Flight Test of L_1 Adaptive Controller on the NASA AirSTAR Flight Test Vehicle

Irene M. Gregory
Dynamic Systems and Control Branch
NASA Langley Research Center

Enric Xargay
Dept. Aerospace Engineering
University of Illinois at Urbana-Champaign

Chengyu Cao
Dept. Mechanical Science & Engineering
University of Connecticut

Naira Hovakimyan
Dept. Mechanical Engineering
University of Illinois at Urbana-Champaign

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Subscale Flight Testing

IRAC research is focused on loss-of-control, failure and damage scenarios, and their mitigation though the application of adaptive control.

Under adverse conditions:

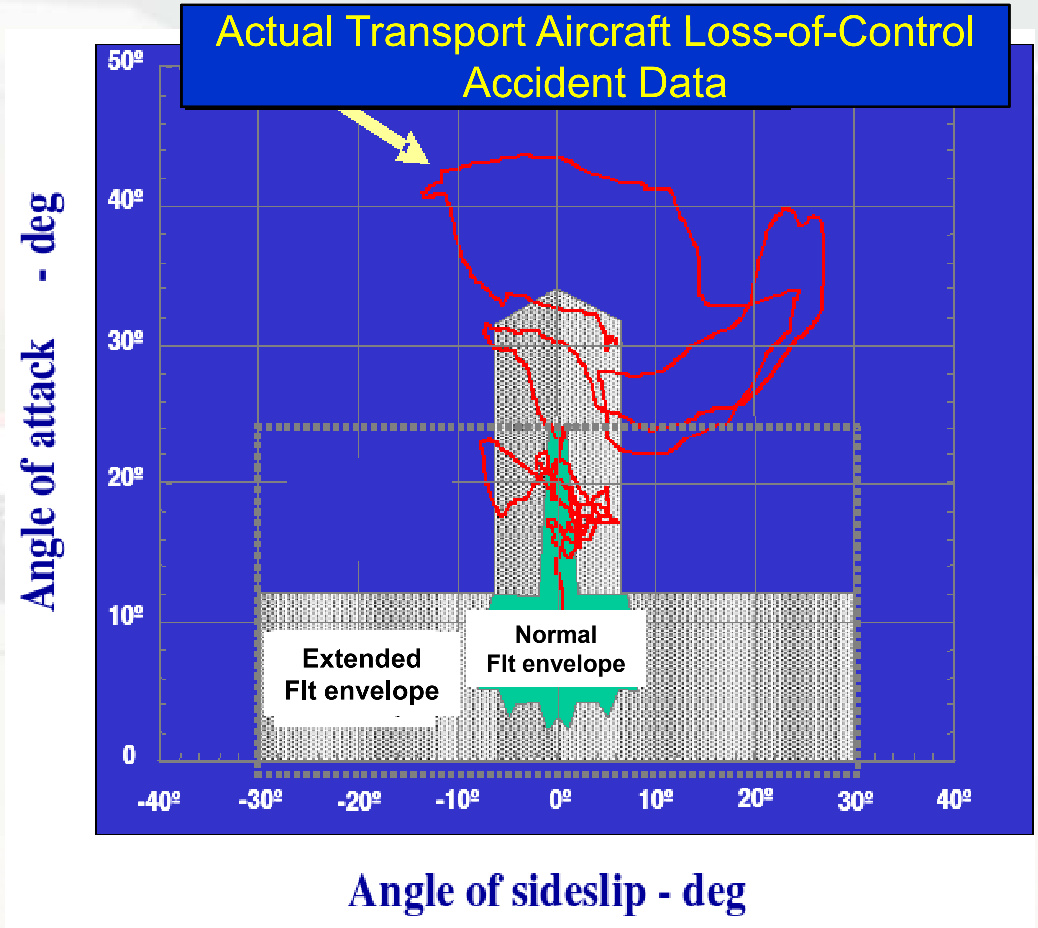
Control law objectives:

- Keep aircraft in the Extended flight envelope
- Return to Normal Flight Envelope

➢ Control actions within 2-4 seconds of failure onset are **critical**

⇒ Transient performance

⇒ Fast adaptation



IRAC = Integrated Resilient Aircraft Control project, part of Aviation Safety Program

AirSTAR GTM aircraft

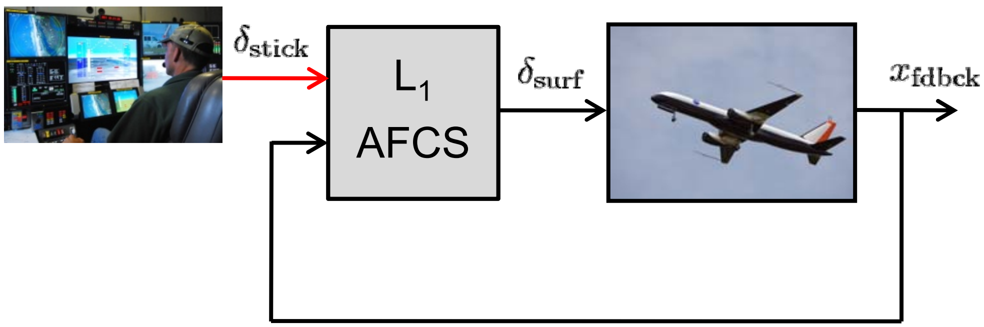
High-risk flight conditions,

some unable to be tested in target application environment.

- 5.5 % geometrically and dynamically scaled model
  - 82 in wingspan, 96 in length, 49.6 lbs (54 lbs full), 53 mph stall speed
  - Model angular response is 4.26 **faster** than full scale
  - Model velocity is 4.26 times slower than regular scale

Why an all-adaptive design?

- Typically direct adaptive controllers have been used as an augmentation to a robust baseline controller.
- Great deal of interest in seeing what adaptation can do as a standalone control strategy
- Stress the L_1 methodology and architecture to better understand
  - the practical performance
  - the controller behavior at the limits
- With a well designed robust baseline controller it is more difficult to assess how much adaptation is helping in providing stability and performance robustness and how much is the baseline controller contributing.
- Baseline controller may hide potential deficiencies of the adaptive controller.



MIMO Nonlinear System with Cross-Coupling

- Consider nonlinear system dynamics

$$\dot{x}(t) = f(x,t) + g(x,t)u(t)$$

- Can be expressed as the following system:

$$\dot{x}(t) = A_m x(t) + B_m \left(\mu(t) + \overbrace{\boxed{f_1\left(x(t), z(t), t\right)}}^{\text{Matched uncertainty}}\right) + \overbrace{\boxed{B_{um} f_2\left(x(t), z(t), t\right)}}^{\text{Unmatched uncertainty}}, \quad x(0) = x_0$$

$$\boxed{z(t) = g_0\left(x_z(t), t\right), \qquad \dot{x}_z(t) = g\left(x_z(t), x(t), t\right), \qquad x_z(0) = x_{z0}}$$

Unmodeled dynamics

$$\boxed{\mu(s) = G_a(s)u(s),}$$

Actuator dynamics

$$y(t) = Cx(t)$$

- Control objective:
  - Design an adaptive state feedback control law *u(t)* to ensure that the system output response *y(t)* tracks the output response $y_m(t)$ of the desired system

$$\dot{x}_m(t) = A_m x_m(t) + B_m K_g r(t)$$

$$y_m(t) = C_m x_m(t)$$

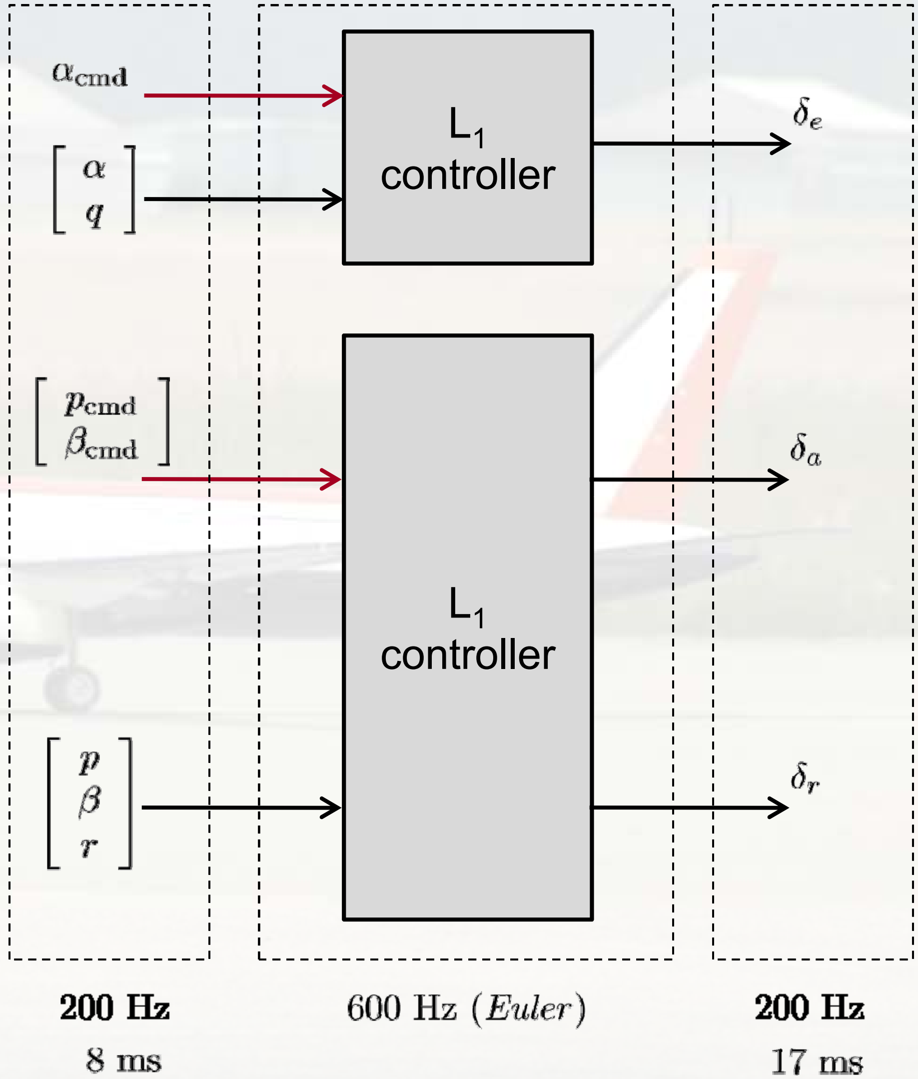
L1 All-adaptive Controller Architecture

- Control augmentation system – α-command, p-β command
- Designed at 1 flight condition – 80-KEAS (~4.5 deg AoA)

