Advanced Control Research Laboratory

University of Illinois at Urbana-Champaign

L_1 Adaptive Control and its Transition to Aerospace Applications

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Outline

- **Overview of Various Control Design Methods**
- **Adaptive Control Methods**
- **Internal Model Control and L_1 Adaptive Control**
- **AirSTAR Project**
  - ✓ L_1 Adaptive Control for Multi-Input Multi-Output System
  - ✓ AirSTAR Flight Tests
- **Ongoing Transition Efforts in Europe**
- **Conclusions**

Controller Design Methods

❖ Non-model Based Approach

- PID Control
- Unfalsified Control (Safonov 1996)
- Fuzzy Logic Control (Zadeh 1965)
- Black Box Adaptive Control
- ...

➢ Tuning of 3 gains to achieve desired specifications

➢ Data driven online selection of a controller among a predefined set of candidates

➢ Smooth switching of control strategy based on predefined events or rules (based on fuzzy logic)

➢ Relies mostly on aposteriori information. Attempts to identify the behavior of the system online.

❖ Model Based Approach

- LQR Control
- Nonlinear Dynamic Inversion
- Internal Model Principle (IMP) (Francis 1976)
- Internal Model Control (IMC) (Morari 1982)
- H_∞ methods (Zames, Helton, Tannenbaum 1970's)
- Gray Box Adaptive Control
- ...

➢ For a given system model generate control which minimizes a quadratic cost function

➢ A method to cancel a known system nonlinearity.

➢ Controller must incorporate known model of disturbance in order to compensate for it

➢ Controller incorporates nominal model of the system

➢ Robust control design for an uncertain system is represented as an optimization problem

➢ Structure of the system and apriori parameter knowledge is available, adaptation is used to address uncertainty in system parameters

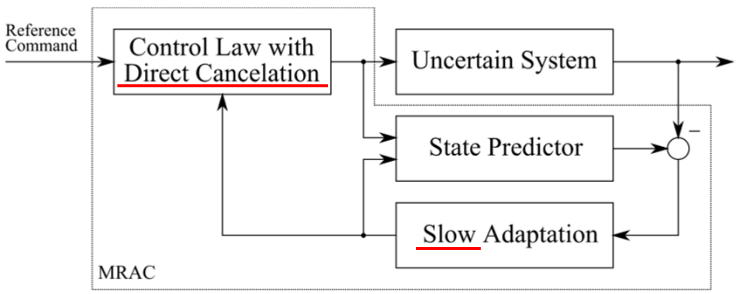
Design procedure of model based approach relies on the apriori available model of the system

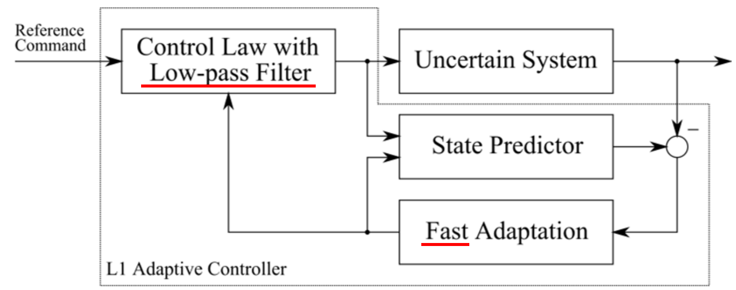
Adaptive Control Solutions

❖ Indirect MRAC

❖ L_1 Adaptive Control

<< Similarity in Structure >>





<< Departure in Philosophy >>

- The current estimated values are used to compensate for the uncertainty
  - Estimation and control run in the same frequency range
  - Resulting coupling may lead to poor performance and instability
- Performance of the estimation loop depends on the adaptation rate
  - Higher rates affect robustness and transient
  - Tradeoff is resolved by adaptation rate

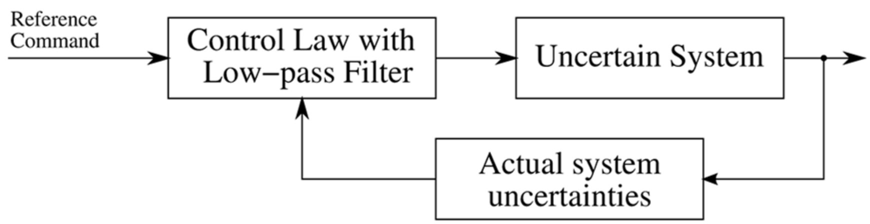
- *MRAC aims for complete compensation of the uncertainty*
  - **Ambitious (not achievable) control objective**

