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Use of Active Inceptor Cueing to Mitigate Pilot-Vehicle System Loss of Control

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Loss of control has been identified as the leading cause of jet transport accidents. Recent high profile accidents have illustrated the need to address pilot response to upsets and unusual attitudes. Another issue no less important is that associated with pilot-vehicle system loss of control. This refers to those incidents that result from the pilot's active manual control of the aircraft and most commonly occur in the form of so called pilot-induced oscillations. Regardless of the implied "fault" of the pilot, these events result from issues with the airframe and flight control system and not the pilot. Examples described in this paper include events with modern fly-by-wire transports in commercial operation and flight test events associated with the evaluation of new adaptive control schemes under various failure conditions. While not always the root cause, flight control system nonlinearities such as control surface rate and position limits are key components in these events. To mitigate loss of control events of this type, force feedback via an active control inceptor and corresponding command path gain adjustments have been investigated using piloted simulation and flight test evaluations. This paper describes the development of effective pilot cueing techniques that make up the Smart-Cue/Smart-Gain system that addresses control surface actuator rate limiting and the Smart Adaptive Flight Effective Cue or SAFE-Cue that addresses more general flight control system nonlinear behavior, particularly that behavior associated with adaptive controllers.

I. Introduction

A study conducted by The Boeing Company of world-wide commercial jet transport accidents has found the most common events to be associated with loss of control.[1] Many of the events that result in loss of aircraft and fatalities result from the inability of the pilots to recover from upsets and unusual attitudes. Another class of loss of control events is associated with the pilot's attempt to tightly control the aircraft, often in response to some triggering event in the environment (e.g., turbulence or severe crosswinds) or aircraft (e.g., flight control system failures or unexpected transitions). While these incidents do not typically generate the same attention associated with upset loss of control events, a recent review conducted by the FAA found that pilot-vehicle system loss of control in the form of pilot-induced oscillations (PIO) continues to be a persistent problem in transport category aircraft often resulting in significant hull damage, injuries, and more rarely fatalities.[2] A summary of recent documented events for all aircraft types as well as a complete description of the interacting components of PIO can be found in Refs. 3 and 4.

To help mitigate these types of loss of control, recent work conducted by Systems Technology, Inc. for NASA Dryden Flight Research Center (DFRC) has focused on the use of active inceptor cueing together with adaptive

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command path gain adjustments to alert the pilot of the impending trouble and to constrain the resulting control actions of the pilot so that loss of control can be avoided. The first concept that was developed and evaluated via piloted simulation and flight test was the Smart-Cue/Smart-Gain system.[5,6] This system was designed to address loss of control scenarios associated with control surface actuator rate limiting, a primary contributor to all of the documented severe PIOs that have occurred with modern fly-by-wire aircraft.[7] Building on the Smart-Cue/Smart-Gain lessons, a new concept, the Smart Adaptive Flight Effective Cue or SAFE-Cue, is now in development as a means to mitigate pilot-vehicle system loss of control in the presence of an active adaptive control system.[8]

The basic Smart-Cue idea is to restore in a fly-by-wire system configuration a force feedback cue akin to an actuator "valve-bottoming" characteristic.[5] Note that Smart-Cue can be applied to non-FBW manual control systems as well; however, the implementation may be more hardware intensive. Cueing and corrective forces, the Smart-Cue, are presented to the pilot as a "proprioceptive display." Following checkout flight tests where the Smart-Cue alone had limited success, piloted simulation was used to rapidly prototype the Smart-Gain concept. Past work includes the PIOS filter used on the space shuttle that employs command path gain reduction techniques.[9] Such techniques estimate the frequency of the pilot's input and then attenuate the input as a function of this frequency. The approach does not, however, take the response of the control system into consideration, so the pilot input is attenuated whether or not it is needed. With the Smart-Gain, the pilot input is attenuated as a function of the same measured Position Error used to define the Smart-Cue. The feasibility of the Smart-Cue/Smart-Gain approach using an active control inceptor implemented in a variable stability aircraft was successfully demonstrated in a flight test program conducted with five evaluation test pilots.[6]

The Smart-Cue/Smart-Gain approach served as the launching point for the SAFE-Cue development in a Phase 1 Small Business Innovation Research program. The lessons learned from the previous work allowed the program to advance beyond the normal breadth of a Phase 1 to the point where SAFE-Cue mechanizations were evaluated formally in a simulator by experienced test pilots.[8] The SAFE-Cue innovative cueing system provides force feedback to the pilot via an active control inceptor with corresponding command path gain adjustments based on a measured System Error between the adaptive controller response and a nominal system response. The SAFE-Cue alerts the pilot that the adaptive control system is active, provides guidance via force feedback cues, and attenuates commands, thus ensuring pilot-vehicle system stability and performance in the presence of damage or failures. While the focus in this work, now in Phase 2, is on an adaptive controller, the SAFE-Cue concept is completely general and can be applied to any flight control system implementation as a means to mitigate loss of control.

This paper continues with a description of the methods used to quantify system behavior when approaching a so-called flying qualities cliff. This is followed by a discussion of the various force feedback cueing methods that have been explored thus far. Next, the adaptive command path gains are described followed by a summary of the results and lessons learned from piloted simulation and flight test activities. Finally, concluding remarks are given.

II. Quantifying the Flying Qualities Cliff

A. Defining the Flying Qualities Cliff

When approaching instability, linear system performance degrades in a manner that is predictable to a pilot. As nonlinearities are introduced, however, gradual degradations can be replaced by sudden changes in aircraft behavior resulting in the so called "flying qualities cliff." With few warning signs provided by the aircraft as one approaches such a cliff, loss of control can easily occur. An example divergent PIO is shown in Figure 1.[6] In this example the pilot is attempting a precision offset landing with an aileron maximum rate of ±30 deg/s. The rate limit nonlinearity results in a diverging PIO as the pilot attempts the final centerline capture. Fortunately, the likelihood of finding a flying qualities cliff in transport category aircraft outside of flight test is rare. Of course, this also means that pilots are typically not prepared to respond when such an encounter occurs. To provide an effective alerting and, if necessary, constraining mechanism, one must first be able to identify an impending cliff. In the case of control surface rate limiting, for example, it is not good enough to simply identify when the rate limiter is active. Because of the nature of rate limiting[7], an aircraft can routinely operate at or near a rate limit without threat of loss of control. Thus to alert the pilot of an active rate limit would diminish the effectiveness of the alert due to the number of false alarms.

For Smart-Cue/Smart-Gain and SAFE-Cue the concept of dynamic distortions[5] is used to define potential flying qualities cliffs. The common theme in both concepts is that the actual flight control system is in some way deviating from an ideal system. The pilot is expecting one type of response, but the actual system is behaving differently because of the distortion in the dynamic system response. Within this general context Ralph A'Harrah of NASA

Headquarters (now retired) proposed the “Loss of Control Inhibition System” (LOCIS)[*] wherein distortions are detected and constraining hard stop-like cues are then introduced to the pilot. It was recognized at the time that this was still a general concept that had yet to be made concrete or specific. It served as a motivation for the Smart-Cue/Smart-Gain development to attempt to quantify such conceptual terms as “distortions” and “idealized systems” as innovative and unifying principles underlying the development of corrective measures in the form of inceptor force feedback cues and later command path gain adjustments.

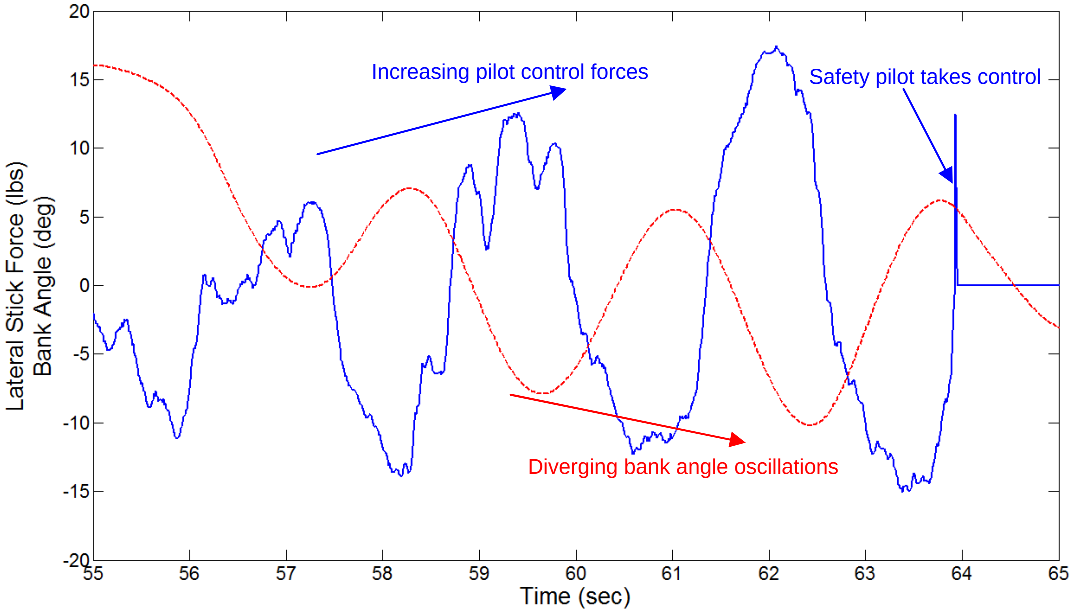

Figure 1: Example flight test divergent PIO.