$$\dot{x}_m = A_m x_m + B_m \delta_{cmd}$$

$$\begin{pmatrix} \dot{\alpha} \\ \dot{q} \end{pmatrix} = \begin{pmatrix} \dfrac{Z_\alpha}{V} & 1+\dfrac{Z_q}{V} \\ M_\alpha & M_q \end{pmatrix} \begin{pmatrix} \alpha \\ q \end{pmatrix} + \begin{pmatrix} \dfrac{Z_\delta}{V} \\ M_{\delta_e} \end{pmatrix} \delta_e$$

$$\begin{pmatrix} \dot{p} \\ \dot{\beta} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} L_p & 0 & 0 \\ 0 & Y_\beta/V & -1 \\ 0 & N_\beta & N_r \end{pmatrix} \begin{pmatrix} p \\ \beta \\ r \end{pmatrix} + \begin{pmatrix} L_{\delta a} & L_{\delta r} \\ Y_{\delta a} & Y_{\delta r} \\ N_{\delta a} & N_{\delta r} \end{pmatrix} \begin{pmatrix} \delta_a \\ \delta_r \end{pmatrix}$$



Flight Control Law Evaluation Matrix I

	Task	1st straight leg	2nd straight leg	Turns
1	Latency Injection (5ms / 5 sec)	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Fault Engaged
2	Δ(Cmα & Clp) ≈ 00%	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
3	Δ(Cmα & Clp) ≈ - 50%	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
4	Δ(Cmα & Clp) ≈ - 75%	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
5	Δ(Cmα & Clp) ≈ -100% (neutrally stable)	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
6	Δ(Cmα & Clp) ≈ -125% (unstable)	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
7	High AoA Capture	No Fault No Doublet	No Fault No Doublet	N/A

- Cmα – degraded by 2 inboard elevator segments → 50% reduction in pitch control effectiveness
- Clp – degraded by spoilers

GTM T2 – Flight Test Evaluation (June 2010)

L1 all-adaptive flight control law → provides performance/stability for nominal and impaired aircraft

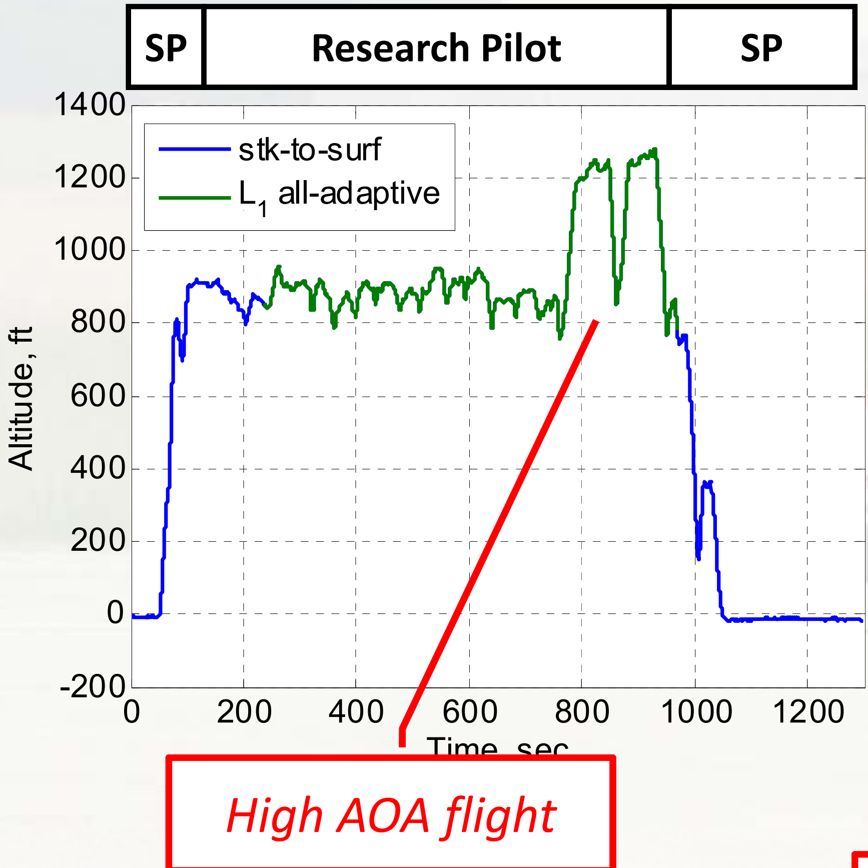
- **Not an augmentation** to a baseline controller, that provides nominal aircraft performance

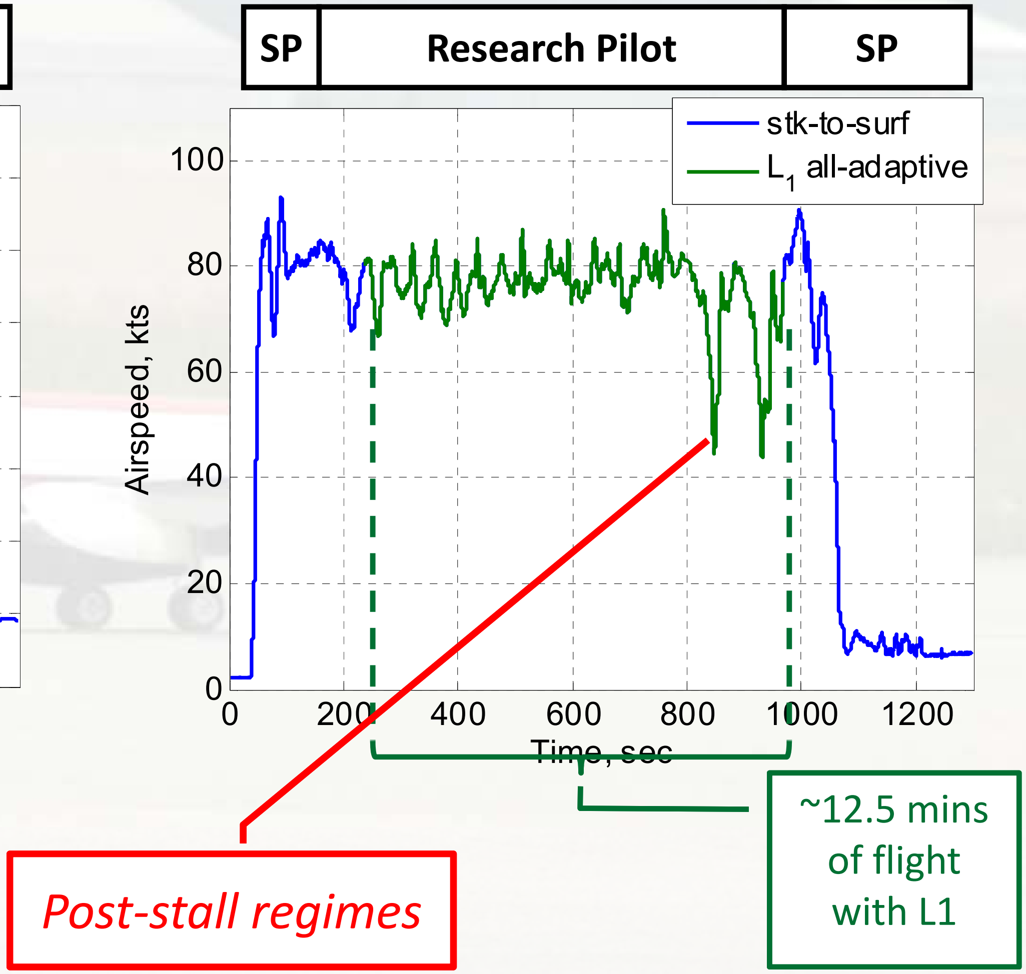
- Flight Control Law related tasks during June 2010 deployment :
  - Injected longitudinal and lateral stick doublets for each fault, continuous stick doublets on straight legs during latency fault
  - **Latency fault**: starting at 20 msec, continuous increase in latency (5 msec every 5 sec) carried through the turns until aircraft is neutrally stable or unstable – want graceful performance degradation
    - ✓ Robust to 0.125 sec additional time delay [0.147 total time delay]
  - **Simultaneous** longitudinal and lateral **stability degradation (Cma/Clp)**:
    - ✓ 50%: nominal performance
    - ✓ 75%: small degradation of performance in roll
    - ✓ 100%: small degradation of performance in pitch, larger degradation in roll
    - ✓ 125%: large amplitude roll with pitch doublet

