



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

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Subscale Flight Testing

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

Under adverse conditions:

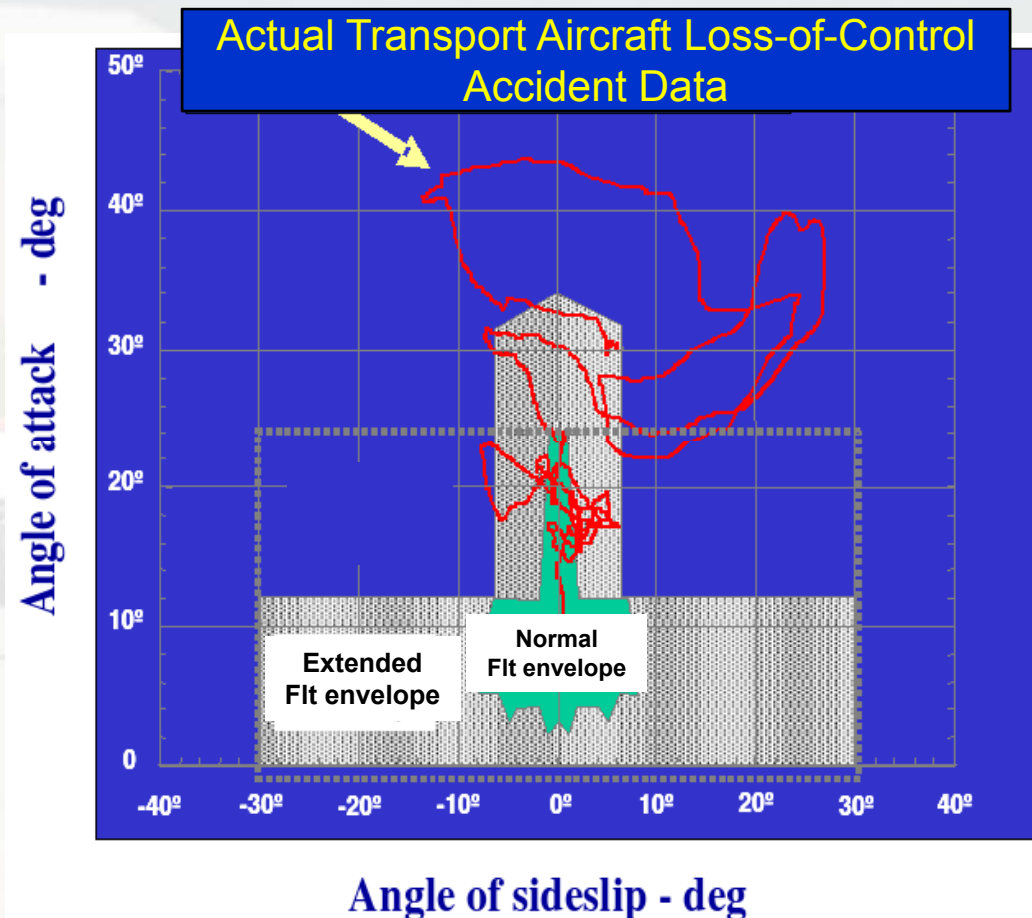
Control law objectives:

- 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.*

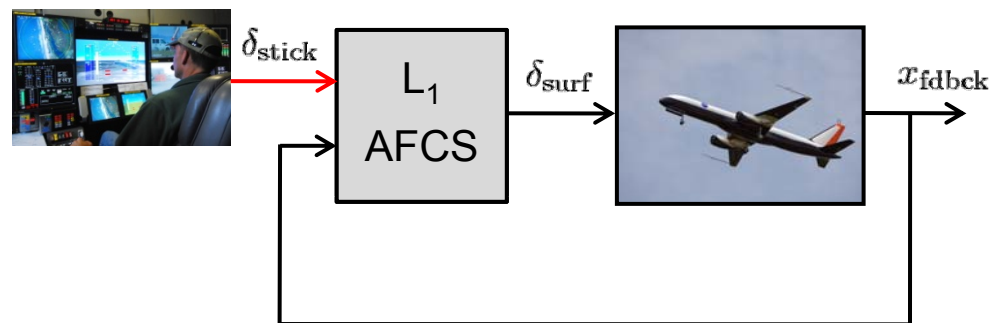


- 5.5 % geometrically and dynamically scaled model
 - 82 in wingspan, 96 in length, 49.6 lbs (54 lbs full), 53 mph stall speed
 - Model angular response is 4.26 **faster** than full scale
 - Model velocity is 4.26 times slower than regular scale



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:

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

Matched uncertainty Unmatched uncertainty

$$z(t) = g_0(x_z(t), t), \quad \dot{x}_z(t) = g(x_z(t), x(t), t), \quad x_z(0) = x_{z0}$$

$$\mu(s) = G_a(s)u(s),$$

Actuator
dynamics

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

Unmodeled
dynamics

- 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

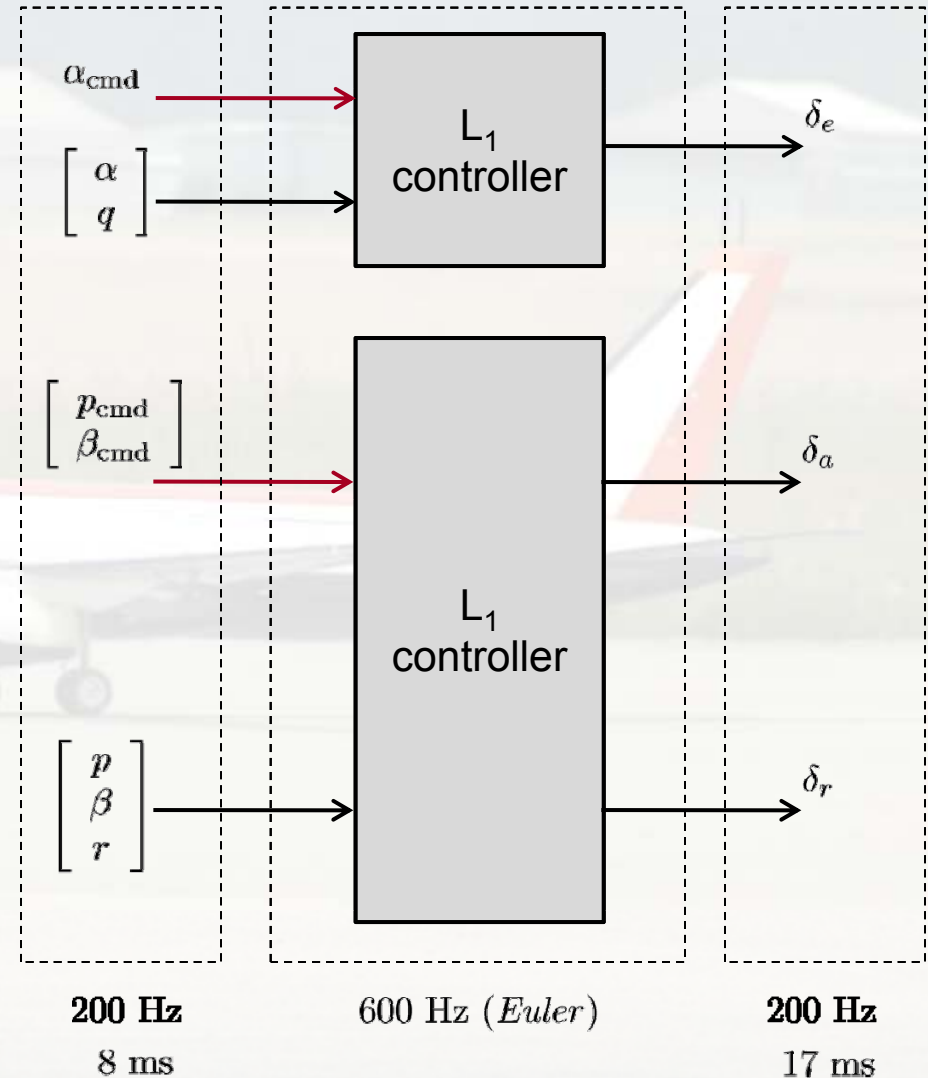


- Control augmentation system – α -command, p- β command
- Designed at 1 flight condition – 80-KEAS (~4.5 deg AoA)

