A.
%     NEGATIVE_FORCE_2 = 5;
%     NEGATIVE_FORCE_BREAKOUT_1 = 3.375;
%     NEGATIVE_FORCE_1 = 15.625;
%     NEUTRAL_FORCE_BREAKOUT = 1.5;
%     POSITIVE_FORCE_1 = 15.625;
%     POSITIVE_FORCE_BREAKOUT_1 = 3.375;
%     POSITIVE_FORCE_2 = 5;
%     POSITIVE_FORCE_BREAKOUT_2 = 10;
%     POSITIVE_FORCE_3 = 10;

%% Building the breakpoints for force
FORCE_BREAKPOINTS(1) = ...
    - NEGATIVE_FORCE_2 ...
    - NEGATIVE_FORCE_BREAKOUT_1 ...
    - NEGATIVE_FORCE_1 ...
    - NEUTRAL_FORCE_BREAKOUT;
FORCE_BREAKPOINTS(2) = FORCE_BREAKPOINTS(1)+NEGATIVE_FORCE_2;
FORCE_BREAKPOINTS(3) = FORCE_BREAKPOINTS(2)+NEGATIVE_FORCE_BREAKOUT_1;
FORCE_BREAKPOINTS(4) = FORCE_BREAKPOINTS(3)+NEGATIVE_FORCE_1;

FORCE_BREAKPOINTS(5) = FORCE_BREAKPOINTS(4)+NEUTRAL_FORCE_BREAKOUT*2;

FORCE_BREAKPOINTS(6) = FORCE_BREAKPOINTS(5)+POSITIVE_FORCE_1;
FORCE_BREAKPOINTS(7) = FORCE_BREAKPOINTS(6)+POSITIVE_FORCE_BREAKOUT_1;

```

```
FORCE_BREAKPOINTS(8) = FORCE_BREAKPOINTS(7)+POSITIVE_FORCE_2;  
FORCE_BREAKPOINTS(9) = FORCE_BREAKPOINTS(8)+POSITIVE_FORCE_BREAKOUT_2;  
FORCE_BREAKPOINTS(10) = FORCE_BREAKPOINTS(9)+POSITIVE_FORCE_3;
```

```
%% Building the breakpoints for G-command
```

```
G_CMD_BREAKPOINTS = [  
    MIN_G_CMD  
    NEGATIVE_G_BREAK  