- **Modeling Tasks**:
  - L_1 used for **β-sweep in flat turn maneuver**

GTM T2 - Flight Test Evaluation (June 2010)

- FLT23: L1 all-adaptive FCL under light turbulence

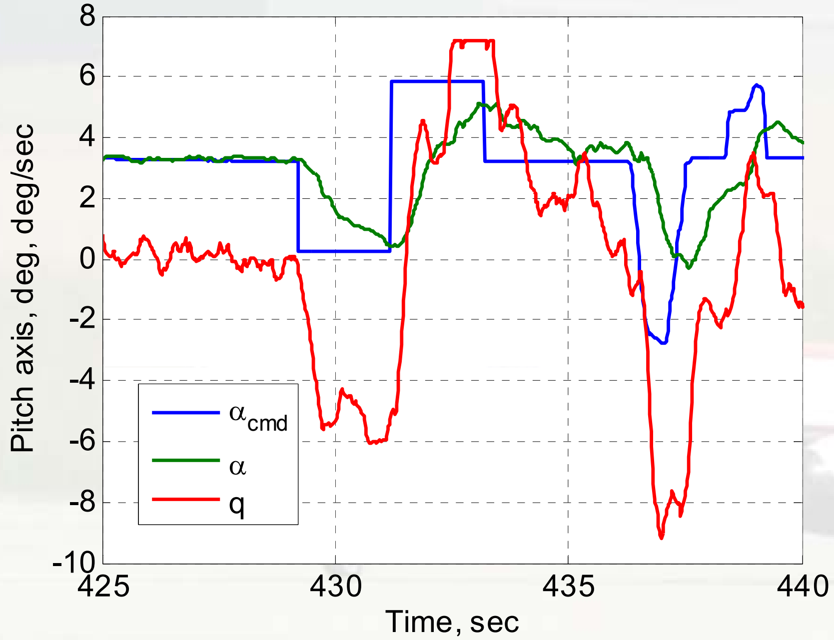




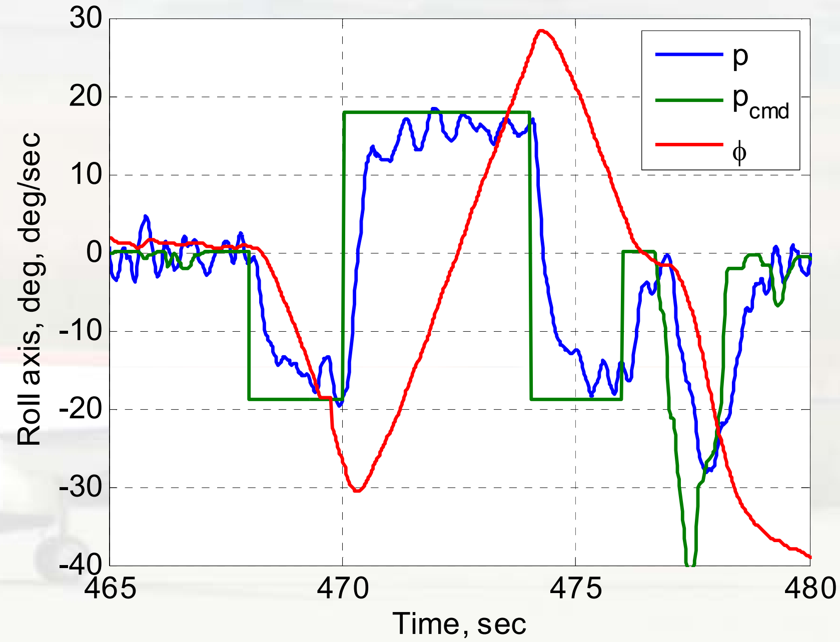
Nominal Aircraft Wave Train Response

- α-cmd and p_cmd wave trains (WT) enter as pilot stick commands
- Pilot asked for hands off during WT – WT characterized by straight lines

Pitch axis – α_cmd doublet



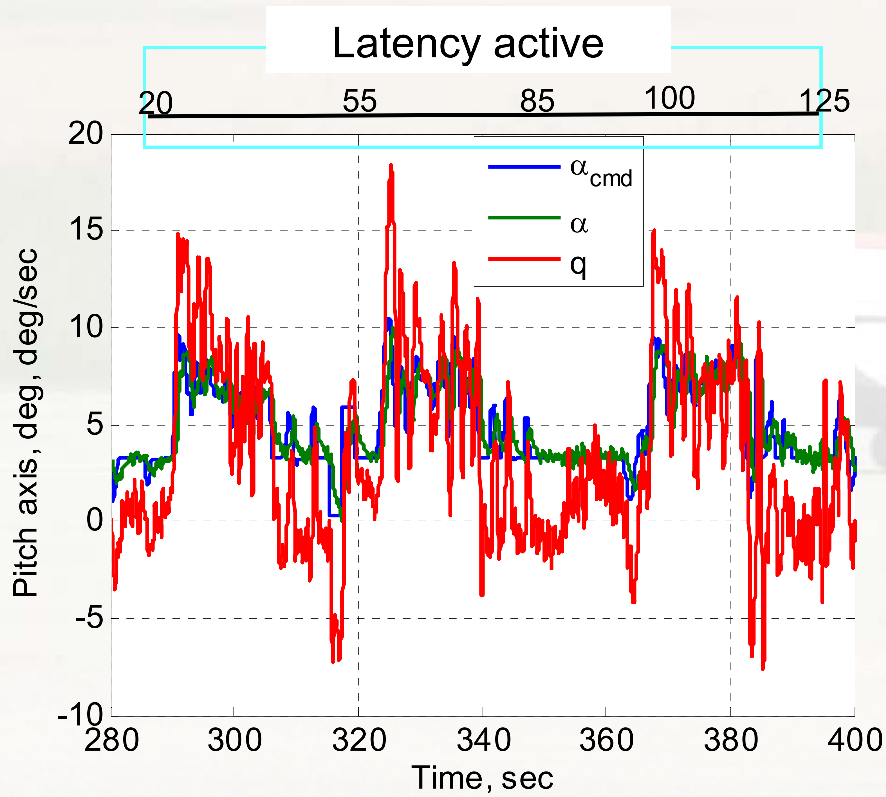
Roll axis – p_cmd doublet

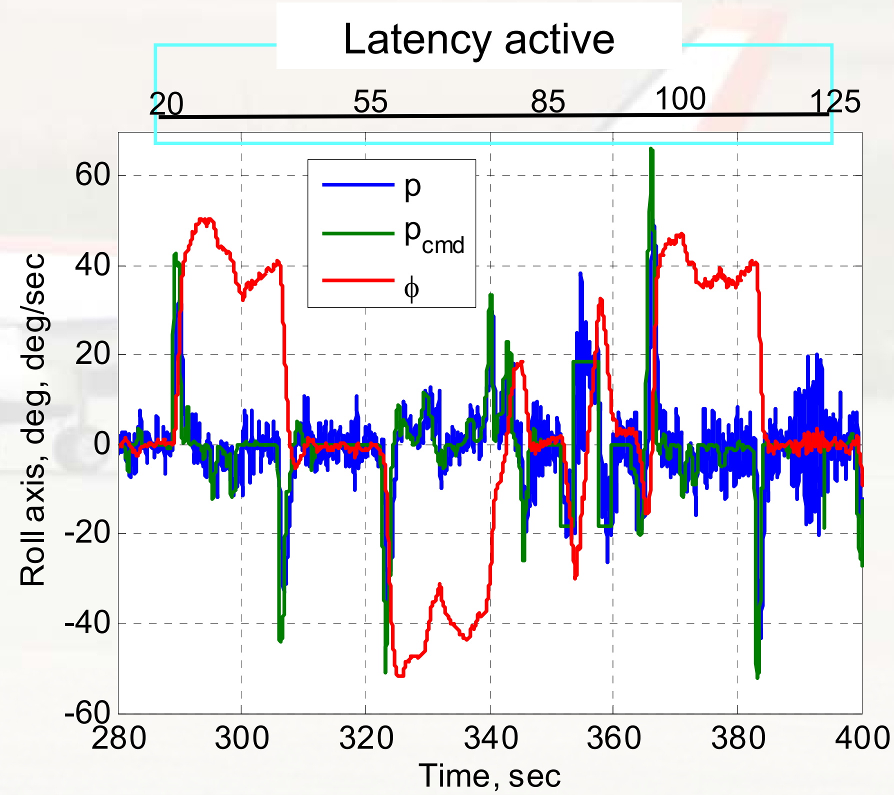


- α-cmd response designed for pilot, not to the maximum potential of the control law [tracking doublet faster – too sensitive for the pilot]
- Roll rate is a very fast and challenging response [with no turbulence – smooth, fast response tracking the p_cmd doublet]