B. The Smart-Cue/Smart-Gain Position Error

As discussed in the Introduction, the Smart-Cue/Smart-Gain concept was designed to mitigate the impact of control surface rate limiting, where deviation from desirable values under highly saturated conditions has been shown to lead to PIO in some circumstances.[7] To determine the magnitude of the cueing force or the extent of the command path gain attenuation, a commanded surface position (δ_c) and actual surface position (δ) are used to define a Position Error (δ_{error}) via an ideal linear system (δ_{ideal}) as shown in Figure 2. Here, the Position Error is the difference between the ideal linear system response and the actual manual flight control system response, $\delta_{error} = \delta_{ideal} - \delta$. The Position Error thus reflects differences due to distortions in the actual system. The magnitude of this difference increases as the pilot-vehicle system approaches a flying qualities cliff.

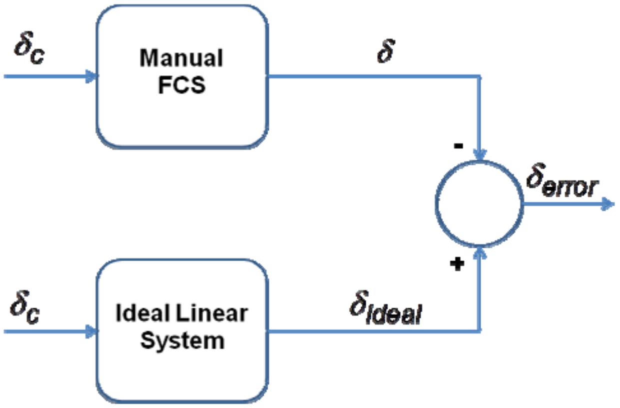

Figure 2: Smart-Cue/Smart-Gain control surface Position Error measure.

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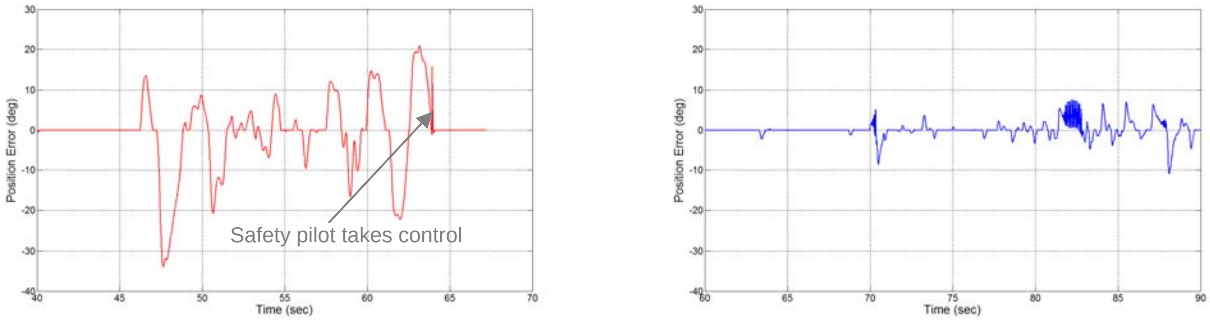
[*] The A’Harrah LOCIS concept was awarded two US Patents (#7,285,932 and #7,285,933).

Two flight test examples of Position Error measurements are shown in Figure 3. Both examples are lateral axis cases as the pilot attempted a precision offset landing with an aileron maximum rate of ±30 deg/s.[6] The Position Error displayed in the Figure 3a plot was generated from a rate limited only run shown in Figure 1. This run is characterized by a large error near 47 seconds that is associated with the initial correction to the runway centerline and Position Errors that are increasing in amplitude beginning at 57 seconds that are associated with the final centerline capture. Note that because of the resulting PIO, the safety pilot took control of the aircraft as indicated after the third diverging oscillation. In Figure 3b the Position Error measured from a Smart-Cue/Smart-Gain run is shown. In this case the maximum aileron rate was again ±30 deg/s. In this example the magnitude of the measured Position Error is greatly reduced when compared to the rate limit only case. Furthermore, the pilot was able to complete the task with no tendency for PIO. There is a noted numerical oscillation in the Position Error just past 82 seconds, but this artifact had no impact on the task performance.



a) Rate limit only case

b) Rate limit plus Smart-Cue/Smart-Gain

Figure 3: Position Error measures for two precision offset landing flight test example runs.

C. The SAFE-Cue System Error

Like the Position Error for Smart-Cue/Smart-Gain, the System Error computation is a key function of the SAFE-Cue mechanization. In general, to compute the error a comparison is made between a model-based nominal system response and the adaptive control system response. The difference between the selected signals is the System Error. As part of the Phase 1 program, the use of both the elevator surface position and the pitch rate output signal were explored analytically and in the simulator. As described above the elevator surface position was a useful measure for the Smart-Cue/Smart-Gain implementations where the concern was control surface rate limiting, an isolated flight control system element. This measure was not, however, appropriate with an active adaptive controller. The adaptive controller is attempting to compensate for an elevator surface failure, so any error computation between the adaptive and nominal systems based on this parameter will result in SAFE-Cue actions that attempt to suppress the actions of the adaptive controller. In contrast, a System Error measure based on the pitch rate output as illustrated in the Figure 4 block diagram allows for a direct comparison between the response of the adaptive and nominal systems. That is, the adaptive controller is attempting to restore the response of the nominal system in the presence of a failure or damage. As the responses of these two systems diverge, the error will build, thus providing the measure needed from which to activate the SAFE-Cue feedback force and command path gain reduction.

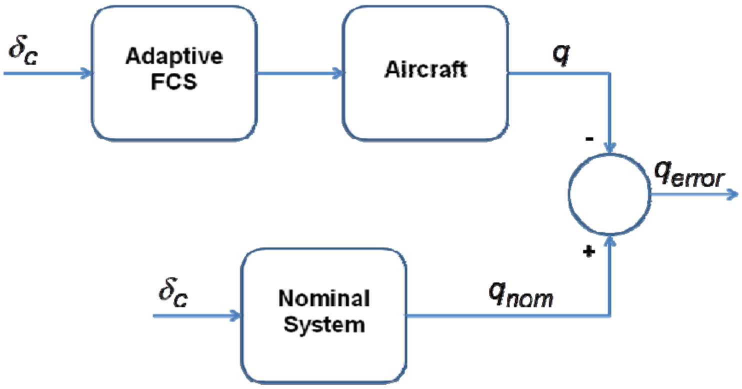
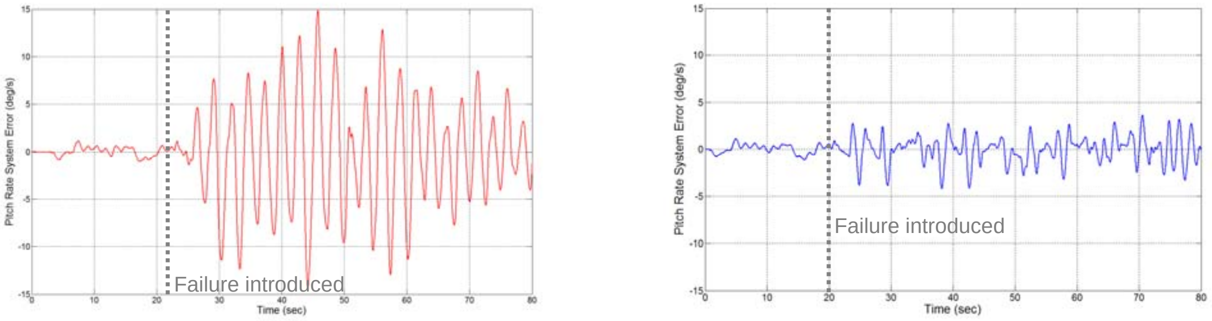


Figure 4: SAFE-Cue pitch rate System Error measure.

Two System Error examples from a piloted simulation evaluation of the SAFE-Cue concept are shown in Figure 5. Both examples are from a scenario in which there is a 25% reduction in elevator effectiveness and corresponding reductions in the elevator rate and position limits from the nominal values of 60 deg/s and ±30 deg to 15 deg/s and ±20 deg, respectively. In both cases the pilot was performing a pitch axis tracking task.[8] For the failure only case of Figure 5a, large System Error oscillations develop soon after the failure is introduced at approximately 22 seconds and persist for the remainder of the run. In sharp contrast is the elevator failure with SAFE-Cue active case of Figure 5b. While the System Error does increase after the failure is introduced at approximately 20 seconds, the magnitude remains bounded with peak values that remain below ±4 deg/s.



a) Elevator failure only case

b) Elevator failure plus SAFE-Cue

Figure 5: System Error measures for two piloted simulation example runs.