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

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

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





Flight Control Law Evaluation Matrix I



	Task	1 st straight leg	2 nd straight leg	Turns
1	Latency Injection (5ms / 5 sec)	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Fault Engaged
2	$\Delta(Cm\alpha \text{ \& } Clp) \approx 00\%$	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
3	$\Delta(Cm\alpha \text{ \& } Clp) \approx -50\%$	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
4	$\Delta(Cm\alpha \text{ \& } Clp) \approx -75\%$	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
5	$\Delta(Cm\alpha \text{ \& } Clp) \approx -100\%$ (neutrally stable)	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault
6	$\Delta(Cm\alpha \text{ \& } Clp) \approx -125\%$ (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

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



Flight Control Law Evaluation Matrix II



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

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



L1 Support Tasks on Modeling – Sept. 2100



	Task	1 st straight leg	2 nd straight leg
1	β - Vane Calibration	<u>Flat turn</u> : 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	<u>Variable α strategy</u> : set engine RPM, let α increase for remainder of straight leg <u>Constant α strategy</u> : set engine RPM, pilot acquires and holds target α for remainder of straight leg	Repeat
3	Unsteady Aerodynamics Modeling	<u>Post-Stall High α Tracking</u> : Attain stable flight at $\alpha=18$, inject wave train: (1) Step [18 $\rightarrow$ 15, 15 $\rightarrow$ 20, 20 $\rightarrow$ 15] (2) Schroeder sweep (3) Variable frequency Sinusoid	



GTM T2 – Flight Test Evaluation (June 2010)



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

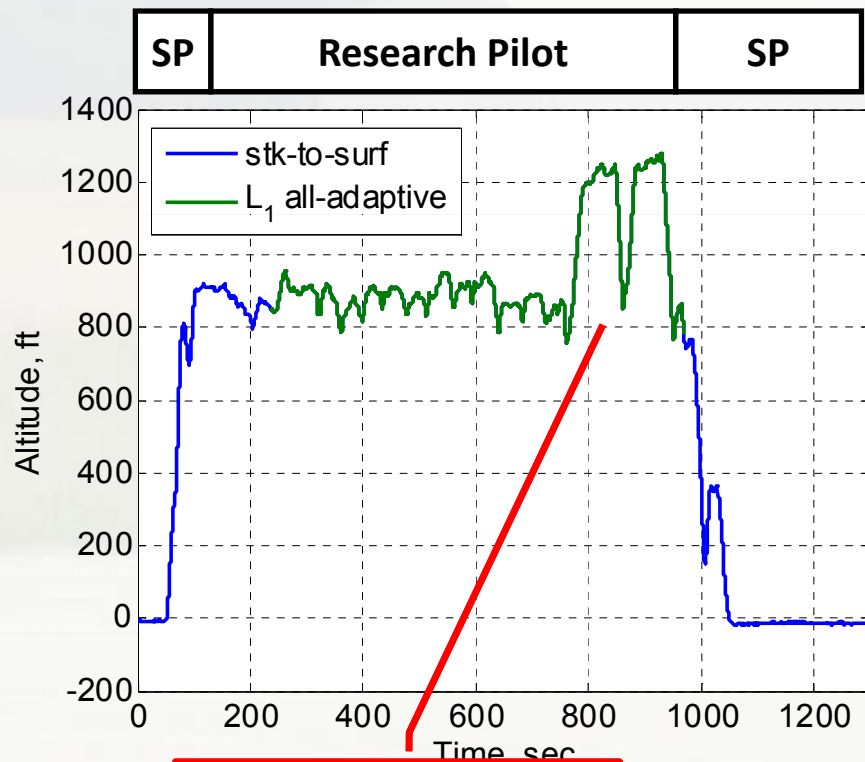
- **Not an augmentation** to a baseline controller, that provides nominal aircraft performance
- Flight Control Law related tasks during June 2010 deployment :
 - Injected longitudinal and lateral stick doublets for each fault, continuous stick doublets on straight legs during latency fault
 - **Latency 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**



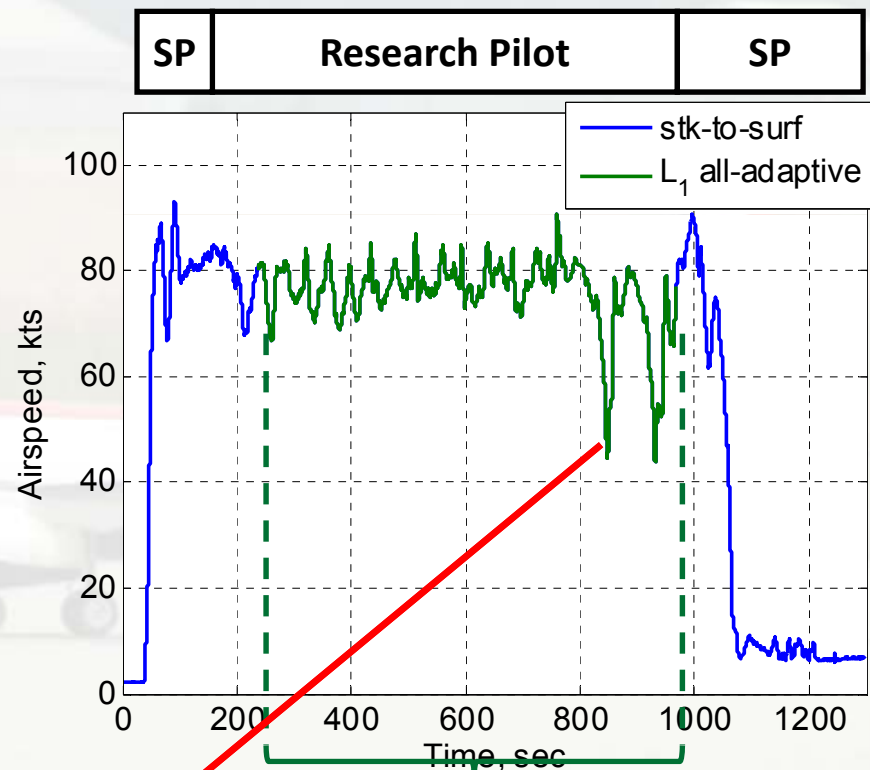
GTM T2 - Flight Test Evaluation (June 2010)