Latency Response

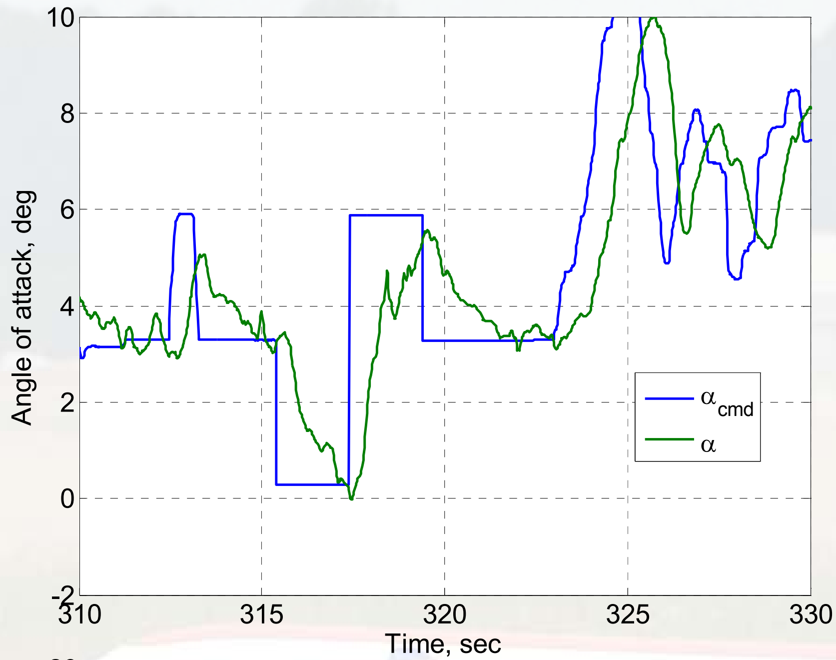
- Latency fault
  - Carried through the turns
  - Engaged around 286 seconds
  - The maneuver was abandoned at 394 seconds due to persistent roll rate oscillations of ± 20 deg/sec