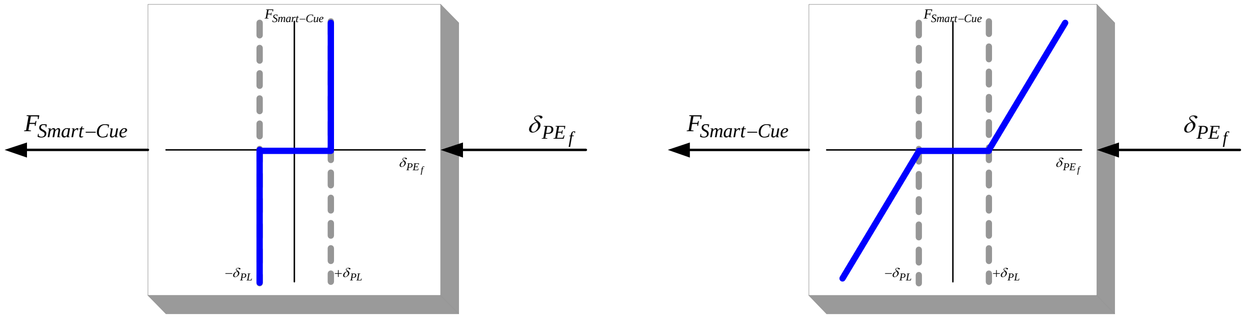
III. Building a Better Cue

Although the fundamental force feedback concept has remained essentially fixed, many options are available regarding how the Smart-Cue or SAFE-Cue is mechanized and integrated within a modern flight control system. As the force feedback cue builds, it first provides an alerting function of an impending flying qualities cliff. Then as the force increases, it provides a constraining function, so that inputs that may lead the pilot-vehicle system over the cliff will be avoided. For the Smart-Cue, piloted simulation was used to evolve the mechanizations that were eventually evaluated in flight. A number of feedback force options were considered individually and in various combinations. Options included a force that produced an effective spring gradient change, a coulomb friction force, and damping forces based on control stick velocity and the rate of change of the Position Error. For the initial SAFE-Cue mechanizations, lessons learned from the Smart-Cue simulator and flight test evaluations were used to more rapidly define effective design options.

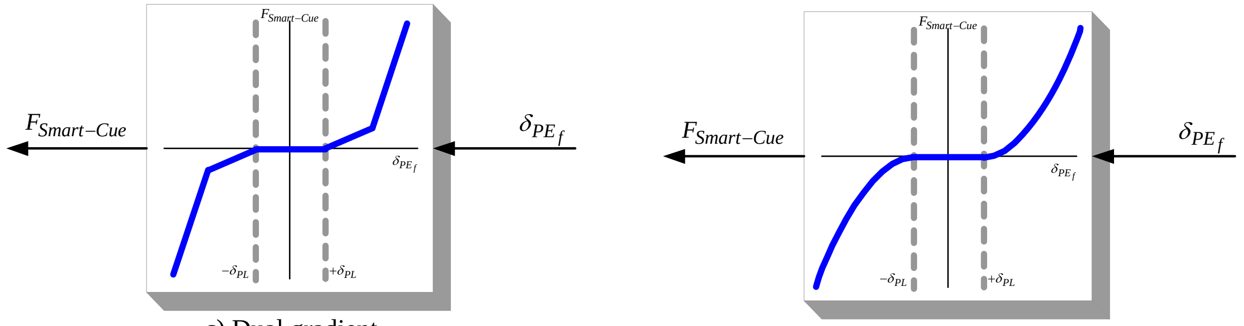
A. The Smart-Cue Gradient Force Feedback Cue

In a typical fly-by-wire system, the inceptor dynamics can be represented most simply by a second order system characterized by a spring gradient, damping, and inertia. Thus, when introducing a force feedback cue, a fundamental force type to consider is one that changes the effective spring gradient. The options for such a cue are shown in Figure 6 wherein each case is shown as if it was one feedback element of a larger block diagram. The four options include a limiting case “hard stop” (Figure 6a), a linear gradient (Figure 6b), a dual gradient (Figure 6c), and a parabolic gradient (Figure 6d). The parabolic gradient may also be approximated by a series of three or more linear gradients. For all options the gradient force is zero whenever the Position Error input is below a defined threshold. This threshold may be zero in the limiting case or may expand as needed for a given application to create a dead zone wherein no feedback forces are generated until the error exceeds the defined value. Once outside this dead zone, the magnitude of the feedback force increases with increasing Position Error according to the defined function.

Following engineering evaluations, two Boeing test pilots participated in the initial simulator evaluations of the gradient force feedback cue. Pitch axis evaluations were made with a sum-of-sines tracking task, while roll axis evaluations were made with a bank angle capture and hold task. For the pitch axis, the evaluations focused on variations in the linear gradient option of Figure 6b. The hard stop option was not strongly considered as there was a desire to define mechanizations that would guide the pilot to successful task completion with reasonable performance. The hard stop may prevent loss of control, but at the expense of task performance if not the task itself. Both pilots found the gradient cue to be helpful in preventing loss of control, although the preferred force levels differed somewhat between the two pilots. While the cue was reasonably effective in the pitch axis, it was clear that other options were needed to improve the results.



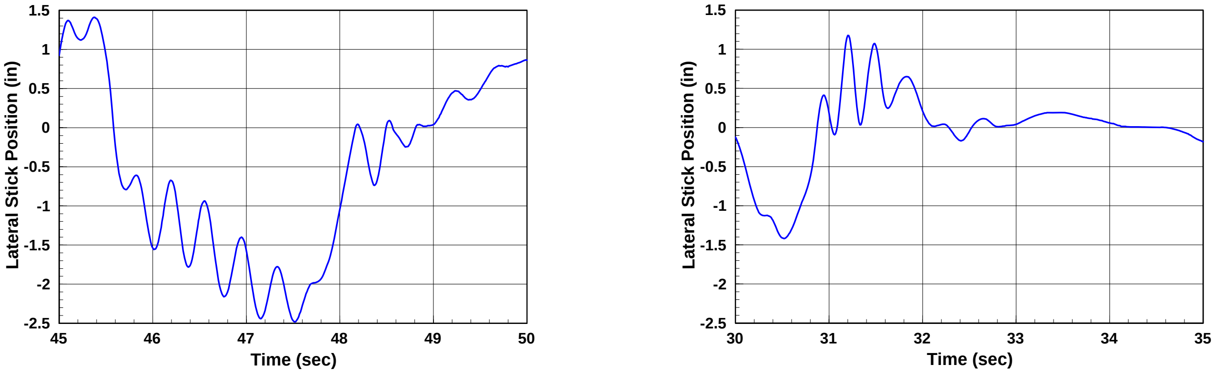
a) Hard stop b) Linear gradient



c) Dual gradient d) Parabolic gradient

Figure 6: Gradient feedback force cue options.

Although only limited roll axis evaluation runs were conducted, much was learned. First, the cueing was not particularly effective in this initial mechanization because a first order filter placed on the Smart-Cue signal resulted in a significant lag in the perceived cueing force. Also, there was a significant "wobble" noted as any significant lateral stick movement was attempted. Later investigations found that the magnitude of the wobble increases as stick damping decreases. The wobble appeared to result from the coupled limb-manipulator mode that is a known lateral axis issue often associated with roll ratchet.[10] The oscillations or wobble had been noted prior to the Boeing pilots' exposure, but the increased lateral stick damping used at that time masked the phenomenon. When the lateral stick damping was reduced, the oscillations became more prominent. The oscillations are clearly evident in the Figure 7a lateral stick position time series plot that was taken from a bank angle capture and hold evaluation task run. The approximate frequency of the oscillation is 16.6 rad/s (2.65 Hz), which is within the frequency range of the previously mentioned limb-manipulator mode. The gradient cue produced similar stick "wobbles" or roll ratchet in the checkout flights (see Figure 7b), which were found to be very objectionable by the pilot. With this occurrence and the success of other force feedback options, the gradient force was no longer considered as a solitary cueing mechanism.



a) Simulator example of roll ratchet b) Flight verification of roll ratchet

Figure 7: Roll ratchet-like phenomenon results from roll stick gradient force feedback cueing.