- The control signal is generated using a lowpass filter
- Large adaptation rates shift estimation dynamics to high frequency range
  - Estimation and control are decoupled
  - Robustness is not affected by adaptation rates
- Performance of the estimation loop can be arbitrarily improved by increasing the adaptation rates

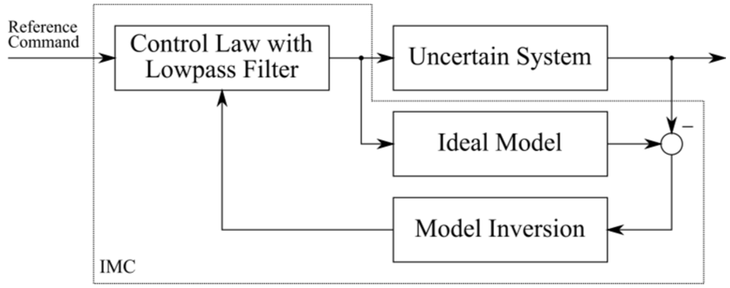
- *L_1 adaptive control system aims for partial compensation of the system uncertainty within the bandwidth of the lowpass filter*
  - **Achievable control objective**

L_1 Adaptive Control and IMC Architectures

- L_1 adaptive controller shares the philosophy with IMC controller
  - Both architectures aim for compensation of the system uncertainty within the bandwidth of the lowpass filter



- L_1 adaptive controller uses <u>fast estimation loop</u> to obtain the estimate of the system uncertainty
- IMC controller <u>inverts the ideal system dynamics</u> to measure the uncertainty at the system input

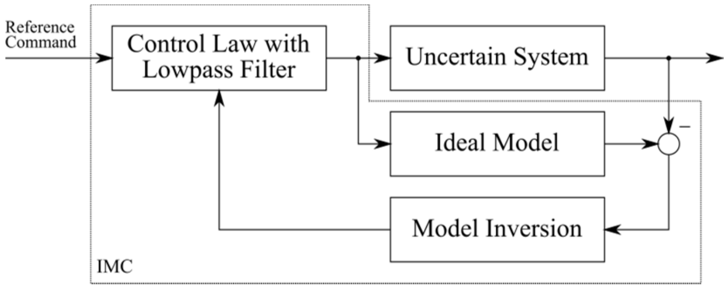


- L_1 adaptive controller achieves the input-output behavior of IMC controller in the presence of fast adaptation rates
  - We refer to IMC controller as "limiting controller"
  - <u>From input-output behavior perspective</u> we can talk about <u>equivalence of these control methods</u>

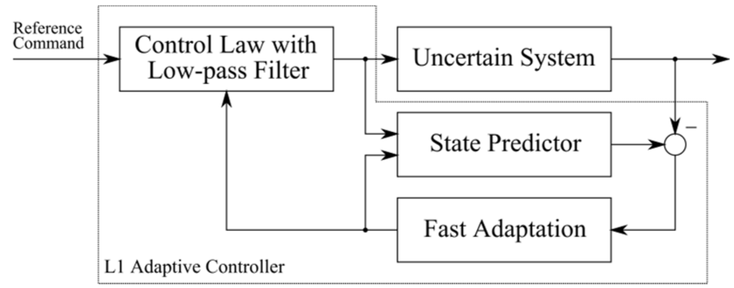
  - Are there any differences between L_1 and IMC from other points of view?