➤ FLT23: L1 all-adaptive FCL under light turbulence



High AOA flight



Post-stall regimes

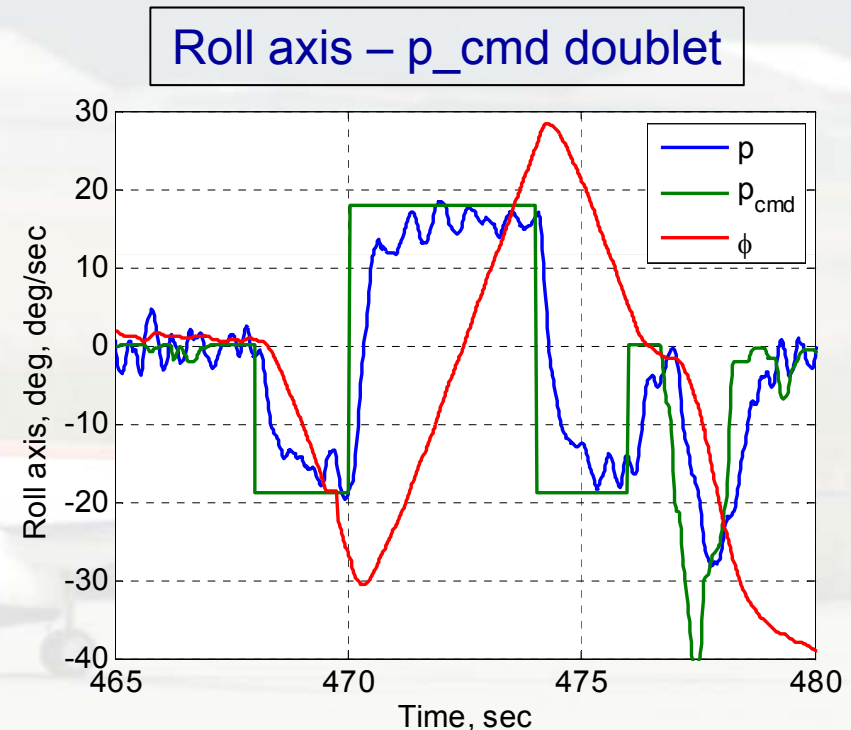
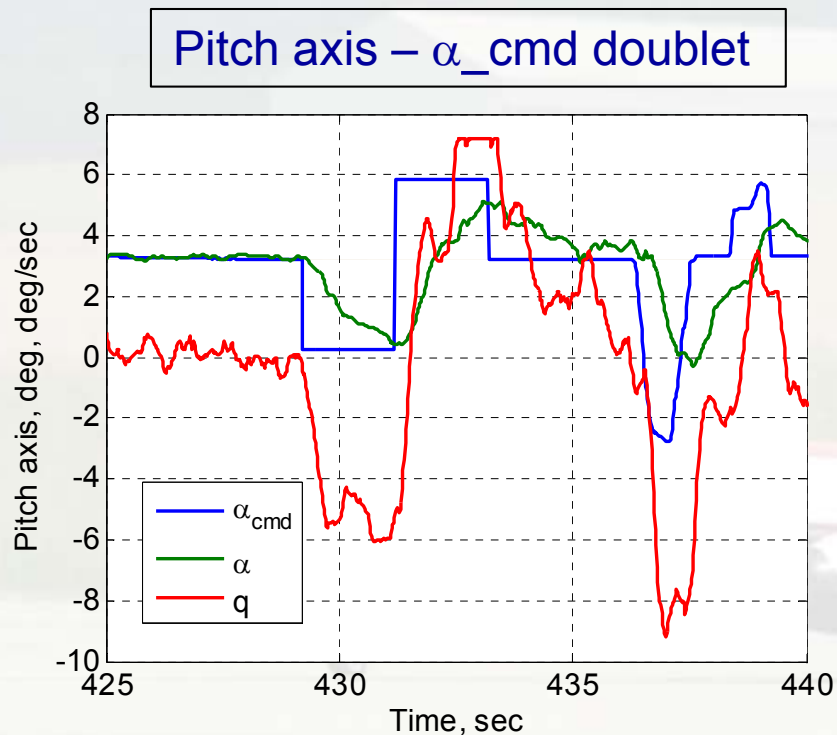
~12.5 mins
of flight
with L1



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



- 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]

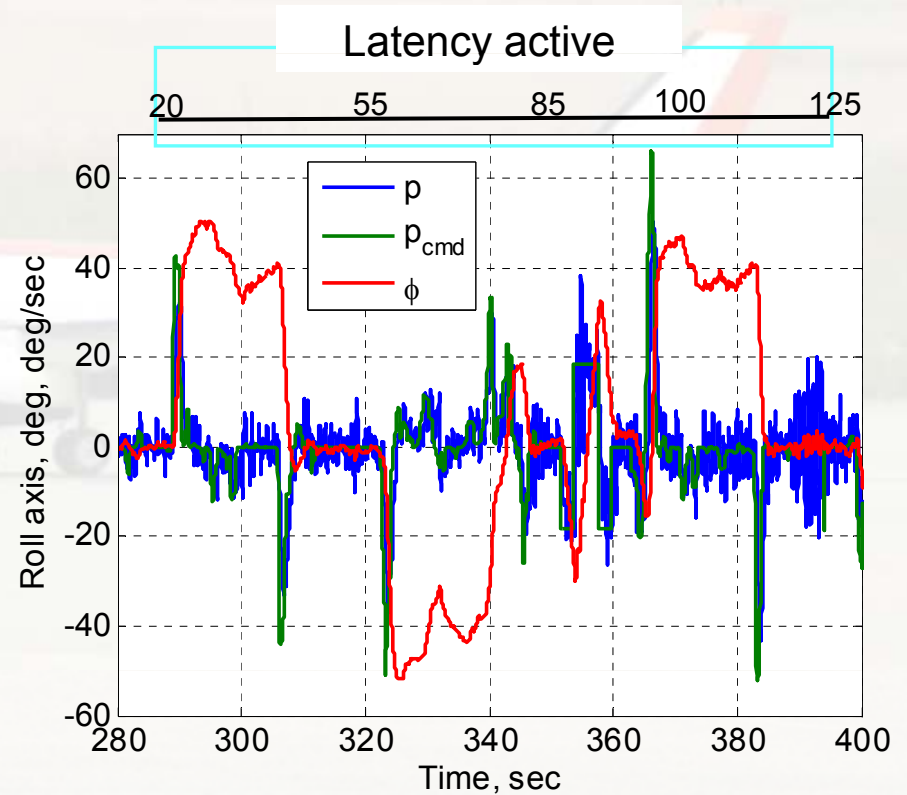
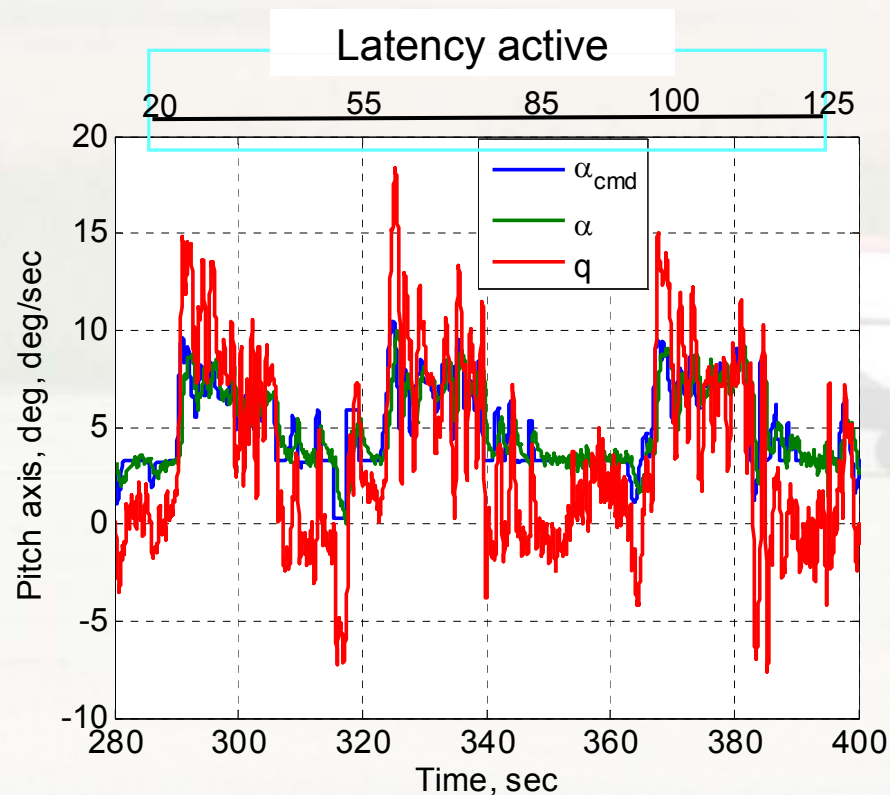