B. Other Smart-Cue Options

Initial piloted simulation results indicated that the gradient force can alone provide an effective cue to the pilot, at least in the pitch axis. The feel of the cue, however, was not always "smooth," and in the roll axis, a roll ratchet condition was often observed. To enhance the performance of the force feedback cue, a damping component was considered. Two damping force options were defined. In the first option, the damping force was computed as a function of the Position Error and stick velocity. In this case the damping force is zero whenever the Position Error is less than or equal to the defined threshold. The stick velocity signal is then passed through a second order Butterworth filter before the damping force is computed. In the second option, the damping force was computed as a function of the rate of change of Position Error. Once again, the damping force is zero whenever the Position Error is less than or equal to the defined threshold. To provide a smooth onset, the damping force is increased from zero to its full value using a gain. Similar to the first damping force option, the Position Error rate signal is passed through a second order Butterworth filter before the damping force is computed. Evaluation of the damping force options via piloted simulation revealed no significant added benefit when used alone or in combination with the gradient force.

Following the simulator evaluations by the Boeing pilots, the desire for an improved constraining force mechanism led to the definition of a coulomb friction-like Smart-Cue force. The benefit of this type of force cue is that no reactive force is generated when the stick is not in motion. Once implemented, this new cue appeared to work well in an engineering simulation checkout. The friction force is a function of the sign of the stick velocity and is activated when the computed Position Error exceeds the defined threshold. This cue worked well in many cases and it eliminated the observed roll ratchet phenomenon, however, a better solution soon came to light.

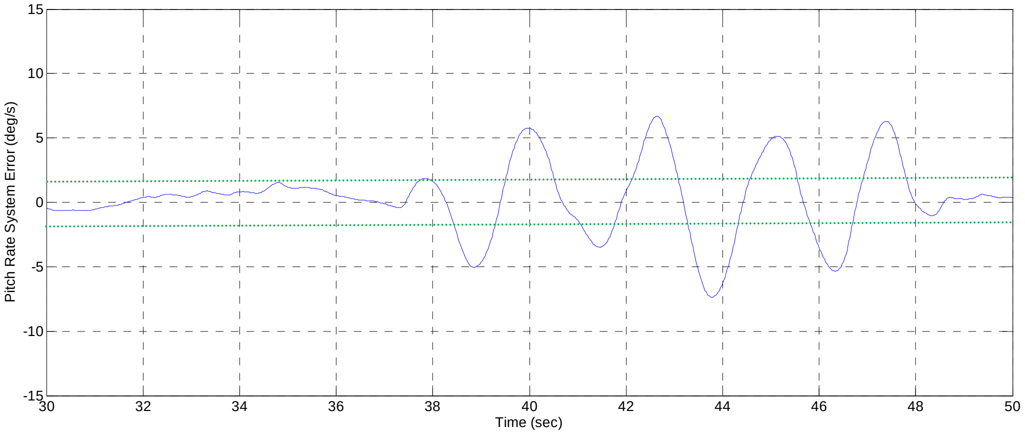
C. The Combined Force Feedback Cue

By exploring options in the simulator, it was found that a combination of the gradient and friction force together produced a much improved force cue. When combined, the two types of forces seemed to "take the edge off" of the shortcomings found with the individual forces. Similar to the friction force alone, the combined force did not result in the roll ratchet observed with the gradient force alone. The benefits of this new combined force were confirmed in formal piloted simulation evaluations with two guest test pilots from the USAF Test Pilot School. Flight test evaluations of the Smart-Cue and Smart-Gain systems found that in terms of both pilot opinion and task performance the combined force provided the most beneficial inceptor cue, especially when used with the Smart-Gain.[6,11]

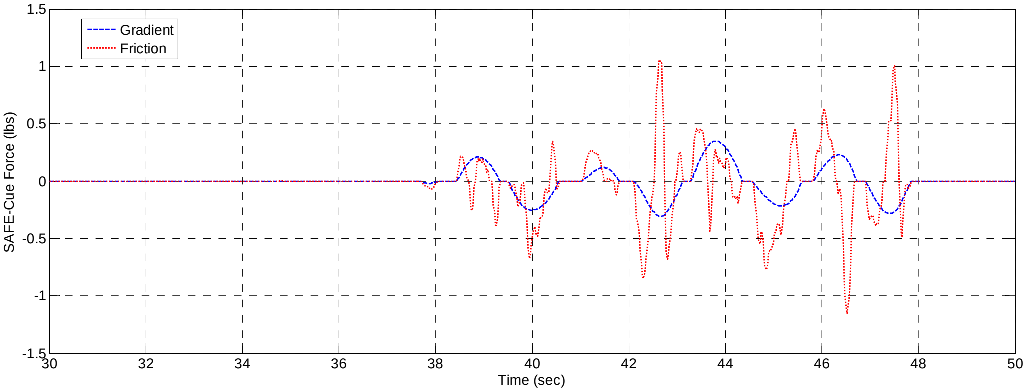
Given the success of the combined friction and gradient force Smart-Cue, such a combination of force feedback cues became a natural starting point for the initial SAFE-Cue developments. Figure 8 and Figure 9 show SAFE-Cue System Error, friction and gradient feedback forces, and total feedback force time histories for two example runs from the Phase 1 piloted evaluations.[8] These runs feature the same failure scenario that was associated with the Figure 5 example runs. Each figure shows a 20-second segment of the overall 80 second runs. The combined SAFE-Cue force only case of Figure 8 received an HQR 5/PIOR 3, while the combined SAFE-Cue force plus gain case of Figure 9 received an HQR 3/PIOR 2. The System Error plots feature green dotted lines that indicate the threshold values used in Phase 1. No feedback forces are generated as long as the System Error remains below the threshold values.

When comparing the two evaluation runs, the impact of the SAFE-Cue gain can clearly be seen in the magnitude and duration of the forces. The presence of the time-varying gain adjustments greatly reduces the feedback forces required. One might surmise then that the feedback forces may not be needed at all. It is important to point out, however, that the best ratings were achieved for those failure cases when the SAFE-Cue gain and forces were both active. Another interesting feature of the two forces is that the gradient force builds more slowly, but has a longer decay. The friction force on the other hand, peaks and decays rapidly. Because the friction force is a function of the stick velocity and not position, it is also more likely to rapidly change direction. As a result, the gradient and friction forces are frequently opposite in sign.

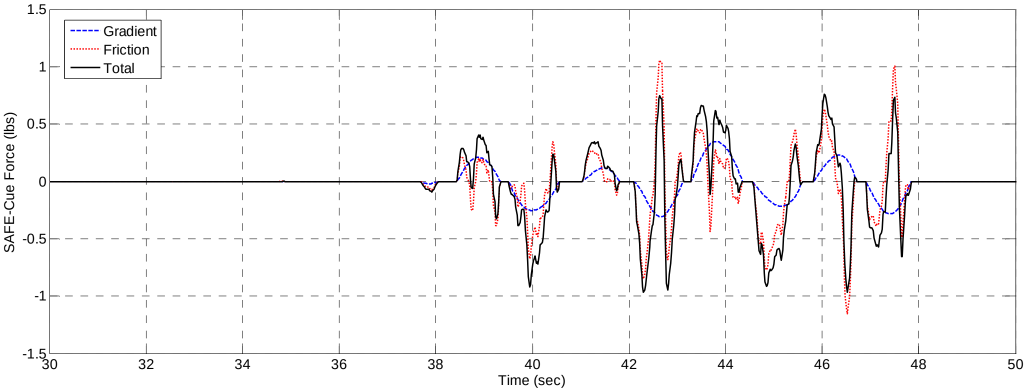
The total force results from a combination of the gradient and friction forces as shown in the bottom panels of Figure 8 and Figure 9. The Combined SAFE-Cue force was clearly preferred by the pilots compared to either force given in isolation. Still, there is considerable design space to identify more optimum mechanizations.