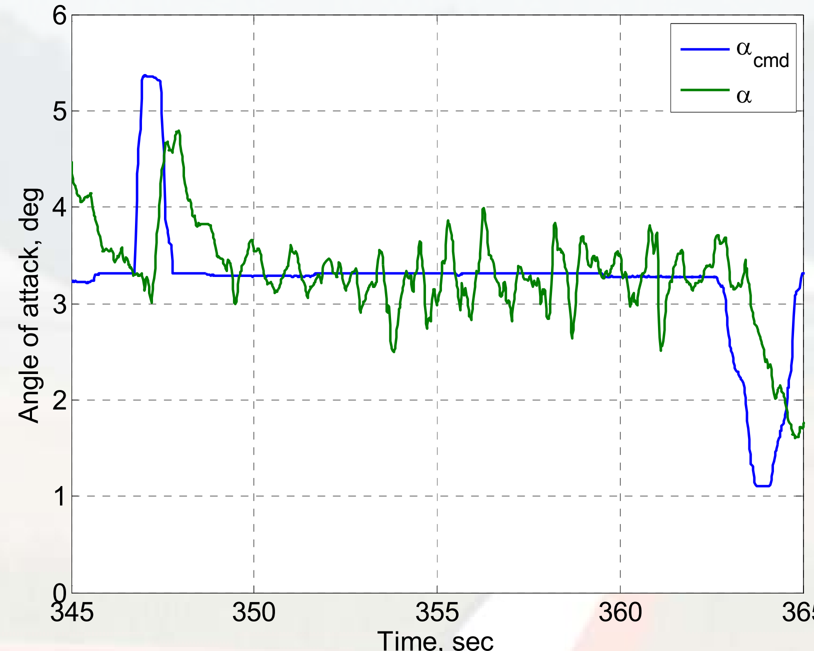




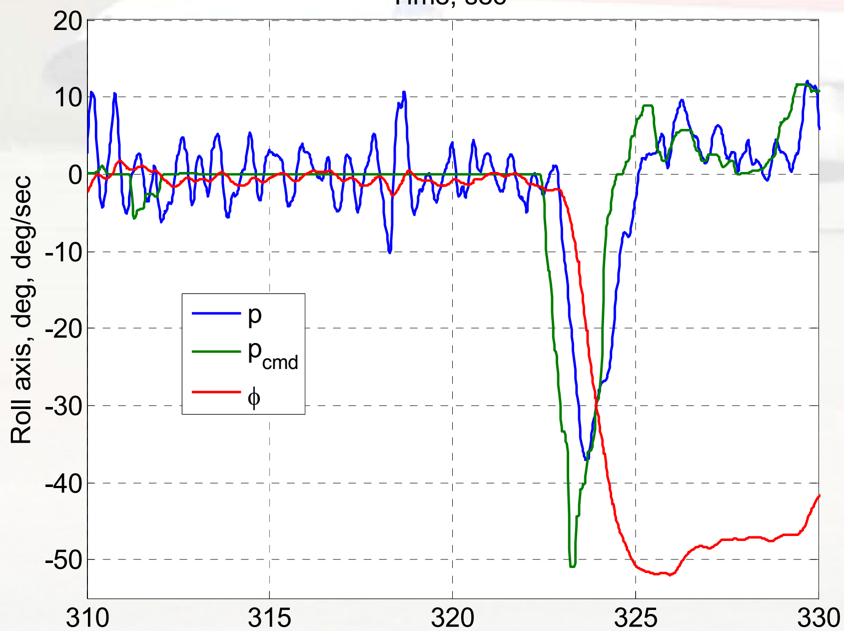
Latency Fault Doublet Response

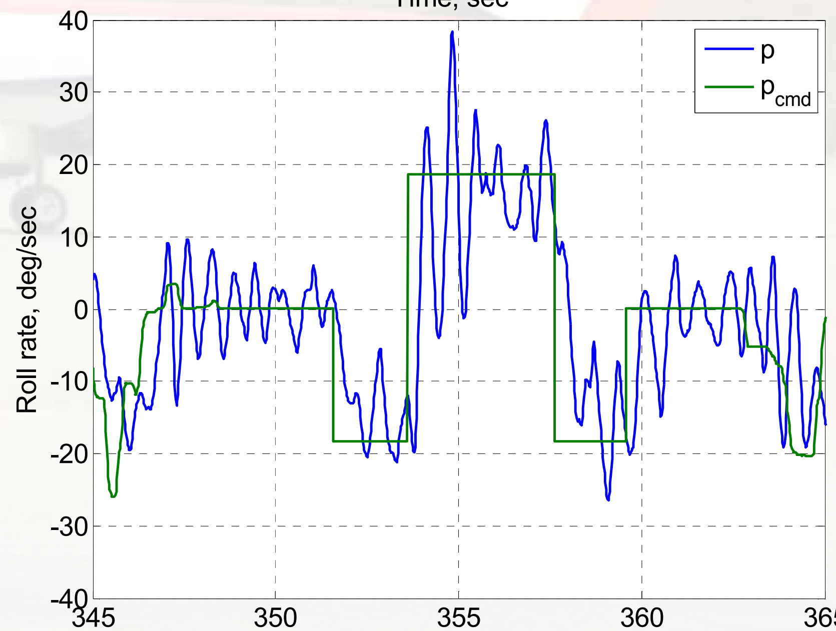
Angle of attack





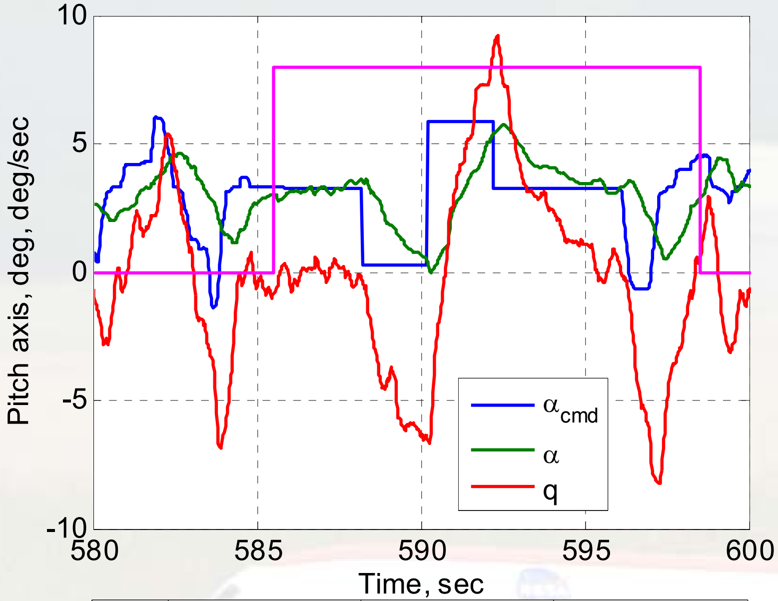
Roll rate



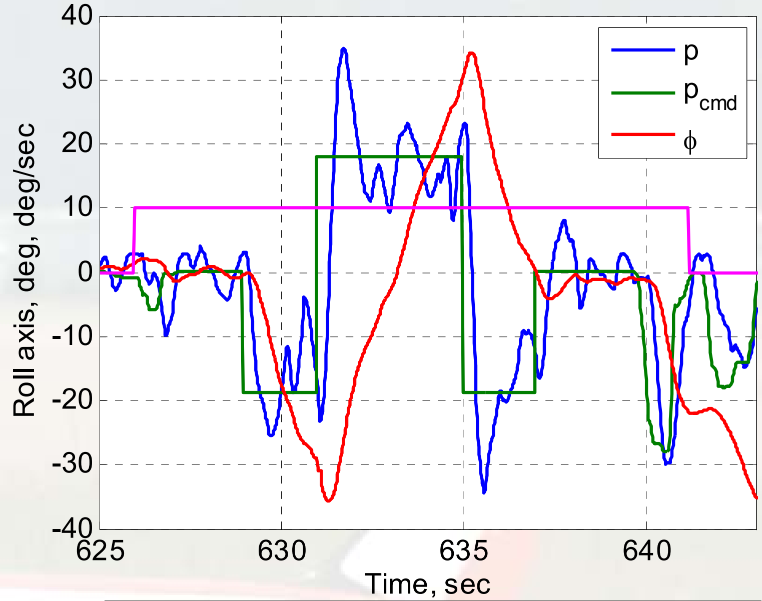


Cmα/Clp Degradation WT Response

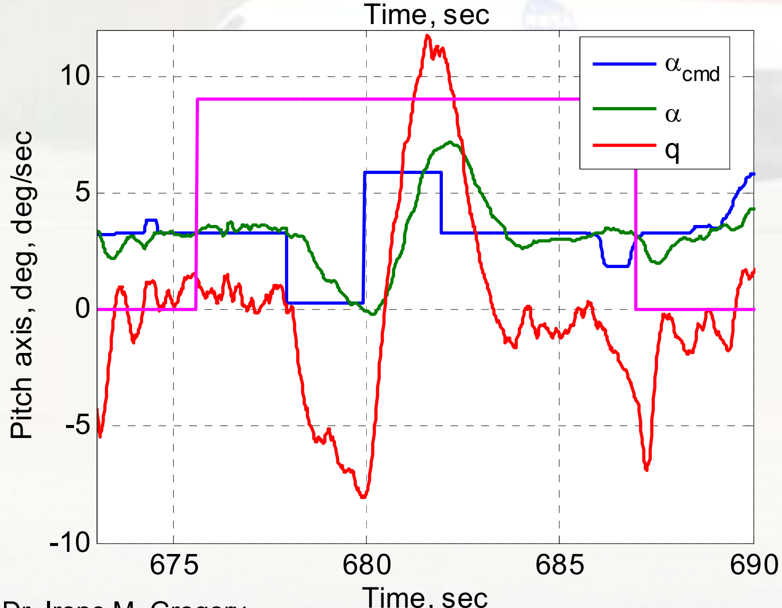
Pitch axis – α_cmd doublet

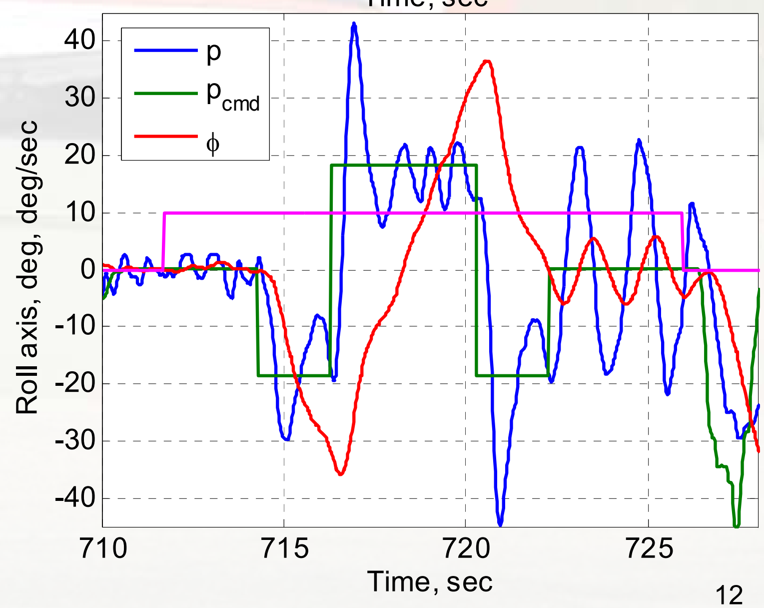


Roll axis – p_cmd doublet



Cmα/Clp
↓ 75%
↓50% long cntrl

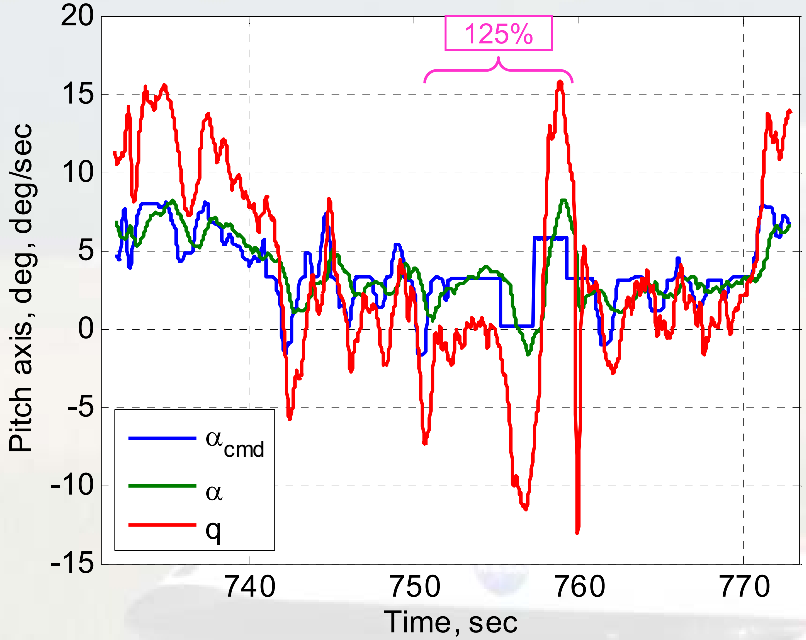




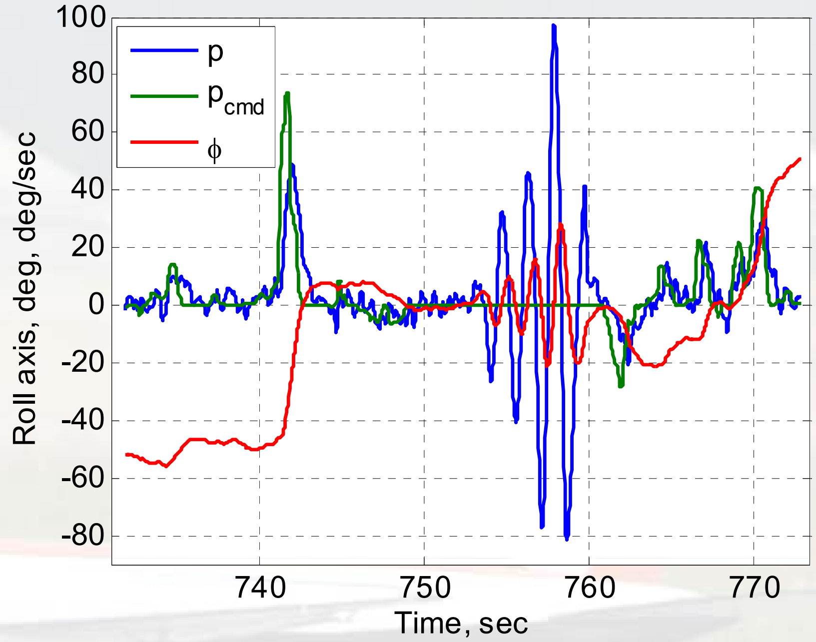
Neutrally stable
Cmα/Clp
↓ 100%
↓50% long cntrl