Latency Response



➤ 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

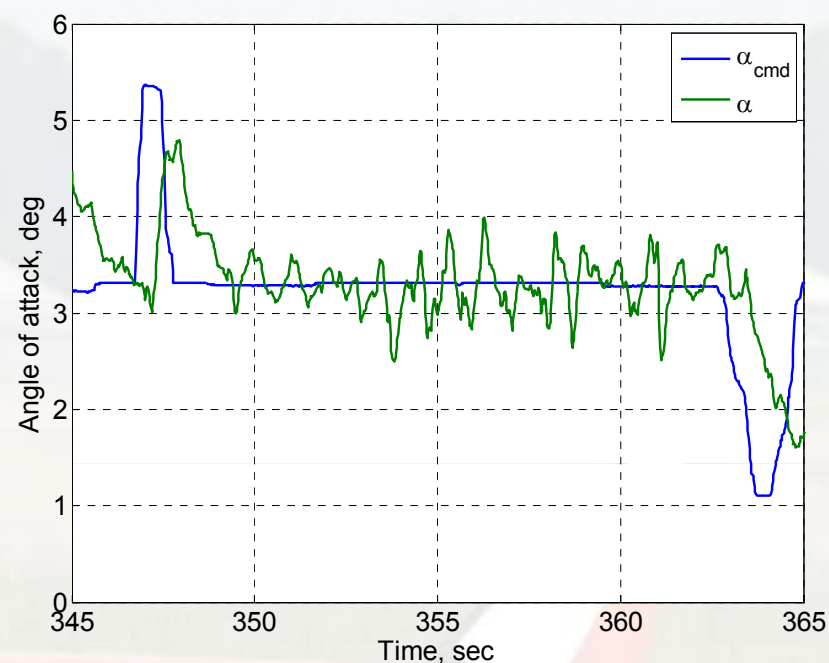
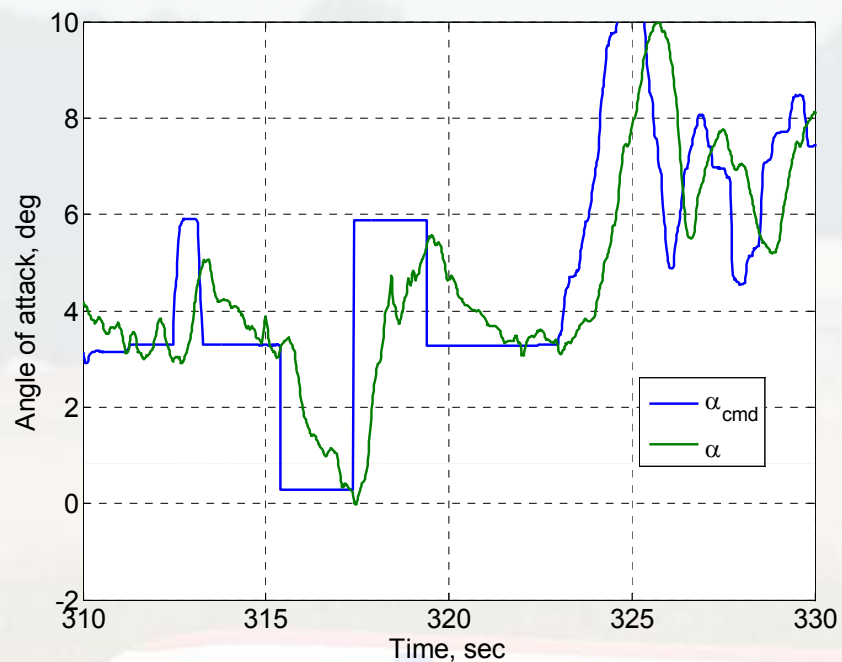




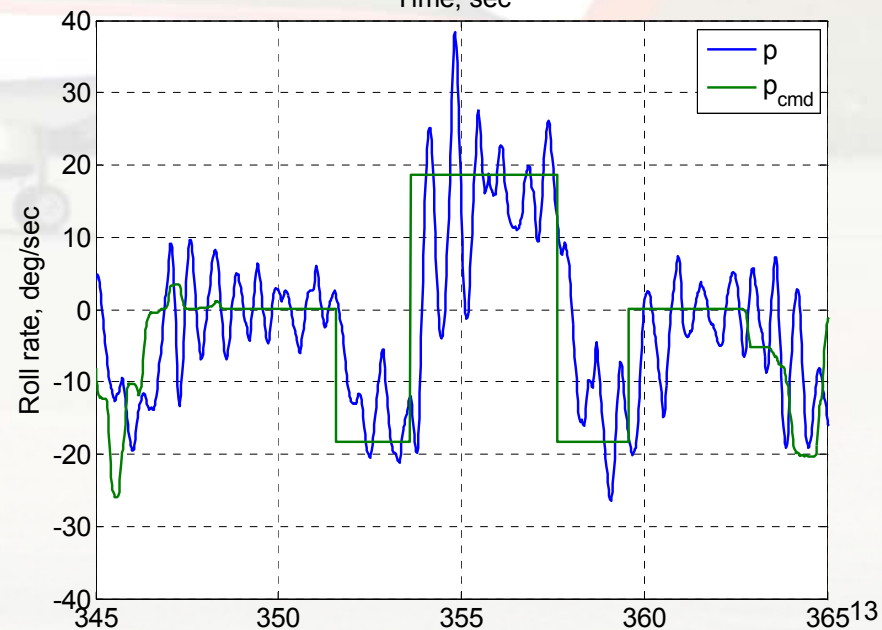
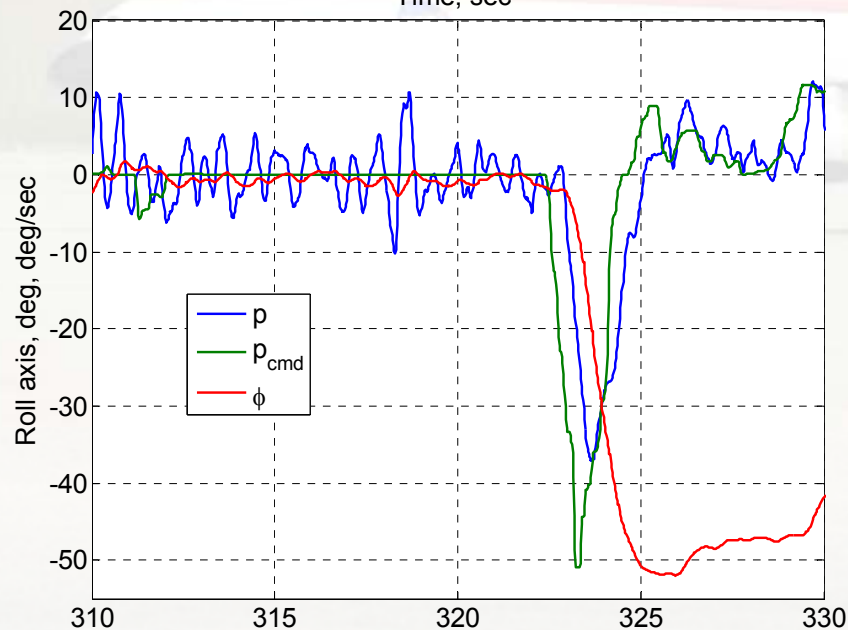
Latency Fault Doublet Response