a) System Error

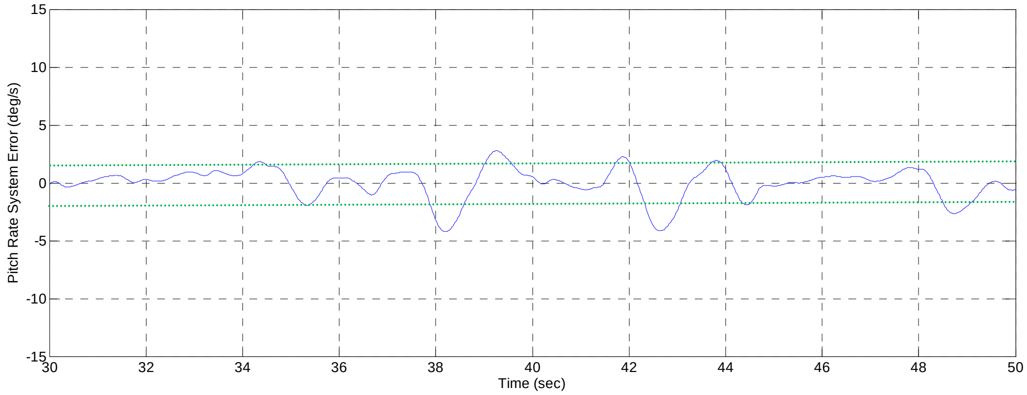


b) SAFE-Cue component forces

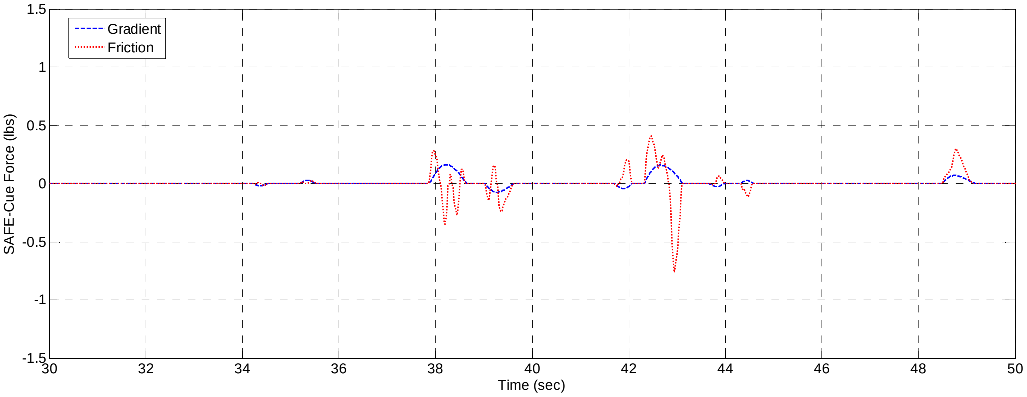


c) SAFE-Cue total force

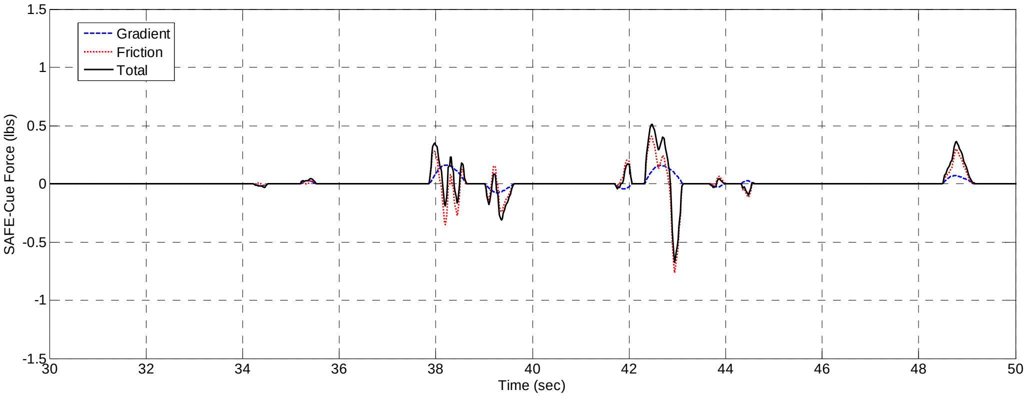
Figure 8: Example SAFE-Cue forces for combined force case.



a) System Error



b) SAFE-Cue component forces



c) SAFE-Cue total force

Figure 9: SAFE-Cue forces for combined force and gain case.

IV. The Adaptive Command Path Gain

A. The Need for a Smart-Gain

A second design concept that is also based on a measure of dynamic distortion, the *Smart-Gain*, evolved from the Smart-Cue checkout flight process. The Calspan Learjet In-Flight Simulator was used to conduct both the checkout flights and formal evaluation flights for the Smart-Cue program. During the checkout flight sorties, several Smart-Cue mechanizations were found to work well for the cruise evaluations in both the pitch and roll axes. Results from the precision offset landing task, however, were far less certain. First, the evaluation pilot appreciated that the Smart-Cue gave an apparent “trough” in which it was safe to move the stick in the presence of significant control surface rate limiting. The size of the trough was more pronounced when the force cueing increased as a function of Position Error. Despite numerous attempts, a force cueing level could not be found that allowed the pilot to comfortably make the required roll axis corrections associated with the offset landing without “fighting” the Smart-Cue forces. These results led to a post flight debrief discussion of possible command path gain adjustments as an alternative to the high feedback forces that would still take advantage of the positive alerting mechanism observed in the checkout evaluations.

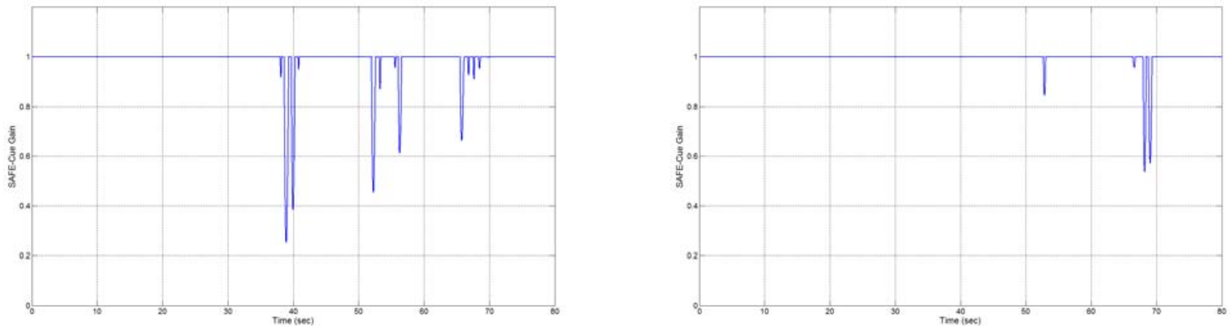
Piloted simulation was used to rapidly prototype such a concept, the Smart-Gain. Techniques like the PIOS filter used on the Shuttle do not, however, take the response of the flight control system or vehicle into consideration, so the pilot input is attenuated whether or not it is needed. With the Smart-Gain, the pilot input is attenuated as a function of the Position Error, the measure of dynamic distortion. A threshold is again used to turn the Smart-Gain on and off. The threshold may be set independently to the values used for the Smart-Cue.

The Smart-Gain was found to be a critical innovation. Repeated successful landings were accomplished during the formal evaluation process with best results coming from a Smart-Cue/Smart-Gain combination.[6]

B. The SAFE-Cue Gain

For the SAFE-Cue implementation, the adaptive command path gain reduction filter is also a function of the pitch rate System Error. When the System Error exceeds the threshold value, which can be different from that used for the SAFE-Cue force, the command path gain is reduced linearly as a function of increasing System Error to a prescribed minimum value. In Phase I a minimum value of 0.25 was used. Thus the pilot would not observe an instantaneous gain reduction greater than 75%. The slope of the reduction can be varied to increase or decrease the rapidity of the gain reduction. The gain reduction is adaptive in that it is only active when the System Error threshold is exceeded, and then the magnitude of the reduction is a function of the instantaneous size of the error.

Two SAFE-Cue gain examples from the Phase I piloted simulation are shown in Figure 10. The failure scenario here is similar to that described previously with the exception that the control surface maximum rate was reduced to 20 deg/s from the nominal 60 deg/s. In the first case, Figure 10a, no feedback forces are present, only the command path gain adjustments. While the pilot did find significant performance improvements compared to the failure only case, overshoots were still present on the large amplitude reversals. When the feedback force cues were added in the run immediately following the Figure 10a example, further improvements in performance are observed by the pilot and only limited SAFE-Cue gain activity is required (see Figure 10b). The pilot found this case to be similar to the baseline, but not as fast in its response.



a) SAFE-Cue gain only case b) SAFE-Cue combined force and gain case

Figure 10: SAFE-Cue command path gain activity from two example piloted simulation runs.

V. Piloted Evaluations

A. Smart Cue/Smart-Gain Flight Test Evaluations

Formal flight test evaluations were conducted from the Calspan facility at Niagara Falls Airport over the two week period from November 7-17, 2006 and a two day period from January 30-31, 2007. Seven test pilots participated in the evaluations, two safety pilots and five evaluation pilots. All pilot participants were graduates of either the USAF or USN Test Pilot Schools. Detailed analysis of the flight test data has been published in previous papers.[6,11,12] The results shown here were selected to emphasize the influence of the Smart-Cue and Smart-Gain in preventing loss of control in the presence of control surface rate limiting.

Flight test time history strip charts are shown for example cruise pitch and roll axis evaluations and a precision offset landing task in Figure 11, Figure 12, and Figure 13, respectively. All evaluations were made by a test pilot with a fighter aircraft background, a classic high gain pilot. Two sets of strip charts are shown in each figure, one for a rate limited only case and one for a rate limited plus Smart-Cue/Smart-Gain case. Signals include stick force and position, output rate and attitude, elevator command and position, and Position Error and Smart-Cue force.