Comparison of the Architectures

<u>Internal Model Control</u>

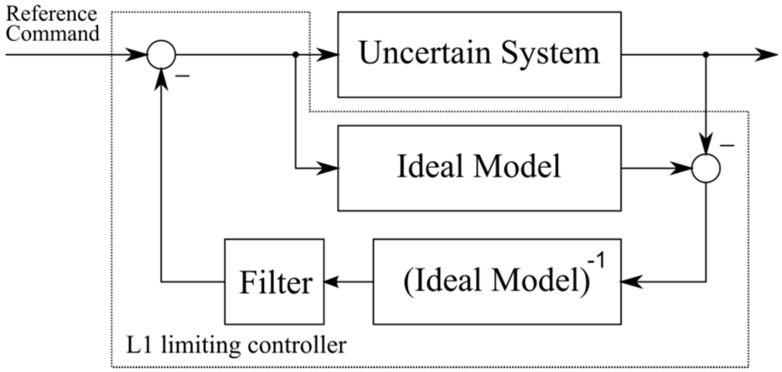


<u>L_1 Adaptive Control</u>

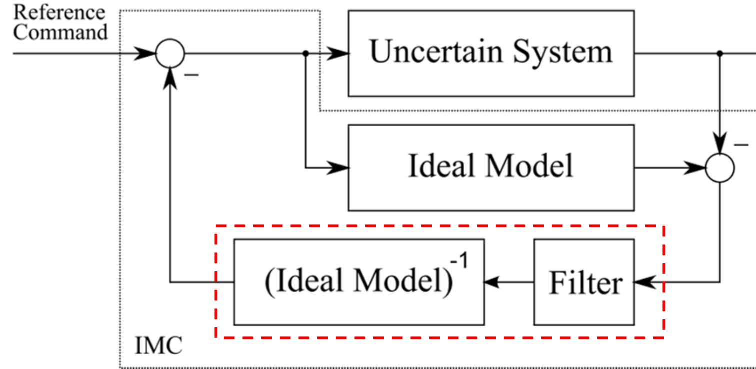


- L_1 adaptive controller offers <u>significantly richer control architecture</u>
  - Straight forward modification of the estimation loop to address real world requirements without affecting the control law performance (Z. Li CDC 2012, Vanness ACC 2012, Kharisov ACC 2012)
- IMC requires explicit inversion of the ideal model
  - Computation of the system inverse may become a limitation
- The estimation loop of L_1 adaptive controller does not require the knowledge of the system inverse; it computes the approximate system inverse with fast estimation (Kharisov GNC 2011)
  - Beneficial from <u>implementation perspective</u>
  - Possible use of the architecture in other fields of engineering