Angle of attack



Roll rate

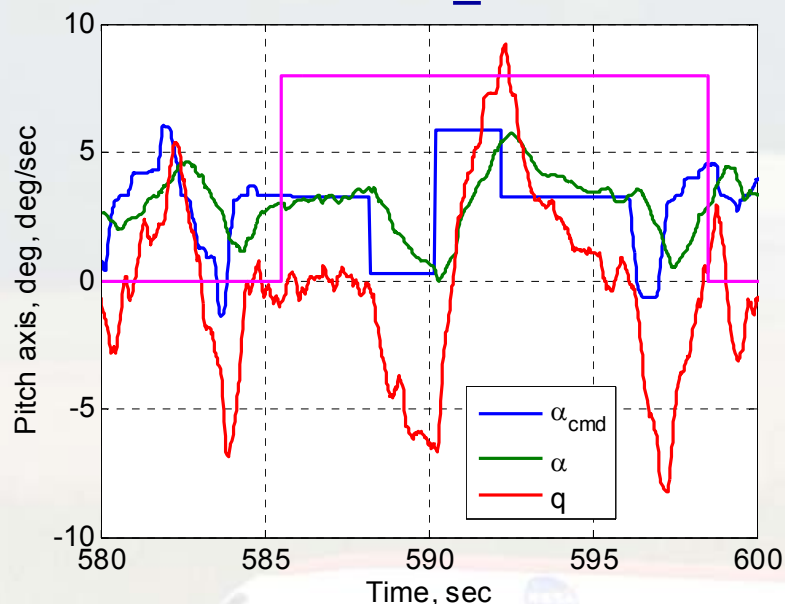




Cm α /Clp Degradation WT Response

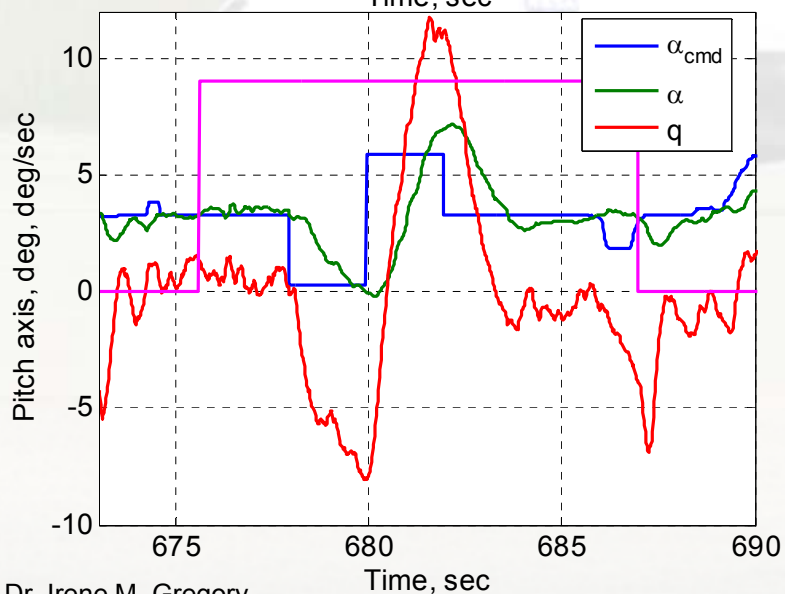
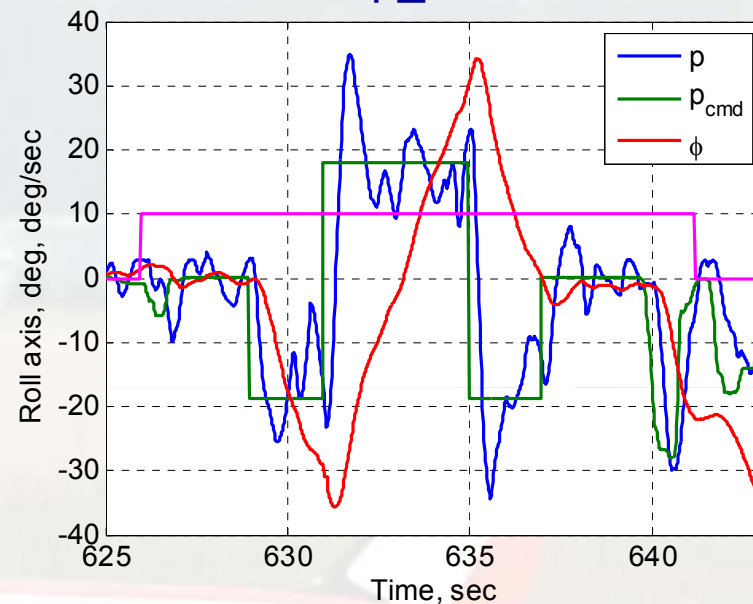