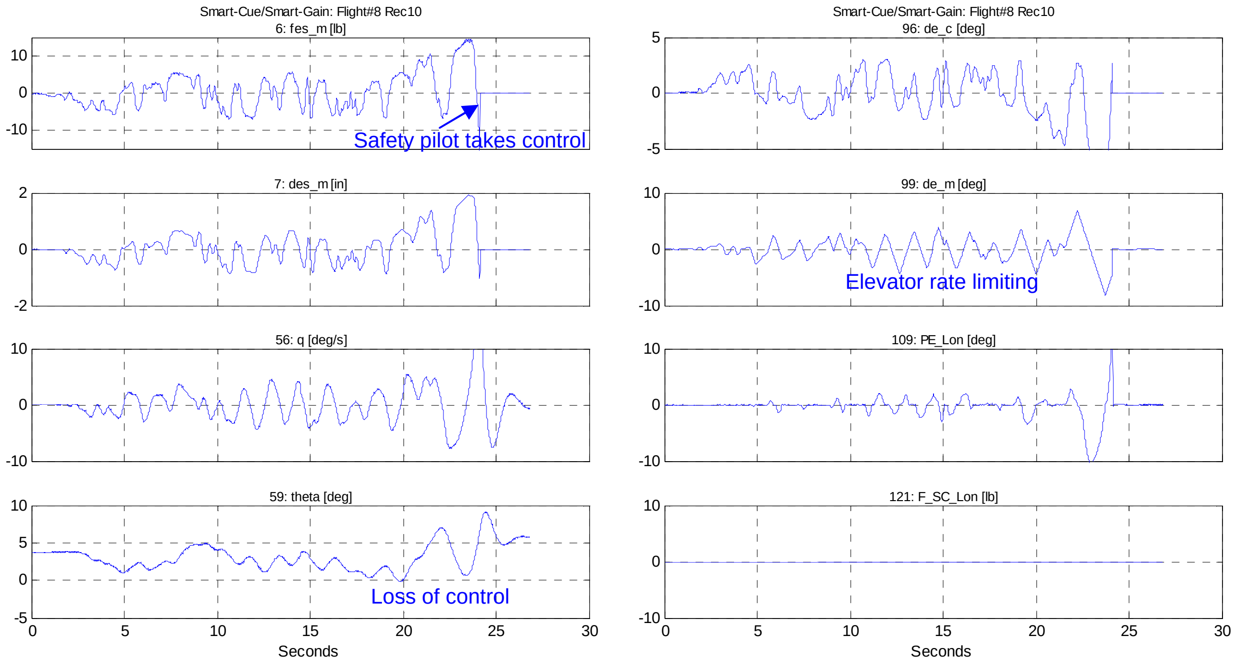
In the pitch axis rate limited only case (Figure 11a and b), the example resulted in a loss of control event where the Learjet safety pilot took control of the airplane. The run is characterized by rate limiting leading to a divergent PIO. When the Smart-Cue/Smart-Gain is engaged (Figure 11c and d), the pilot attained desired performance with no significant rate limiting or PIO. Note also that the Position Error measure of dynamic distortion is greatly reduced. For the roll axis evaluations the pilot performed a series of ±30º and wings level bank angle captures. While loss of control did not result in the example, the pilot was not able to achieve even adequate performance and each capture was characterized by a significant overshoot followed by a bounded PIO (Figure 12a). This run was also characterized by severe rate limiting as seen in Figure 12b. No such overshoots or PIO can be found in any of the Smart-Cue/Smart-Gain captures (Figure 12c). As shown in Figure 12d a relatively large magnitude Smart-Cue force was needed to suppress the overshoot associated with each initial capture.

A precision offset landing task was used to evaluate Smart-Cue and Smart-Gain mechanizations in the approach and landing flight condition. For the rate limited only case there was a large bank angle overshoot associated with the initial correction of near 50º followed by a divergent PIO as the pilot attempted to make final centerline corrections prior to landing (Figure 13a). The safety pilot took control of the airplane following the third oscillation. There is a dramatic change in performance with the Smart-Cue/Smart-Gain active. As detailed in Ref. 6, the clear performance enhancer for the approach and landing evaluations was the Smart-Gain. The combination of the Smart-Cue with the Smart-Gain, however, was needed to provide a smooth initial correction to the runway centerline and prevent oscillations in the final correction. The impact of both the cue and gain on mitigating the effects of rate limiting can be seen when the Position Error measures (Figure 13c and d) are compared for the two runs.

B. SAFE-Cue Simulator Evaluations

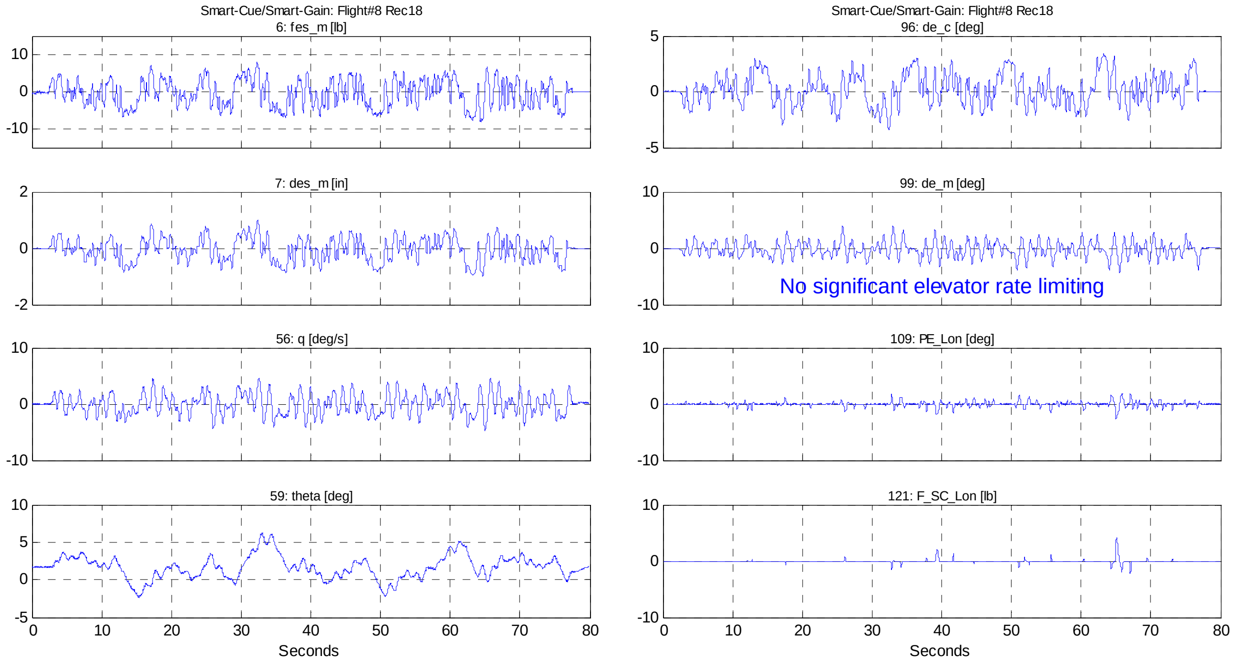
Two formal simulator evaluation sessions were conducted to assess feasibility of the SAFE-Cue approach. The first session was conducted on June 14, 2010. The participating pilot flew nearly 40 evaluation runs, spanning all four failure/damage scenarios. The second evaluation session was conducted on July 20, 2010. The participating pilot flew 42 evaluation runs, spanning three of the four failure/damage scenarios. Both pilots are graduates of the USAF Test Pilot School and have extensive transport experience that was well suited for the evaluations conducted in the Phase I program. Detailed analysis of the simulator test data has been published previously.[8] The results shown here were selected to emphasize the influence of the SAFE-Cue in preventing loss of control with an active adaptive controller in the presence of failure/damage.