Explicit vs. Approximate System Inversion

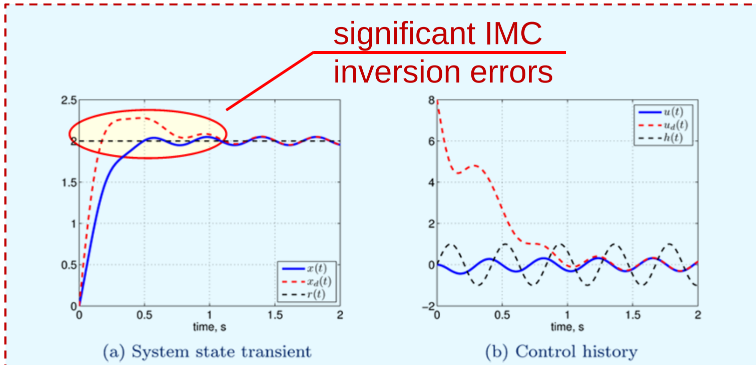


not implementable



implementable

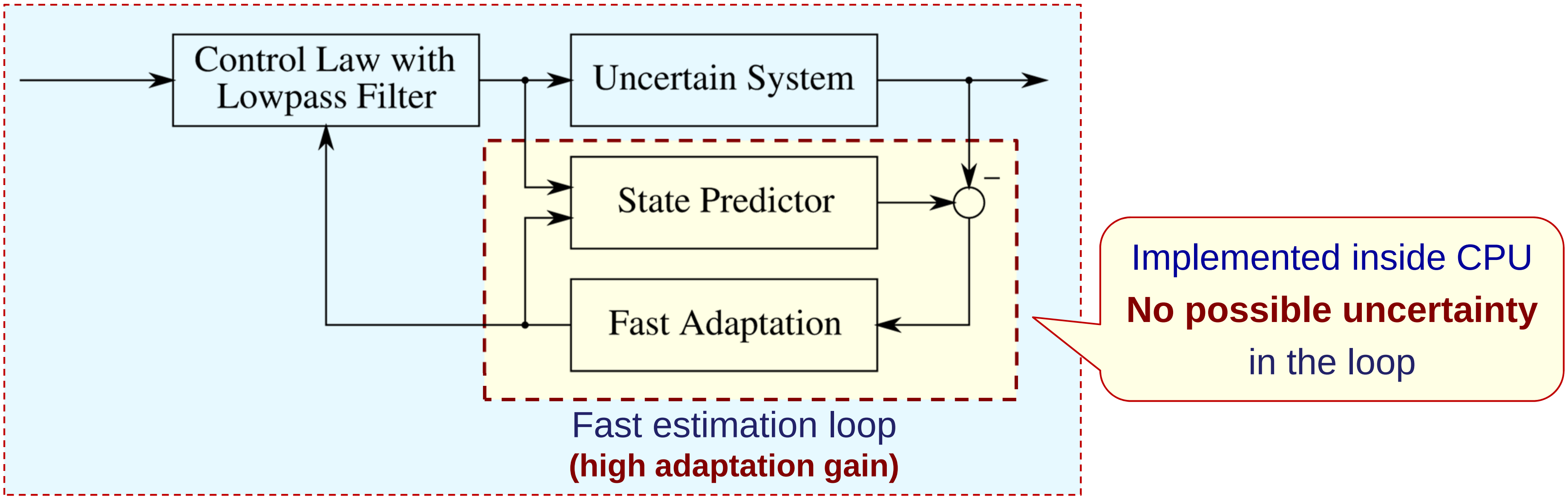
- In the presence of fast adaptation L_1 adaptive controller achieves its limiting controller, which is not implementable
- L_1 adaptive controller does not require the system inversion
- IMC controller uses lowpass filter to compute the output derivatives needed for the ideal model inversion
  - for nonlinear ideal model the blocks do not commute
  - may lead to significant transient errors



(a) System state transient

(b) Control history

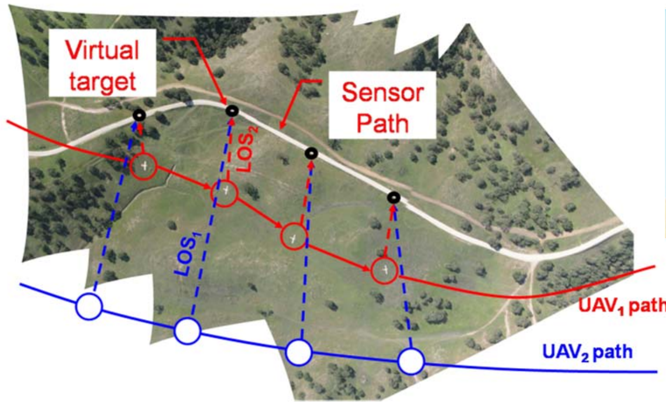
L_1 Adaptive Architecture: Decoupling Estimation from Control



- L_1 adaptive controller **achieves decoupling of estimation from control**, which **eliminates uncertainties from the estimation loop**
- Decoupling of estimation from control allows for various modifications of the estimation scheme **without violating robustness** of the system
- MRAC **does not have decoupling** between control and estimation
- Non-adaptive controller **does not have an estimation loop**

Adaptive Control in Transition

- *Fast* adaptation
- Single design AFCS



NPS FlightTest Program
Sig RASCAL

IRAC
(NASA)
GTM T2

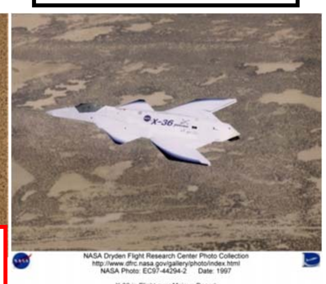
60s | 90 | 95 | 00 | 05 | 10

X-15
(NASA/USAF/
US Navy)

IFCS
(NASA/Boeing)
F-15 ACTIVE

- Gen I: flown 1999, 2003
- Gen II: 2002 – 2006
  - ✓ flight test 4th Q 2005
- Gen III: 2006

RESTORE
(AFRL-VA/Boeing)
X-36



Adaptive Control
for Munitions
(AFRL-MN/GST/Boeing)
MK-84

J-UCAS
(DARPA/USAF/US Navy)
Boeing X-45A & X-45C

evaluated in flight
sim environment

MK-82 L-JDAM

in production

MK-84 JDAM

in production

- *Slow* adaptation
- "Expensive" gain-scheduled AFCS

Source: Kevin Wise, Boeing (adapted)

Integrated Resilient Aircraft Control (IRAC)

Develop validated, multidisciplinary integrated aircraft control design tools and techniques for enabling safe flight in the presence of adverse conditions (faults, damage, and/or upsets).