Pitch axis – α_{cmd} doublet

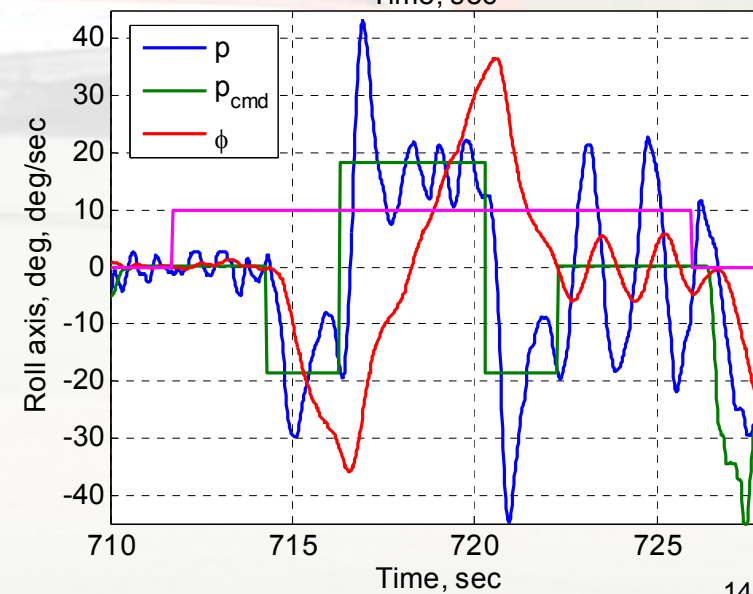


Cm α /Clp
↓ 75%
↓50% long cntrl

Roll axis – p_{cmd} doublet



Neutrally stable
Cm α /Clp
↓ 100%
↓50% long cntrl

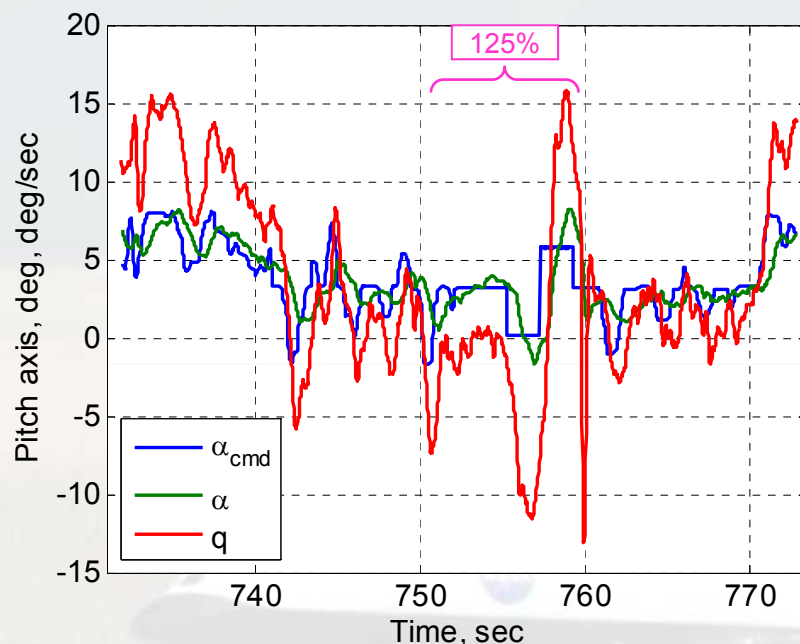




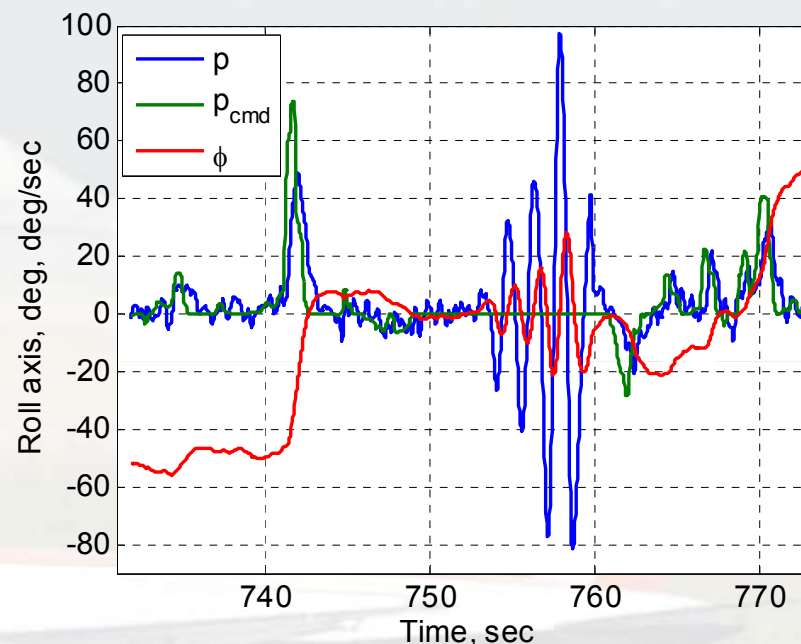
125% $C_{m\alpha}/C_{lp}$ Degradation WT Response



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)

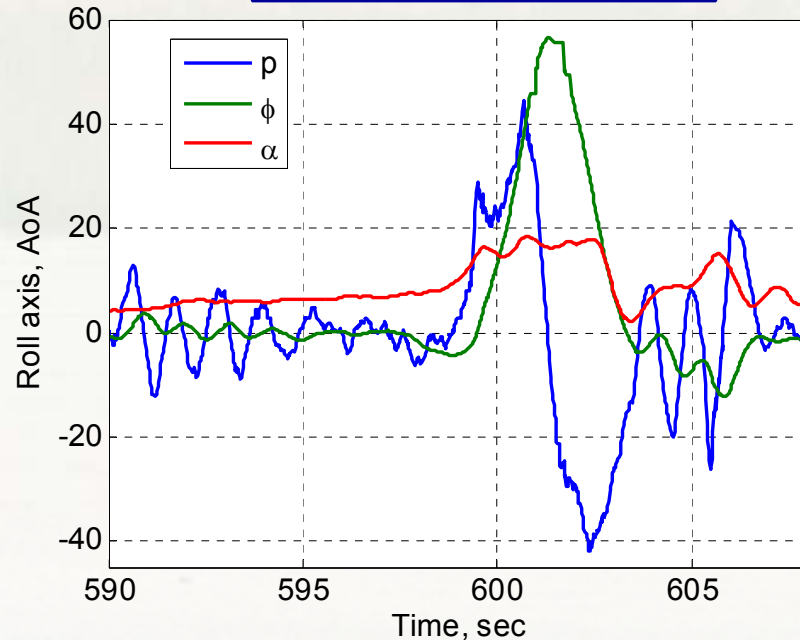


L1 Adaptive FCL – High AOA Flight

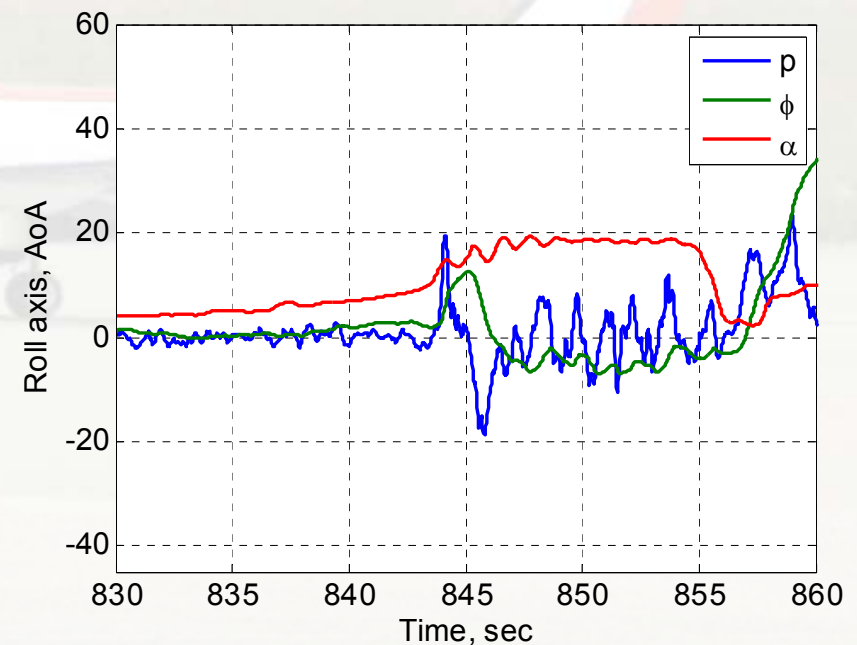


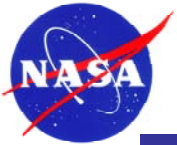
- **Open-loop aircraft** tends to aggressively **roll off** between 13deg and 15deg AOA and exhibits significant degradation in pitch stability
- L_1 all-adaptive controller significantly improved pilot's ability to fly the aircraft at high angles of attack and decreased his workload.
- Robust to control deflection saturation