125%Cmα/Clp Degradation WT Response

Pitch axis – α_cmd doublet



Roll axis response

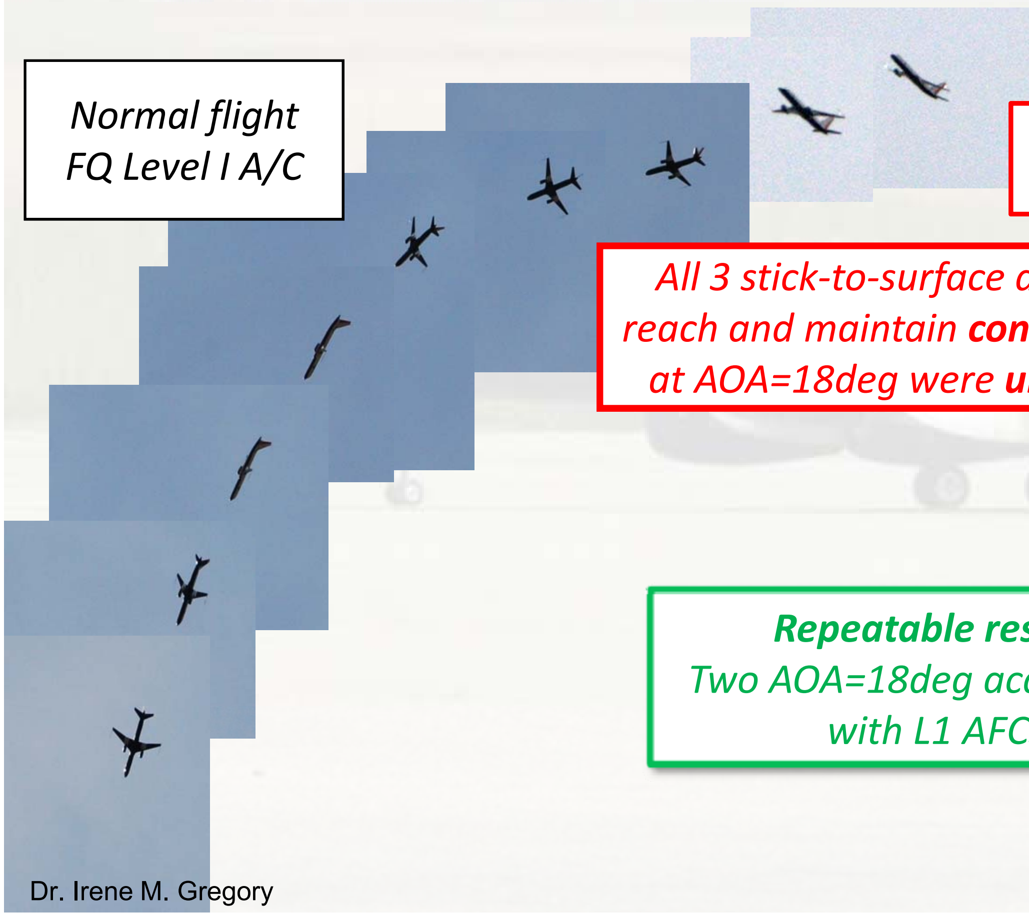


- Pilot called "knock it off" but did not abandon the control law
- Test engineer simply flipped the switch to turn off the stability degradation fault and the controller recovered its nominal performance immediately.
- The pilot proceeded to fly into a typical aggressive turn less than 10 seconds after the fault was terminated (~ 770 seconds)

L1 Adaptive FCL – Post-stall, High AOA Flight

- **Open-loop aircraft** tends to aggressively **roll off** between 13deg and 15deg AOA and exhibits significant degradation in pitch stability
- **L1 controller** significantly improved pilot's ability to fly the aircraft at high angles of attack and decreased his workload
  - Robust to control deflection saturation

Normal flight
FQ Level I A/C

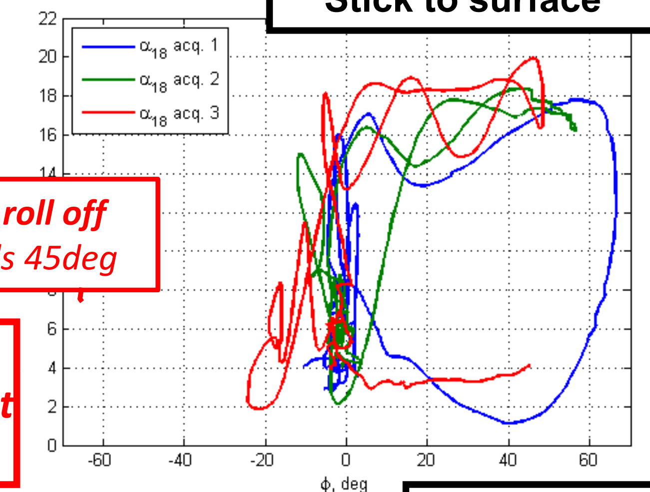


Aggressive roll off
Bank exceeds 45deg

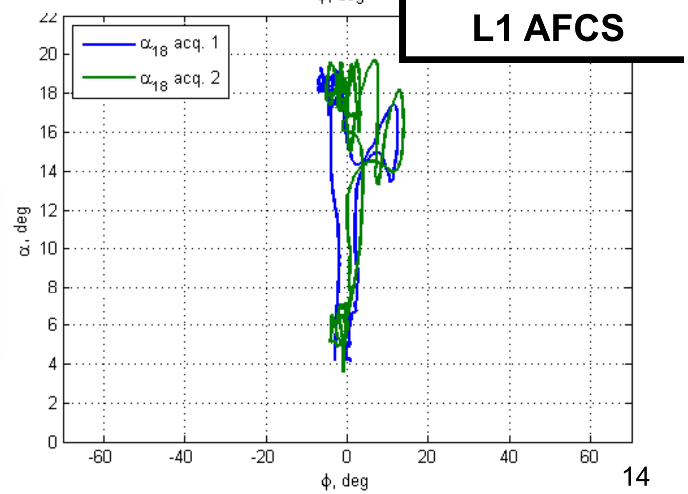
*All 3 stick-to-surface attempts to reach and maintain **controlled flight** at AOA=18deg were **unsuccessful***