    NEGATIVE_G_BREAK  
    0  
    0  
    POSITIVE_G_BREAK_1  
    POSITIVE_G_BREAK_1  
    POSITIVE_G_BREAK_2  
    POSITIVE_G_BREAK_2  
    MAX_G_CMD];
```

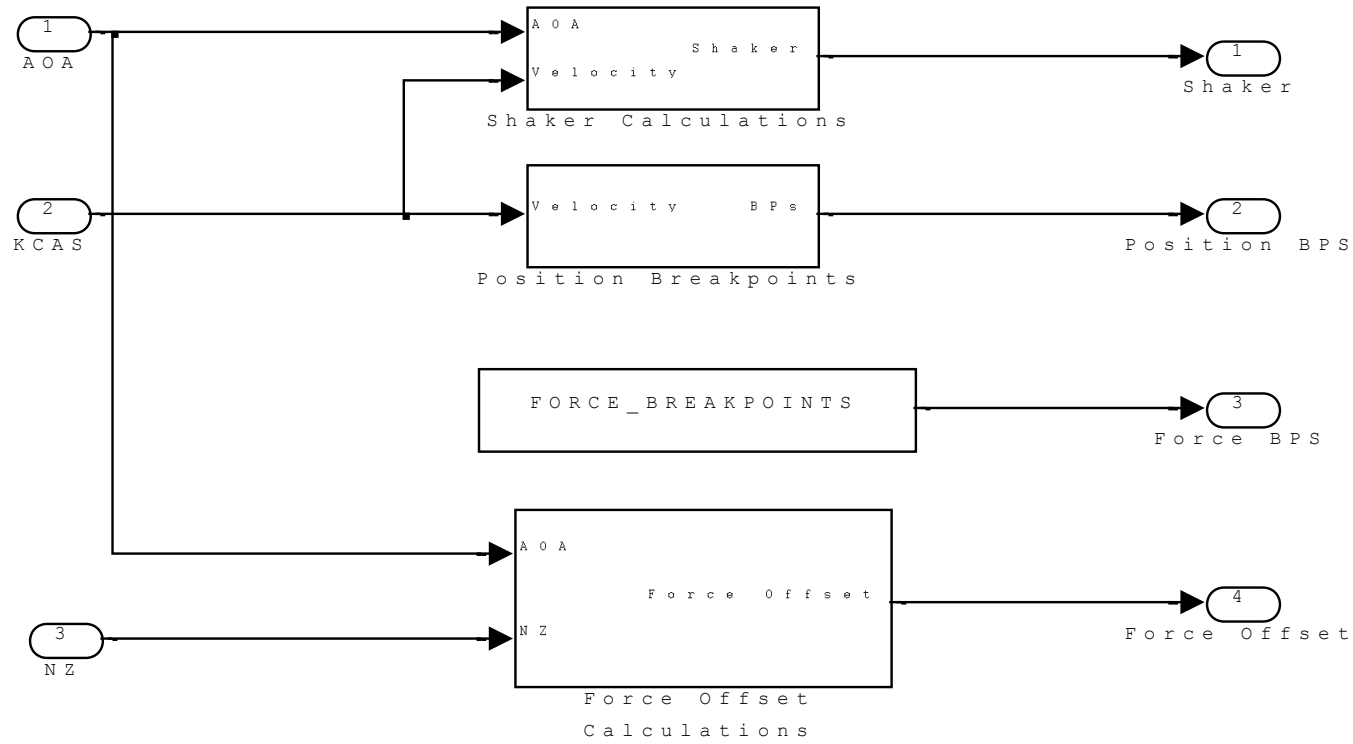


Figure F - 2: Active Stick Block

The Active Stick block was designed using breakpoints associated with forces and positions. These breakpoints allowed the Active Stick team to define any stick force gradient. The stick force gradient could include both soft and hard stops to provide aircraft envelope awareness and protection. The Active Stick block also provided feedback using a stick shaker that was