Flt 25: stick - surface



Flt 23: L1 all-adapt
 α , p - β cmd

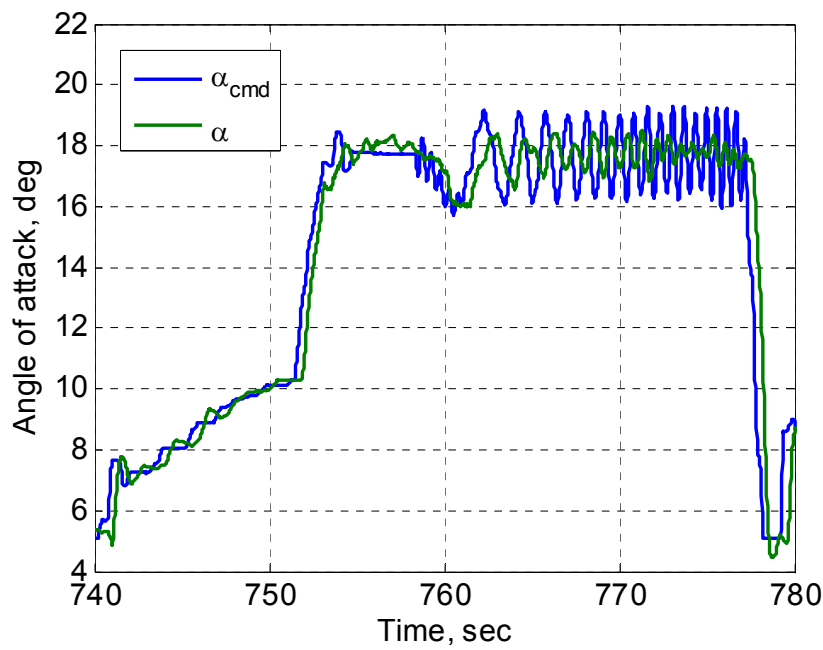




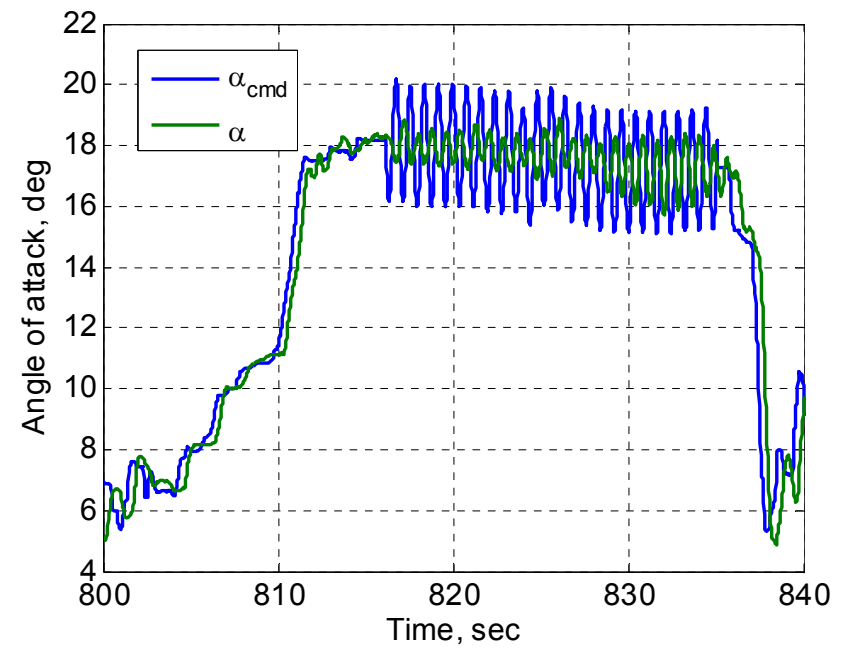
High AoA Tracking – Unsteady Aero

- 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

Schroeder Input



Sinusoids Input

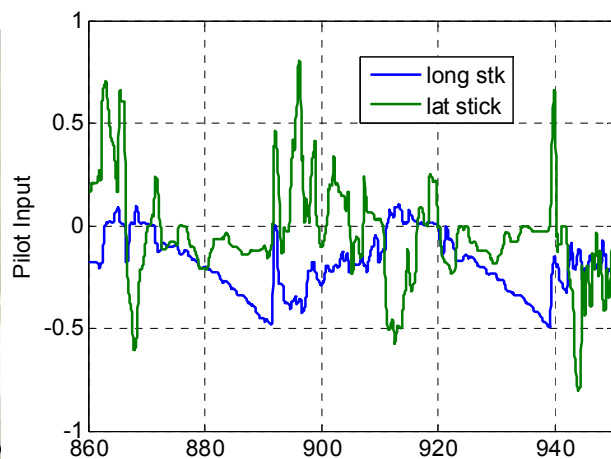
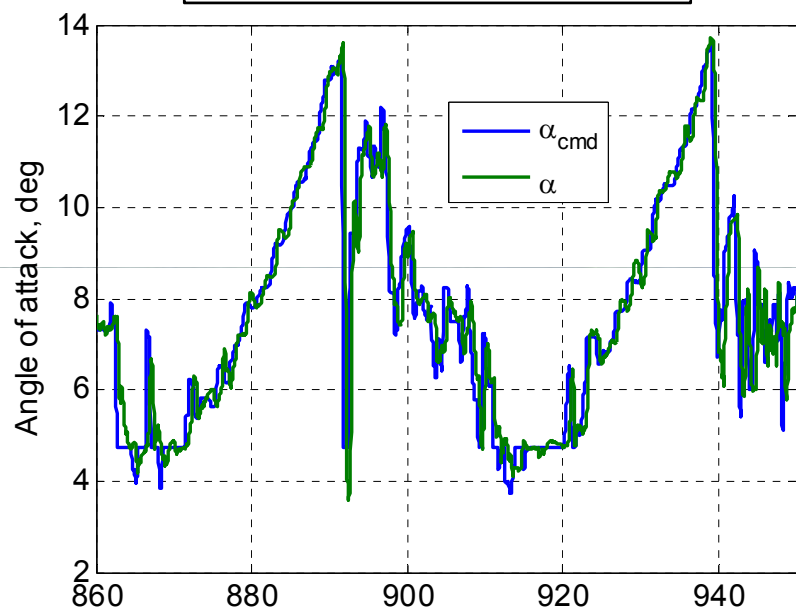