If one had to classify the two pilots, Pilot 1 would be considered a high gain, continuous controller, while Pilot 2 would also be considered high gain, but with a much more open loop (i.e., pulse and wait) technique. Despite these differences, both pilots had similar overall results regarding the various configurations presented. Example results for the pitch axis sum-of-sines tracking task[8] evaluations are shown in Figure 14. The scoring interval is indicated by the solid red vertical lines, while the dotted red vertical lines indicate the elevator failure insertion point. For each pilot, a failure only case and a SAFE-Cue combined force and gain case are included. The failure only cases are both characterized by severe pilot-induced oscillations throughout the scoring interval. Achieving reasonable desired (±1°) and adequate (±2°) tracking in these cases was more due to luck than actual pilot-vehicle system performance. A quite different result is noted for the failure with SAFE-Cue examples. Here there were no pilot-induced oscillations or even undesirable motions that affected task performance. Furthermore, both pilots were only a few percentage points from achieving desired performance and they easily met adequate performance requirements.



a) Pilot stick force/position and aircraft outputs b) Elevator cmd./position, Position Error/Smart-Cue

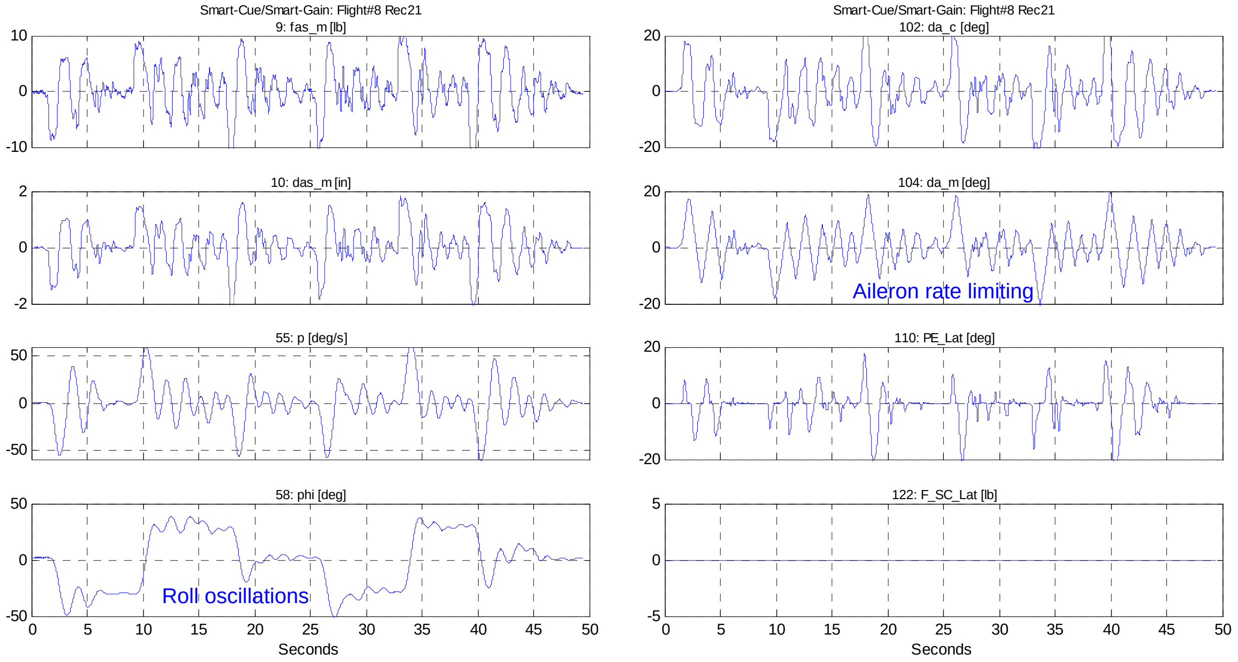
10 deg/s elevator rate limit, HQR 8/PIOR 4



c) Pilot stick force/position and aircraft outputs d) Elevator cmd./position, Position Error/Smart-Cue

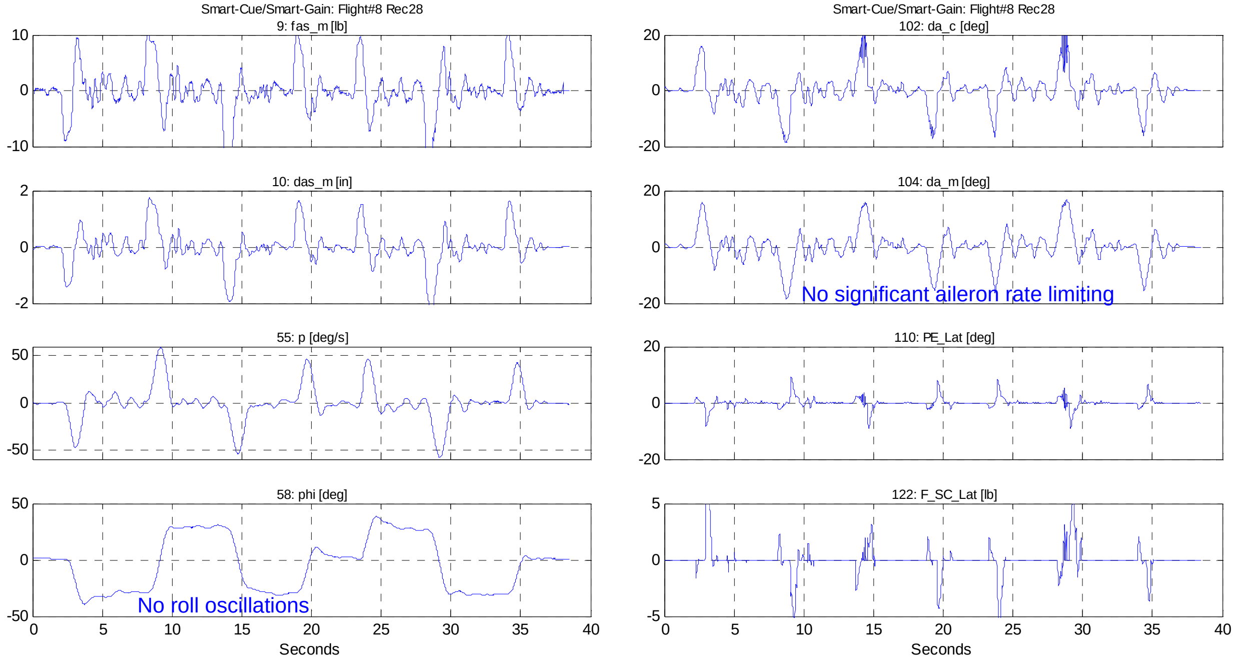
10 deg/s elevator rate limit, Smart-Cue/Smart-Gain active, HQR 4/PIOR 2

Figure 11: Pitch axis sum-of-sines tracking task flight test results.



a) Pilot stick force/position and aircraft outputs b) Aileron cmd./position, Position Error/Smart-Cue

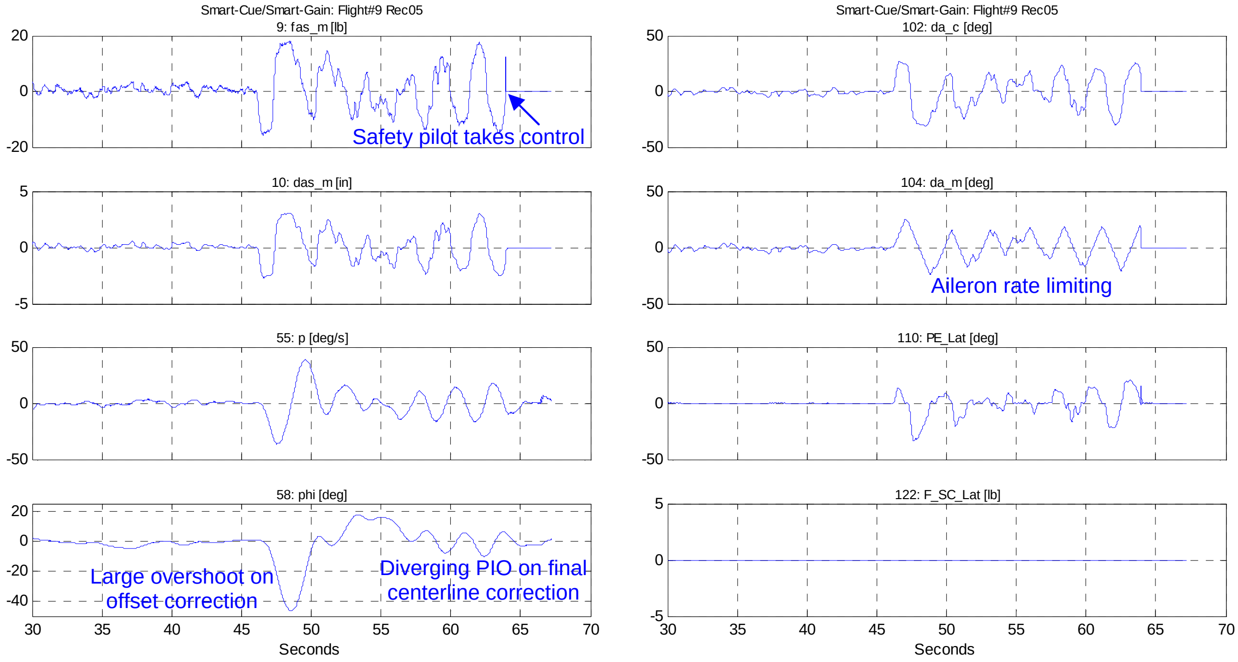
30 deg/s aileron rate limit, HQR 8/PIOR 4



c) Pilot stick force/position and aircraft outputs d) Aileron cmd./position, Position Error/Smart-Cue