a function of airspeed or angle of attack. Finally, the Force Offset block provided the means to add bobweight features associated with load factor or stick pushers associated with angle of attack. Figures F-35, F-36, and F-37 show the next level of each block in the active stick design.

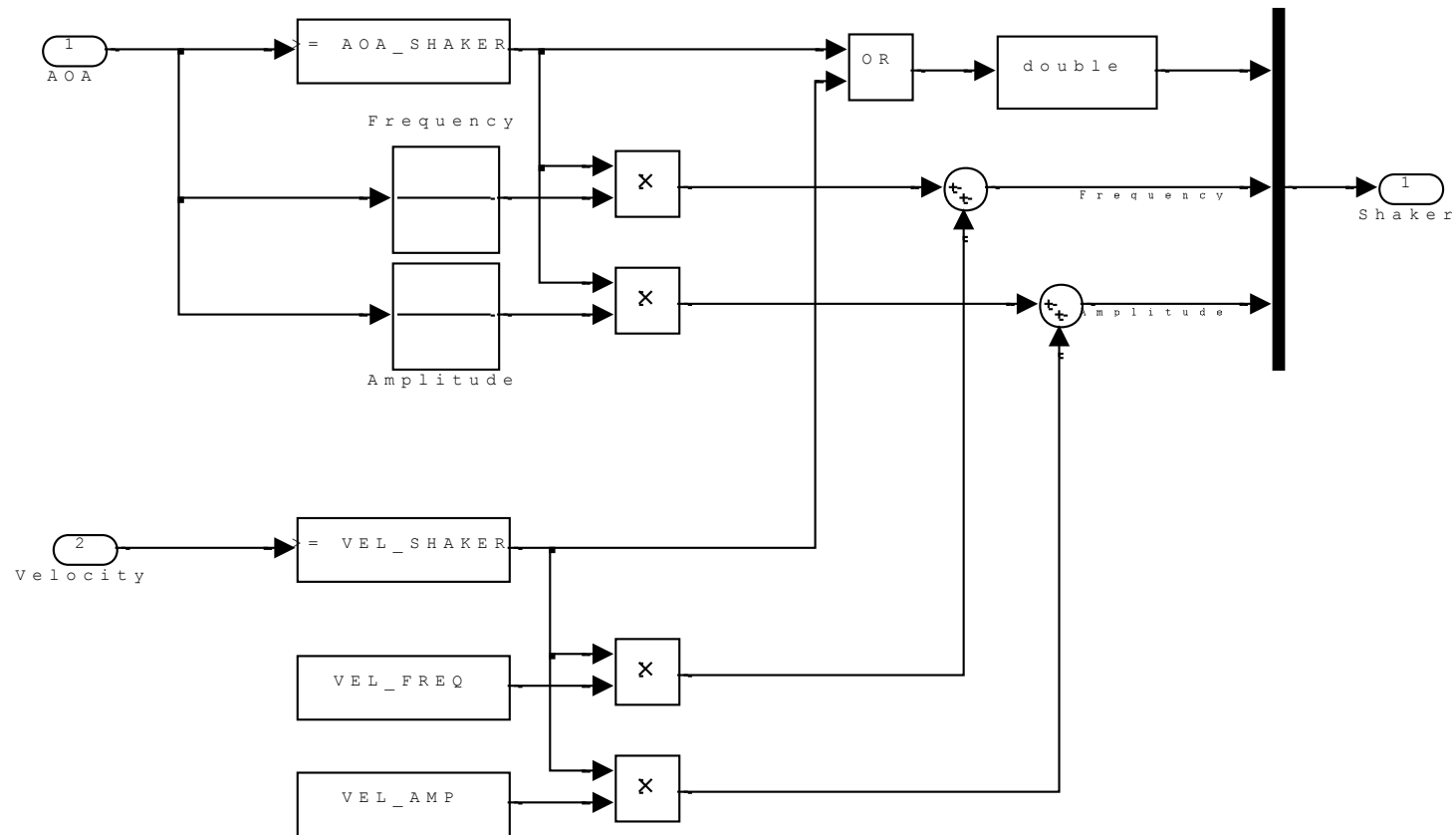


Figure F - 3: Shaker Calculations Block

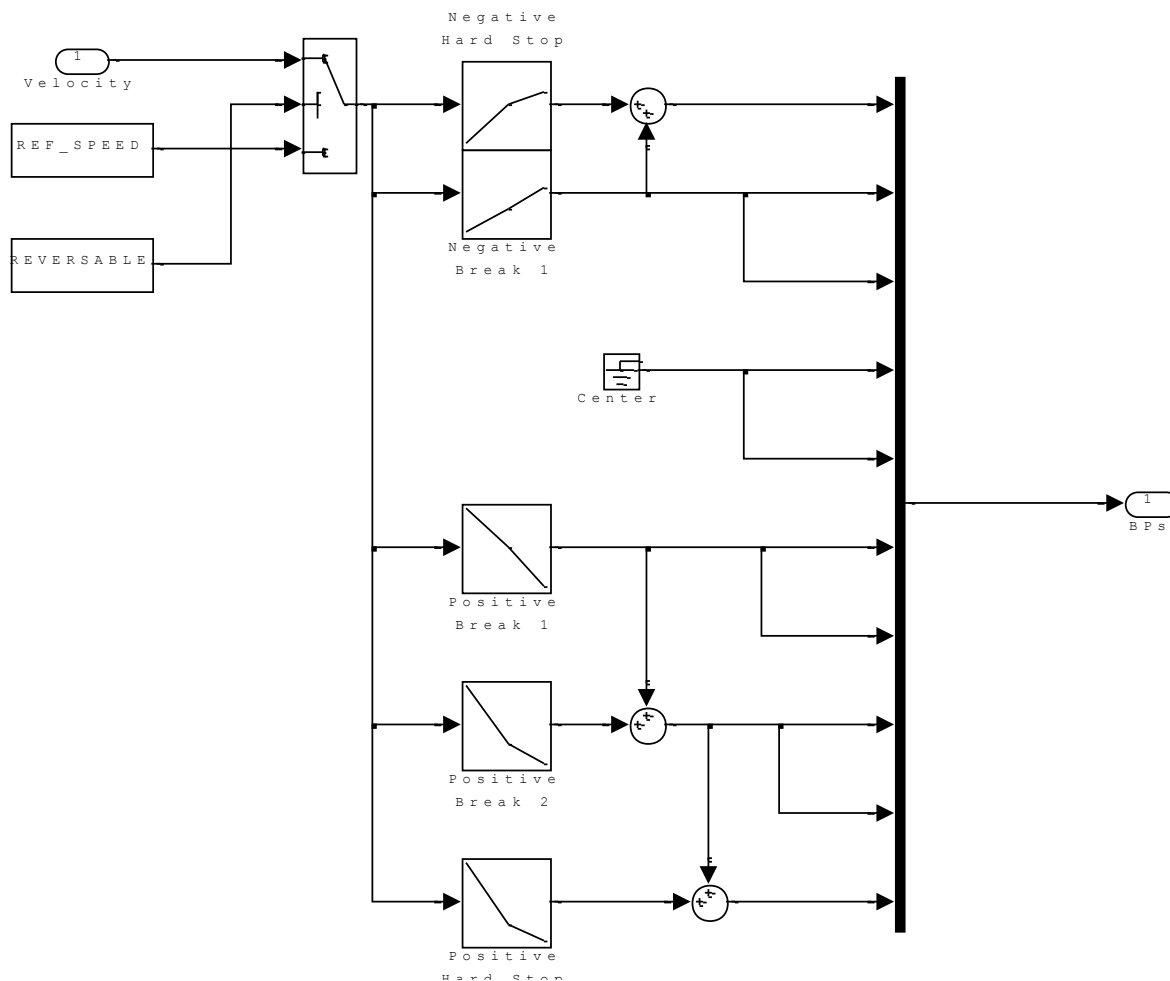


Figure F - 4: Top Level Active Stick Block Diagram

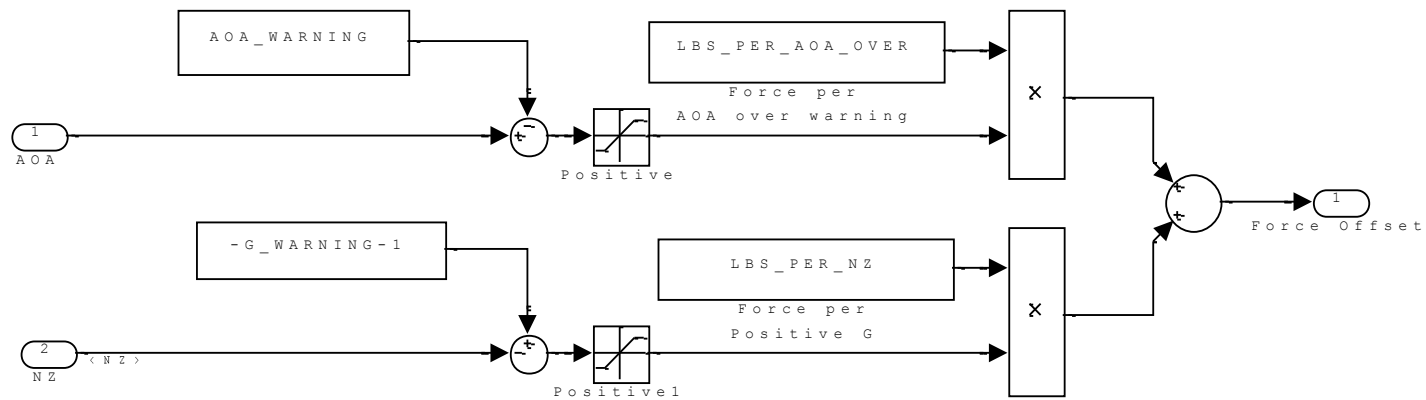


Figure F - 5: Force Offset Calculations Block

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