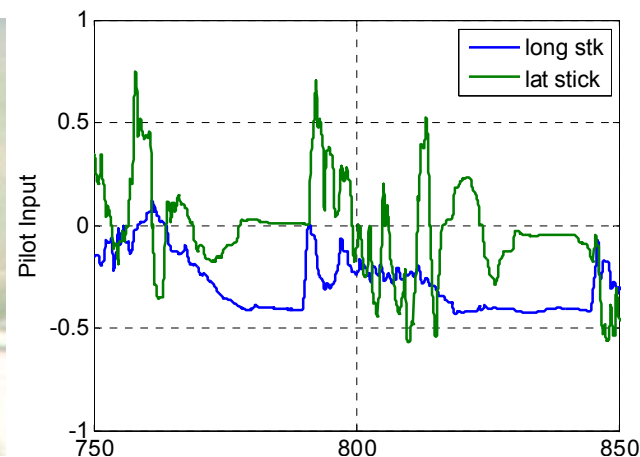
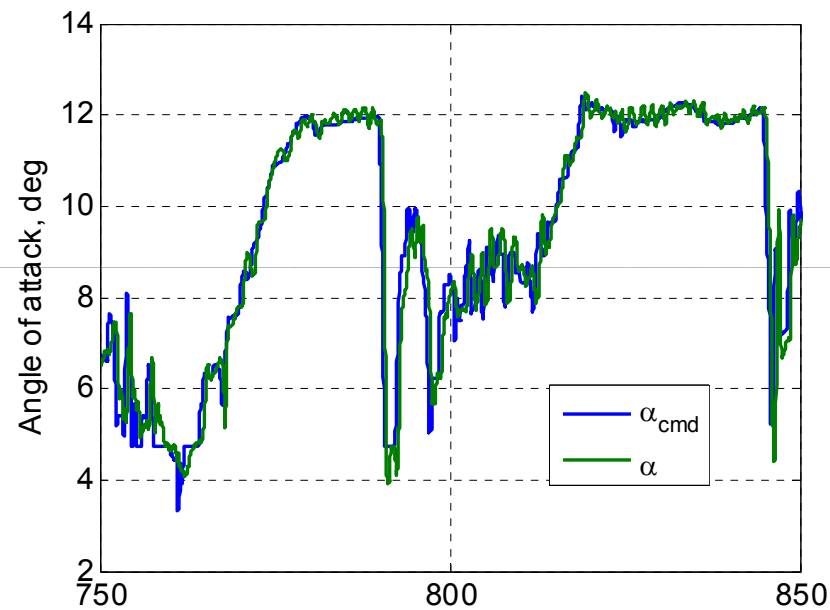
Angle of Attack Vane Calibration

- Stall occurs between 12 and 13 deg AoA

Variable AoA Strategy



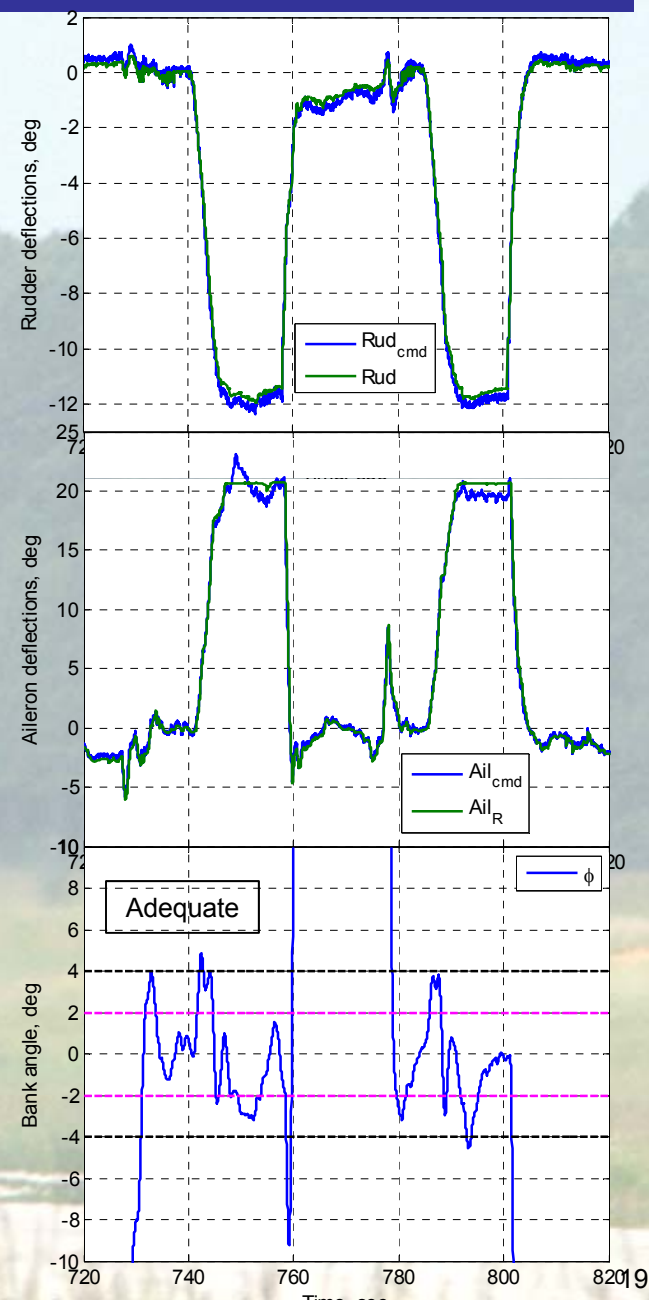
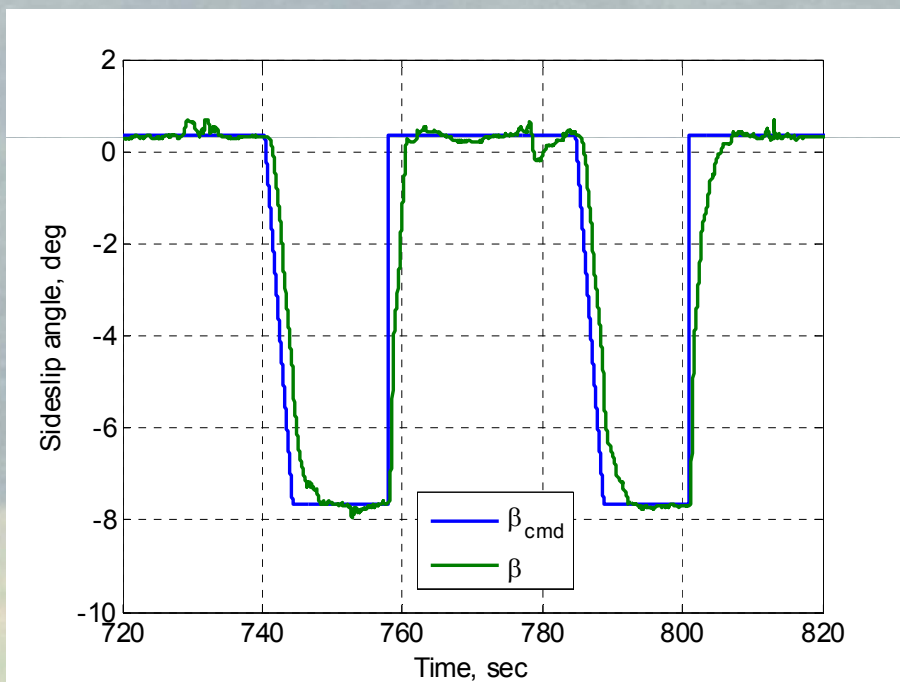
Constant AoA Strategy





Sideslip Angle Vane Calibration

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





Offset Landing

- Initial altitude is 100 ft
- Initial offset is 75 ft from centerline
- Performance boundaries:
 - Desired – $|\text{bank}| = \pm 10$; $|\text{gamma}| = \pm 1$; landing box = 3'x10'
 - Adequate - $|\text{bank}| = \pm 20$; $|\text{gamma}| = \pm 3$; landing box = 9'x30'
- Flying qualities ratings taken for nominal, neutrally stable, unstable airplane

Insert HUD video here
nominal

CHR 4

Insert HUD video here
Neutrally stable

CHR 4

Insert HUD video here
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?