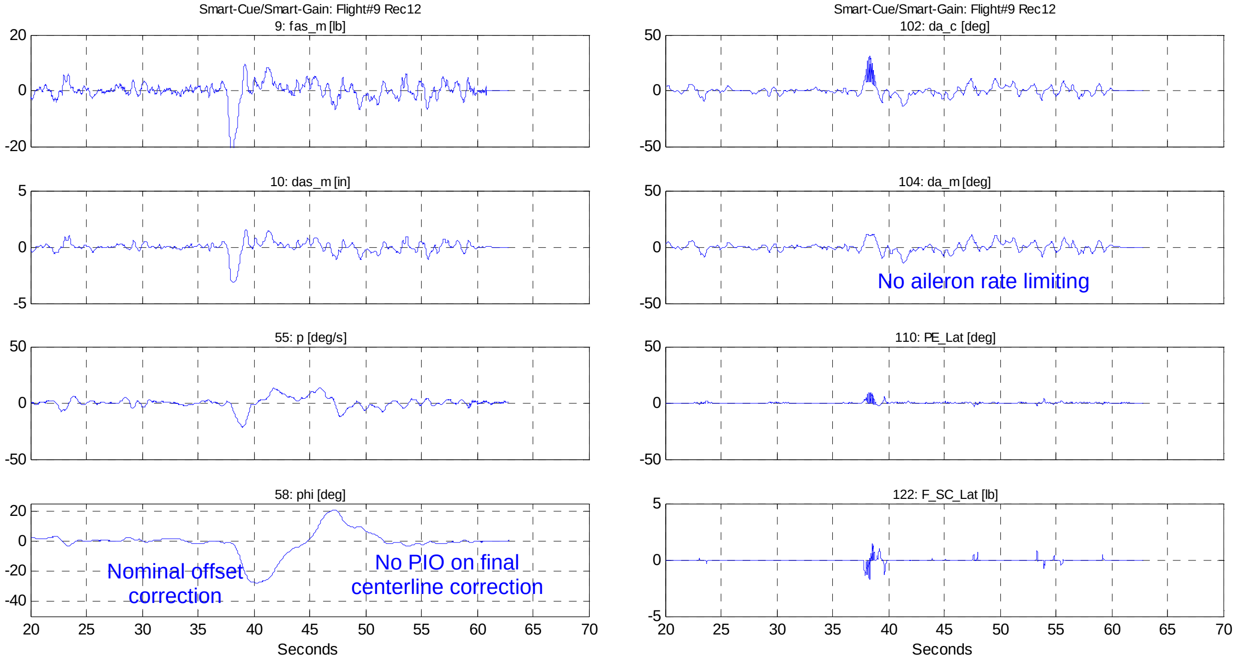
30 deg/s aileron rate limit, Smart-Cue/Smart-Gain active, HQR 4/PIOR 2

Figure 12: Bank angle capture and hold flight test results.



a) Pilot stick force/position and aircraft outputs b) Aileron cmd./position, Position Error/Smart-Cue

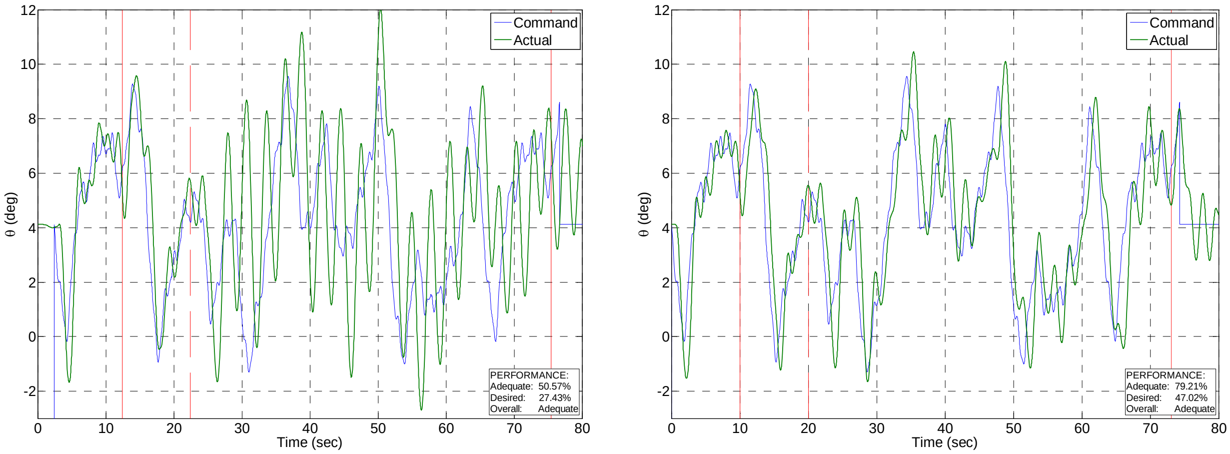
30 deg/s aileron rate limit, HQR 10/PIOR 5



c) Pilot stick force/position and aircraft outputs d) Aileron cmd./position, Position Error/Smart-Cue

30 deg/s aileron rate limit, Smart-Cue/Smart-Gain active, HQR 4/PIOR 2

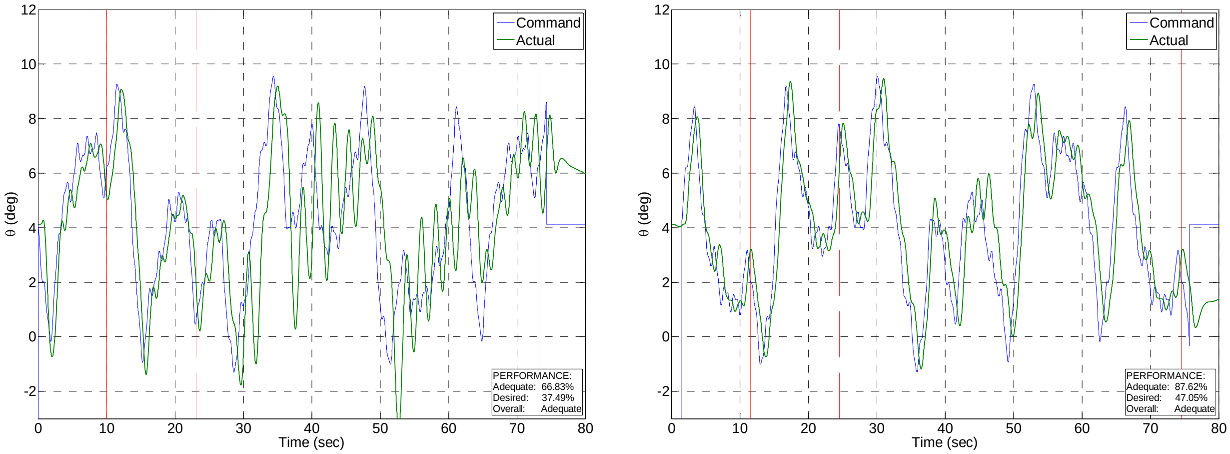
Figure 13: Precision offset landing task flight test results.



a) Failure only case, HQR 7/PIOR 4

b) Failure with SAFE-Cue combined force and gain, HQR 3/PIOR 2

Pilot 1 example evaluations



c) Failure only case, HQR 6/PIOR 4

d) Failure with SAFE-Cue combined force and gain, HQR 4/PIOR 2

Pilot 2 example evaluations

Figure 14: SAFE-Cue pitch axis tracking task piloted simulation results.

VI. Conclusions

Pilot force cueing via an active control inceptor can be used in combination with adaptive command path gain reductions to mitigate pilot-vehicle system loss of control. Two such concepts have been developed for this role, the Smart-Cue/Smart-Gain that was developed to alleviate the impact of control surface actuator rate limiting and the SAFE-Cue that was developed to improve pilot-vehicle performance in the presence of an adaptive flight controller and failures or damage. Regarding these two concepts the following conclusions are made:

- For Smart-Cue/Smart-Gain the Position Error was used to provide a quantitative measure of dynamic distortion, while for SAFE-Cue the pitch rate System Error measure was found to be an effective means of distinguishing performance of the adaptive system with failure/damage and a nominal (healthy) system. Piloted simulation and flight test results have shown these measures to be an appropriate indicator of impending flying qualities cliffs that are associated with flight control system nonlinear behavior.

- For both concepts the feedback force that resulted in the best performance and most favorable pilot opinion resulted from a combination of an effective gradient and coulomb friction force.
- A combination of Smart-Cue feedback force and Smart-Gain command path gain adjustments was found to best mitigate the impact of control surface actuator rate limiting. Similarly, the SAFE-Cue combined force and gain were most effective at suppressing pilot-vehicle system oscillations for the given failure/damage scenarios, allowing the pilots to focus on the task at hand rather than simply maintaining control.
- The SAFE-Cue approach has wider applicability beyond that of adaptive control. Given an active inceptor, the output System Error can be used as the catalyst for the SAFE-Cue force feedback or adaptive gain reduction whenever the flight control system (conventional, fly-by-wire, adaptive, etc.) significantly deviates from the nominal system behavior as a protection against loss of pilot-vehicle system control.

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