Repeatable results
Two AOA=18deg acquisitions with L1 AFCS

Stick to surface

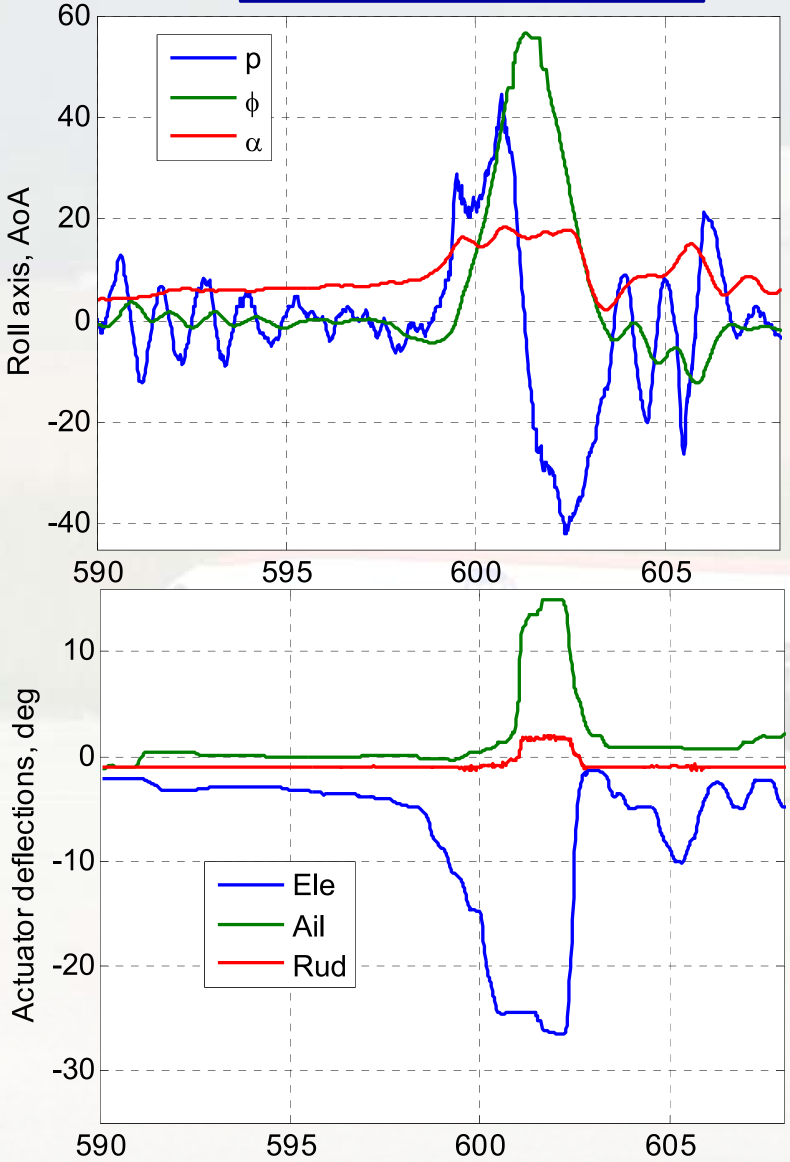


L1 AFCS

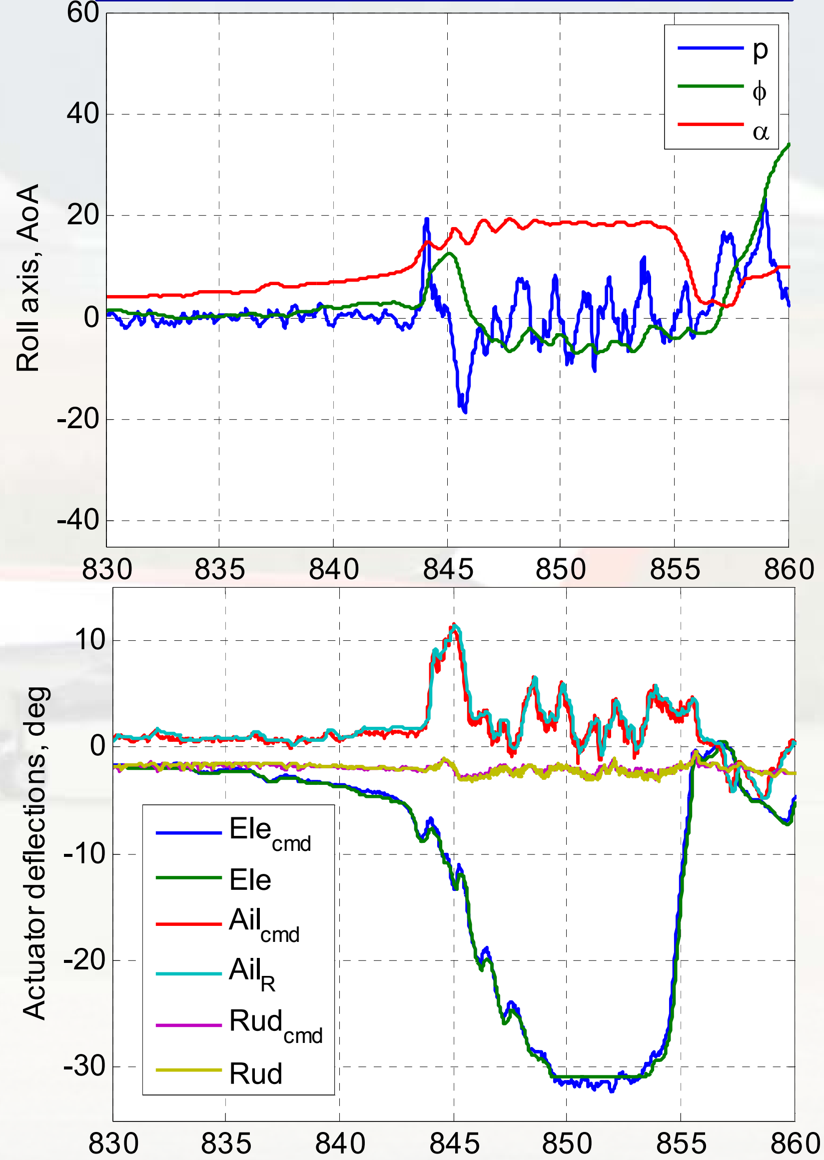


L1 Adaptive FCL – High AOA Flight

Flt 25: stick – surface



Flt 23: L1 all-adapt - α, p-β cmd



September 2010 Deployment

L1 adaptive controller enabled unsteady aerodynamic modeling at post-stall AoA*

Changes made to L1 adaptive controller to improve AoA tracking performance in post-stall regime

- Changed from body to stability axis for roll and yaw rate
- Added SAS feedback in roll rate for 11<α<17
- Increased bandwidth of AoA low pass filter in the L1 Control Law

- Penalty: decreased tolerance to time delay (from 125 msec to 95 msec)

*Stall AoA characterized by abrupt roll-off, $\alpha_{stall} = 13.5\deg$

Flight Control Law Evaluation Matrix II

	Task	Downwind straight leg	Upwind straight leg	Turns
1	Offset Landing	Achieve good trim	No fault 1st – Practice landing 2nd - Evaluation landing	N/A
2	Offset Landing Neutrally stable: $\Delta(C_{m\alpha}$ & $C_{lp}) \approx -100\%$	Achieve good trim	Fault Engaged Evaluation landing	Disengage Fault
3	Offset Landing Unstable: $\Delta(C_{m\alpha}$ & $C_{lp}) \approx -125\%$	Achieve good trim	Fault Engaged Evaluation landing	Disengage Fault

- $C_{m\alpha}$ – degraded by 2 inboard elevator segments → 50% reduction in pitch control effectiveness
- Clp – degraded by spoilers

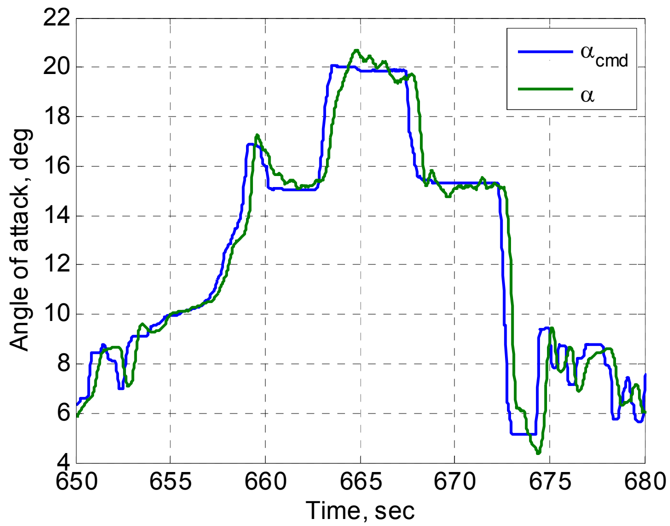
L1 Support Tasks on Modeling – Sept. 2100

	Task	1st straight leg	2nd straight leg
1	β - Vane Calibration	Flat turn: 2 deg/s ramp up to desired β value hold for the remainder of straight leg $\beta = [\pm 2, \pm 4, \pm 6, \pm 8]$ 1 deg/s ramp up to desired β value; $\beta = \pm 8$	Repeat
2	α - Vane Calibration	Variable α strategy: set engine RPM, let α increase for remainder of straight leg Constant α strategy: set engine RPM, pilot acquires and holds target α for remainder of straight leg	Repeat
3	Unsteady Aerodynamics Modeling	Post-Stall High α Tracking: Attain stable flight at α=18, inject wave train: (1) Step [18→15, 15→20, 20→15] (2) Schroeder sweep (3) Variable frequency Sinusoid	

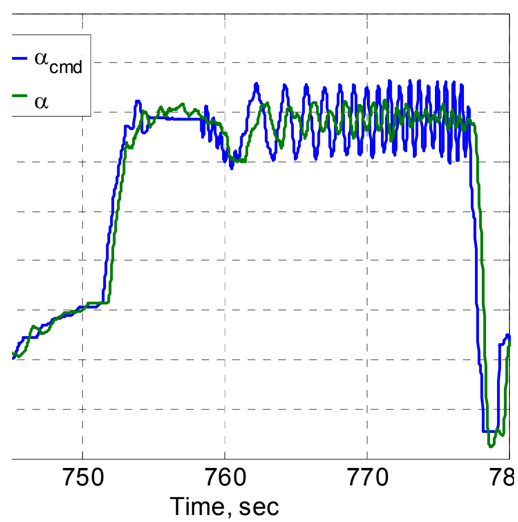
High AoA Tracking – Unsteady Aero

- Modeling unsteady aerodynamics by emulating the dynamic motion in the wind tunnel – determining efficacy of GTM to be a “flying wind tunnel”
- Target AoA = 18 deg – post-stall
- Injected inputs for L1 FCL to track – Step, Schroeder, Sinusoids