• ***Advance the state-of-the-art in adaptive control*** *as a design option that will provide enhanced stability and maneuverability margins for safe landing in adverse conditions*

***Source: NASA**

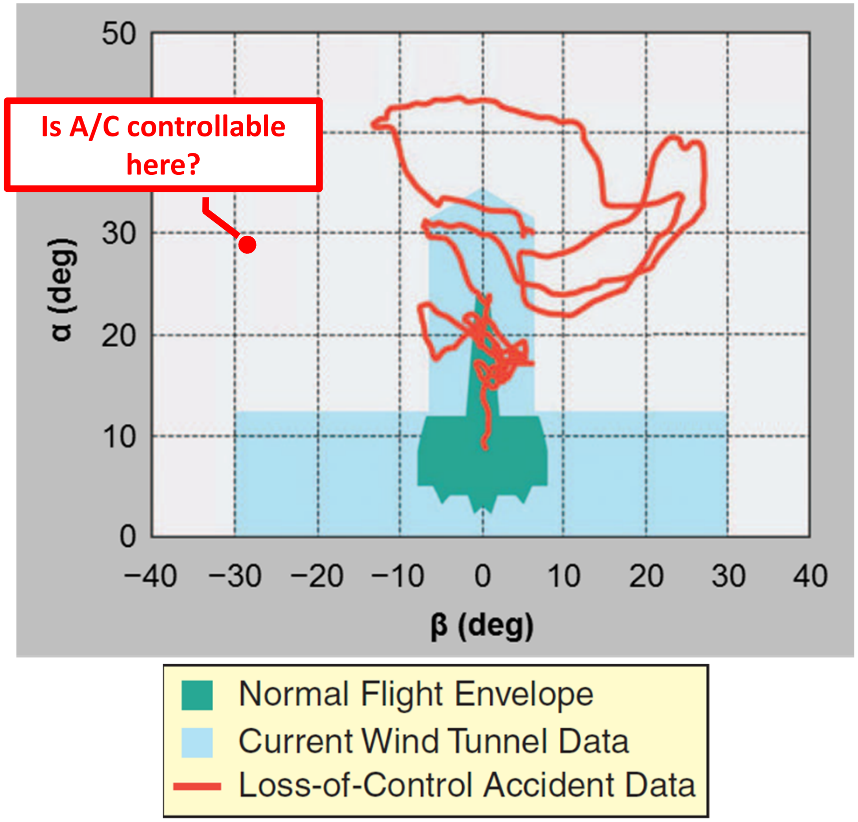
Robust Fast Adaptation: the key to *safe flight*

Predictable :: Repeatable :: Testable :: Safe

Control law objectives:

- Keep aircraft in the *wind tunnel data envelope* (accurate models)
- Eventually, return to *normal flight envelope*

Source: NASA



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

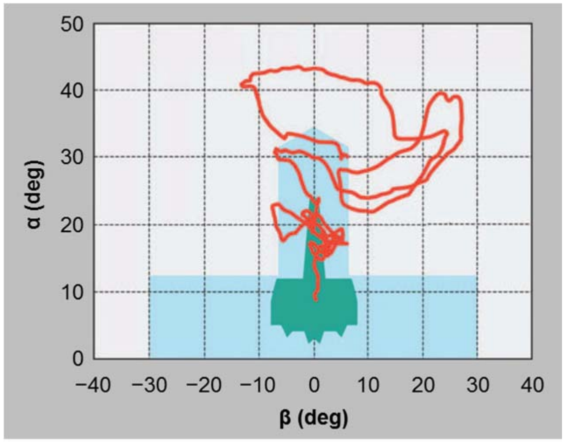
✓ Need for **transient performance guarantees**

✓ **Predictable** response

✓ Need for **fast adaptation**

Failure of **conventional adaptive control**
(limited to slow adaptation)

Main Features of L_1 Adaptive Control

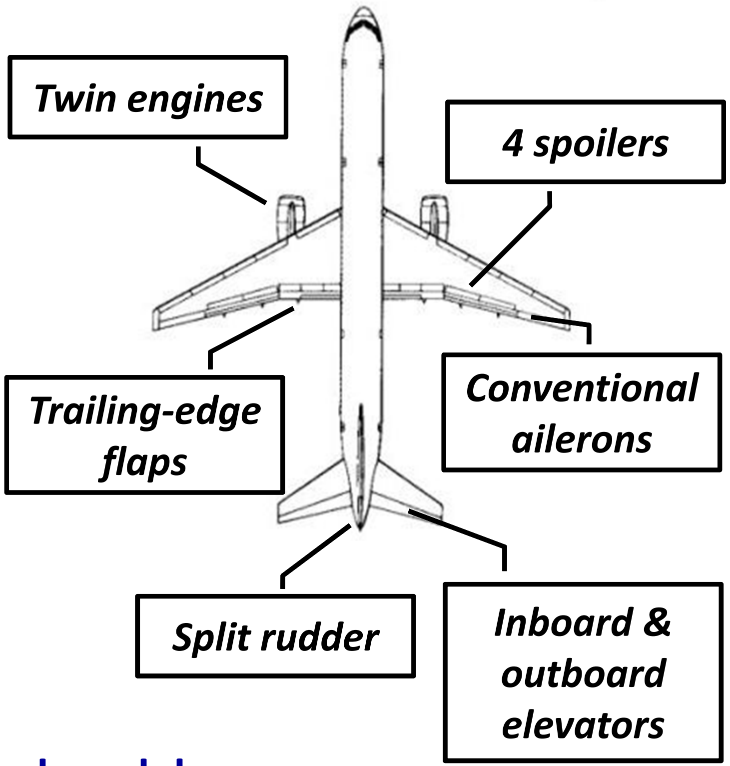


- **Separation between adaptation and robustness**
- **Speed of adaptation subject only to hardware limitations**
- Guaranteed **robustness** with **fast adaptation**
- Guaranteed **transient response** for **input and output**
  - **NOT** achieved via **high-gain feedback** or **persistence of excitation** or **gain-scheduling** or **control reconfiguration**
- Guaranteed (bounded away from zero) **time-delay margin**
- Uniform **scaled transient response** dependent on changes in initial conditions, uncertainties, and reference inputs
- **Verifiable** software with **computationally predictable** numerical characteristics
- **Systematic** design guidelines suitable for flight verification

Suitable for development of **theoretically justified Verification & Validation tools** for feedback systems

NASA Langley AirSTAR :: Generic Transport Model

***<u>High-risk flight conditions</u>**, some unable to be tested in target application environment.*

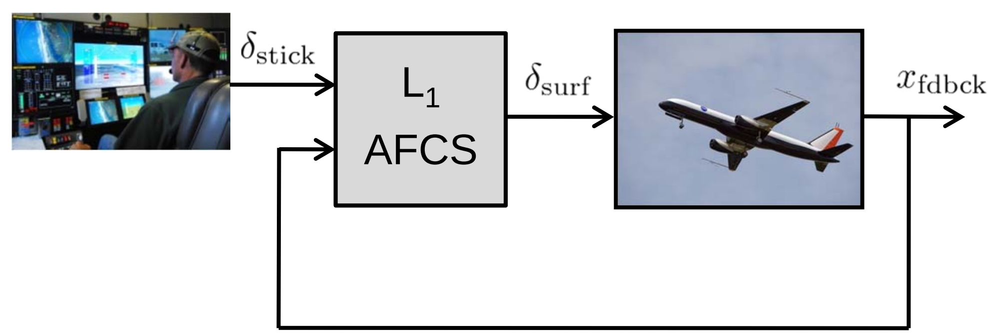


- **5.5 % geometrically and dynamically scaled model**
  - 82in wingspan, 96in length, 49.6 lbs (54 lbs full), 53 mph stall speed
  - Model angular response is 4.26 <u>faster</u> than full scale
  - Model velocity is 4.26 times <u>slower</u> than regular scale

AirSTAR :: Challenges

- Inner-loop state-feedback controller for tracking **angle of attack, roll rate, and sideslip angle commands**.