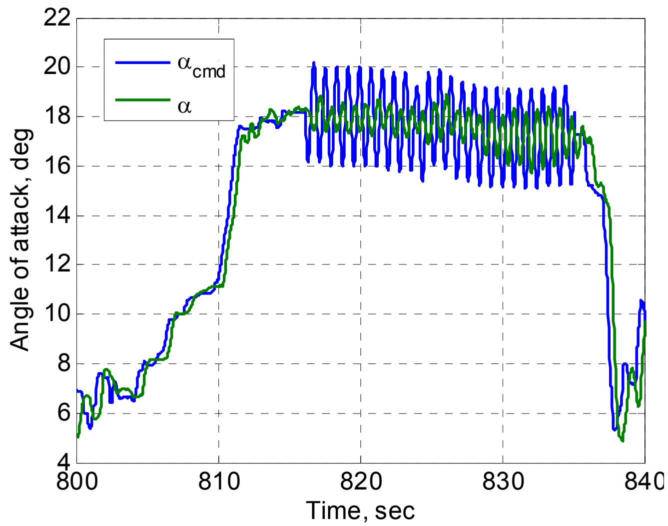
Step Input



Schroeder Input



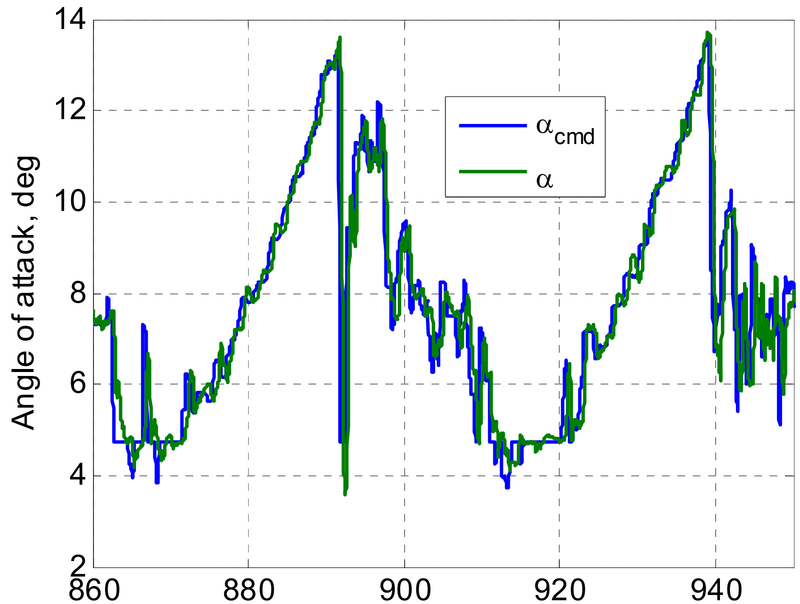
Sinusoids Input

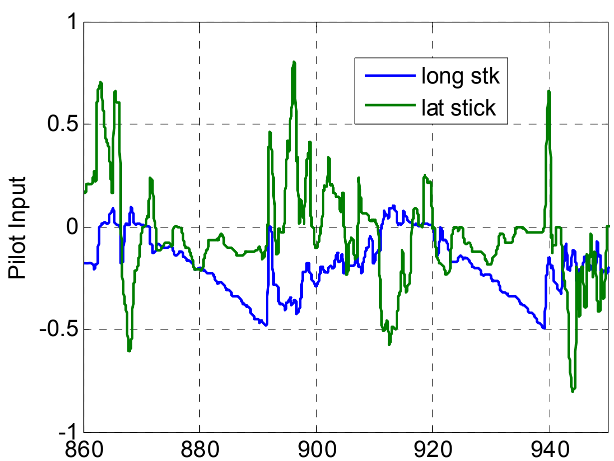


Angle of Attack Vane Calibration

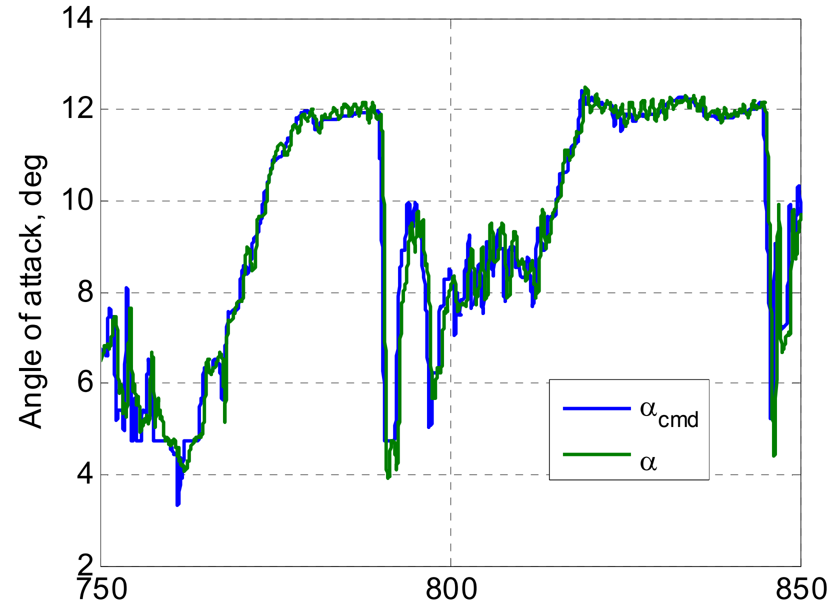
- Stall occurs between 12 and 13 deg AoA

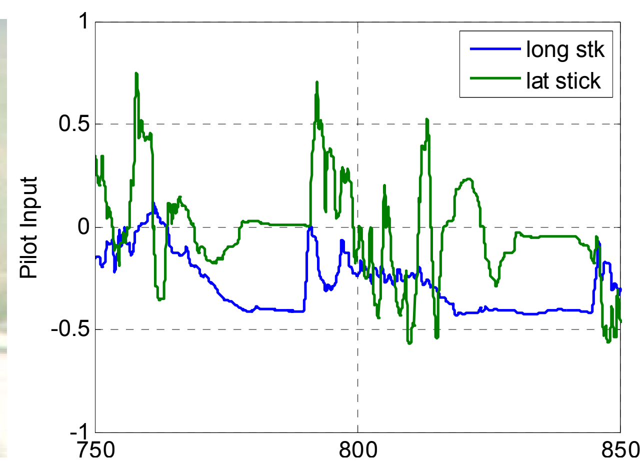
Variable AoA Strategy





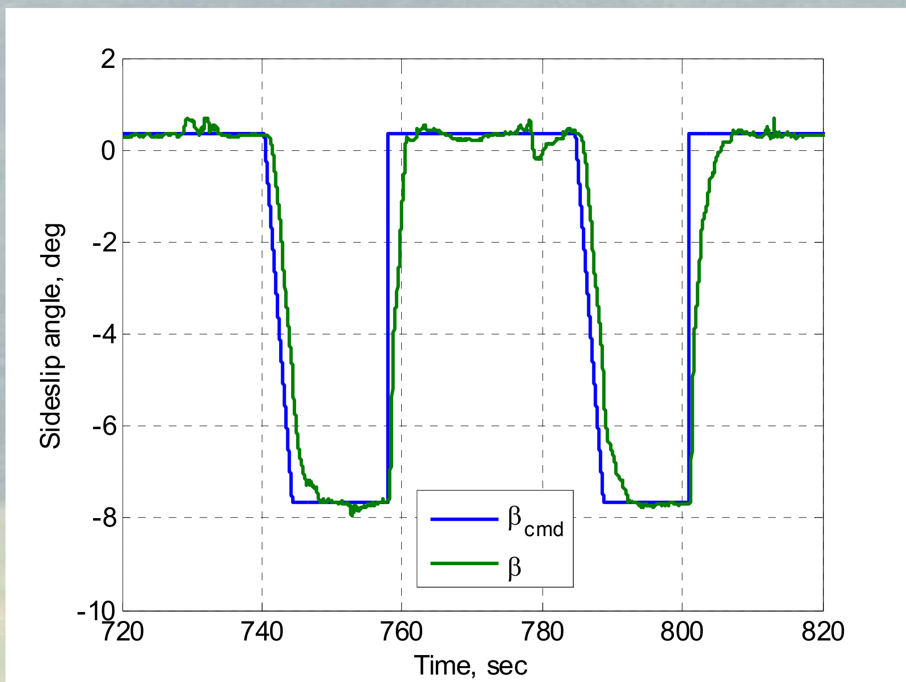
Constant AoA Strategy

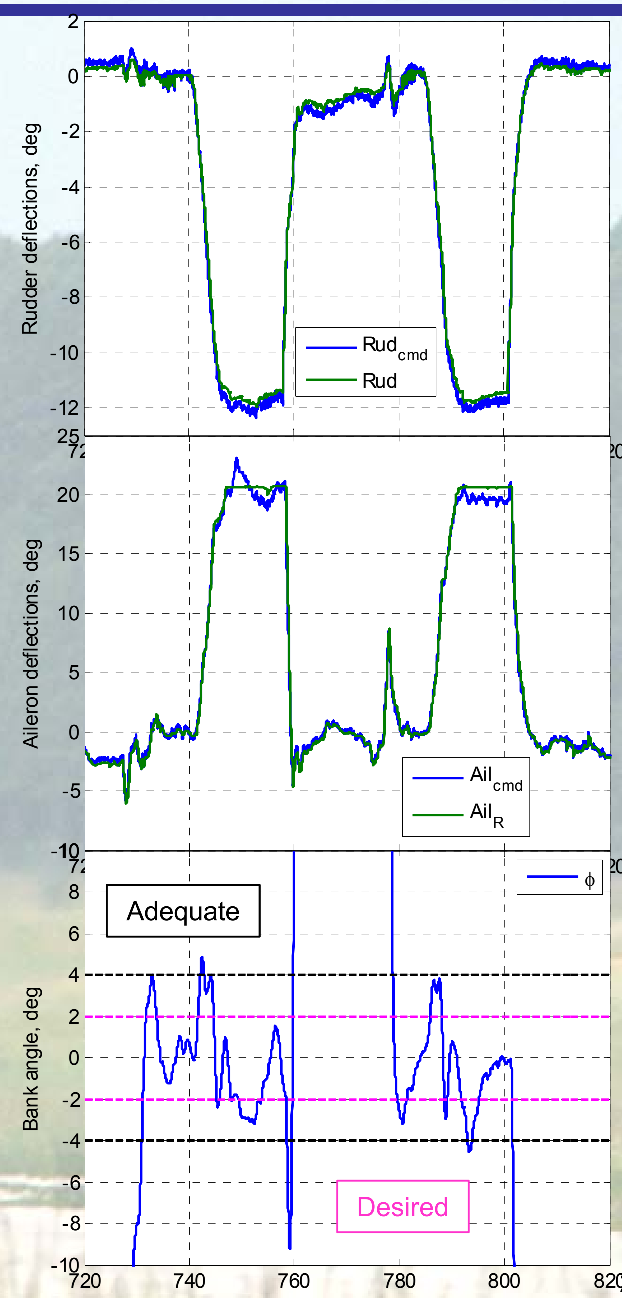




Sideslip Angle Vane Calibration

- Flat turn – hold target sideslip
  - Minimize lateral axis excursions





Offset Landing

- Initial offset
  - 90 ft. lateral, 1800 ft. downrange, 100 ft. above the runway
- Performance boundaries:
  - Desired – $|\phi|$ =±10 deg; $|\gamma|$=±1 deg; landing box = 24’x328’
  - Adequate - $|\phi|$ =± 20 deg; $|\gamma|$=± 3 deg; landing box = 9’x30’
- Flying qualities ratings taken for nominal, neutrally stable, unstable airplane

Nominal

CHR 3

Neutrally stable

CHR 4

Unstable

CHR 7

L1 Adaptive Controller Flight Test Summary

- An all adaptive controller that provides both nominal aircraft performance and takes care of large changes in aircraft dynamics
  - No gain scheduling, no baseline to assist
- One controller designed at nominal flight condition (80KEAS, 4 deg AOA) to provide satisfactory FQ and robustness
- Controller able to handle large additional latency in the system (robustness measure) and provide nominal to slightly degraded performance for stability degraded cases (doublet tracking with neutrally stable aircraft).
- Controller provided **predictable response** to the pilot under stability degradation and **graceful performance degradation** once nominal response was unachievable
- Improved response in post-stall flight → providing controllable aircraft to the pilot and facilitating safe return to normal flight
- The classical tradeoff between robustness to system latency vs. performance was found to be consistent with the theory.

QUESTION?