- ***<u>Challenges:</u>***
  - **Single <u>all-adaptive</u> CAS design** for the **entire flight envelope** (including stall and post stall high α conditions), ***without gain scheduling***
  - Compensation for structural damage/actuator failures ***without FDI methods***
  - Compensation for **unmatched uncertainties** – variations is α, β, *V* dynamics with flight condition
  - **Strict performance requirements**:
    - High precision tracking
    - Reduced workload
    - **Predictable response!!!**
  - **Hardware requirements:**
    - Euler integration at 600Hz



L1 AFCS :: Problem Formulation

- **System dynamics:**

$$\begin{aligned} \dot{x}(t) &= A_m x(t) + B_m \omega u(t) + f(x(t), z(t), t), \quad x(0) = x_0 \\ z(t) &= g_o(x_z(t), t), \quad \dot{x}_z(t) = g(x_z(t), x(t), t), \quad x_z(0) = x_{z0} \\ y(t) &= Cx(t) \end{aligned}$$

$\|x_0\| \leq \rho_0 < \infty$

General unmatched uncertainties that cannot be addressed by recursive design methods

- **System dynamics *(reformulation)*:**

$$\begin{aligned} \dot{x}(t) &= A_m x(t) + B_m (\omega u(t) + f_1(x(t), z(t), t)) + B_{um} f_2(x(t), z(t), t), \quad x(0) = x_0 \\ z(t) &= g_o(x_z(t), t), \quad \dot{x}_z(t) = g(x_z(t), x(t), t), \quad x_z(0) = x_{z0} \\ y(t) &= Cx(t) \end{aligned}$$

- $B_m^\top B_{um} = 0$
- $\mathrm{rank}([B_m \; B_{um}]) = n$

$$\begin{bmatrix} f_1(x(t), z(t), t) \\ f_2(x(t), z(t), t) \end{bmatrix} = \begin{bmatrix} B_m & B_{um} \end{bmatrix}^{-1} f(x(t), z(t), t)$$

L1 AFCS :: Assumptions

Assumption 1 *[Partial knowledge of the system input gain] The system input gain matrix ω is assumed to be an unknown (non–singular) strictly row–diagonally dominant matrix with* $\mathrm{sgn}(\omega_{ii})$ *known. Also, we assume that there exists a known compact convex set Ω, such that $\omega \in \Omega \subset \mathbb{R}^{m\times m}$, and that a nominal system input gain $\omega_0 \in \Omega$ is known.*

Assumption 2 *[Stability of internal dynamics] The x_z–dynamics are BIBO stable both with respect to initial conditions x_{z0} and input $x(t)$, i.e. there exist L_z, $B_z > 0$ such that for all* $t \geq 0$

$$\|z_t\|_{\mathcal{L}_\infty} \leq L_z \|x_t\|_{\mathcal{L}_\infty} + B_z\,.$$

Assumption 3 *[Semiglobal Lipschitz condition] For any $\nu > 0$, $\exists$ $K_{1_\nu}, K_{2_\nu}, B_{10}, B_{20} > 0$ such that*

$$\begin{aligned} \|f_i(X_1,t) - f_i(X_2,t)\|_\infty \ &\leq \ K_{i_\nu}\|X_1 - X_2\|_\infty\,, \\ |f_i(0,t)| \ &\leq \ B_{i0}\,, \qquad\qquad i = 1,2\,, \end{aligned}$$

for all $\|X_j\|_\infty \leq \nu$, $j = 1,2$, uniformly in t.

Assumption 4 *[Stability of matched transmission zeros] The transmission zeros of the transfer matrix $H_m(s) = C(s\mathbb{I} - A_m)^{-1}B_m$ lie in the open left–half plane.*

L1 AFCS :: Control Objective

Design an adaptive state feedback controller to ensure that $y(t)$ tracks the output response of a *desired system*

$$M(s) \triangleq C\,(s\mathbb{I} - A_m)^{-1}\,B_m K_g(s)$$

to a given bounded reference signal $r(t)$ *both in transient* and *steady-state*, while all other signals remain bounded.

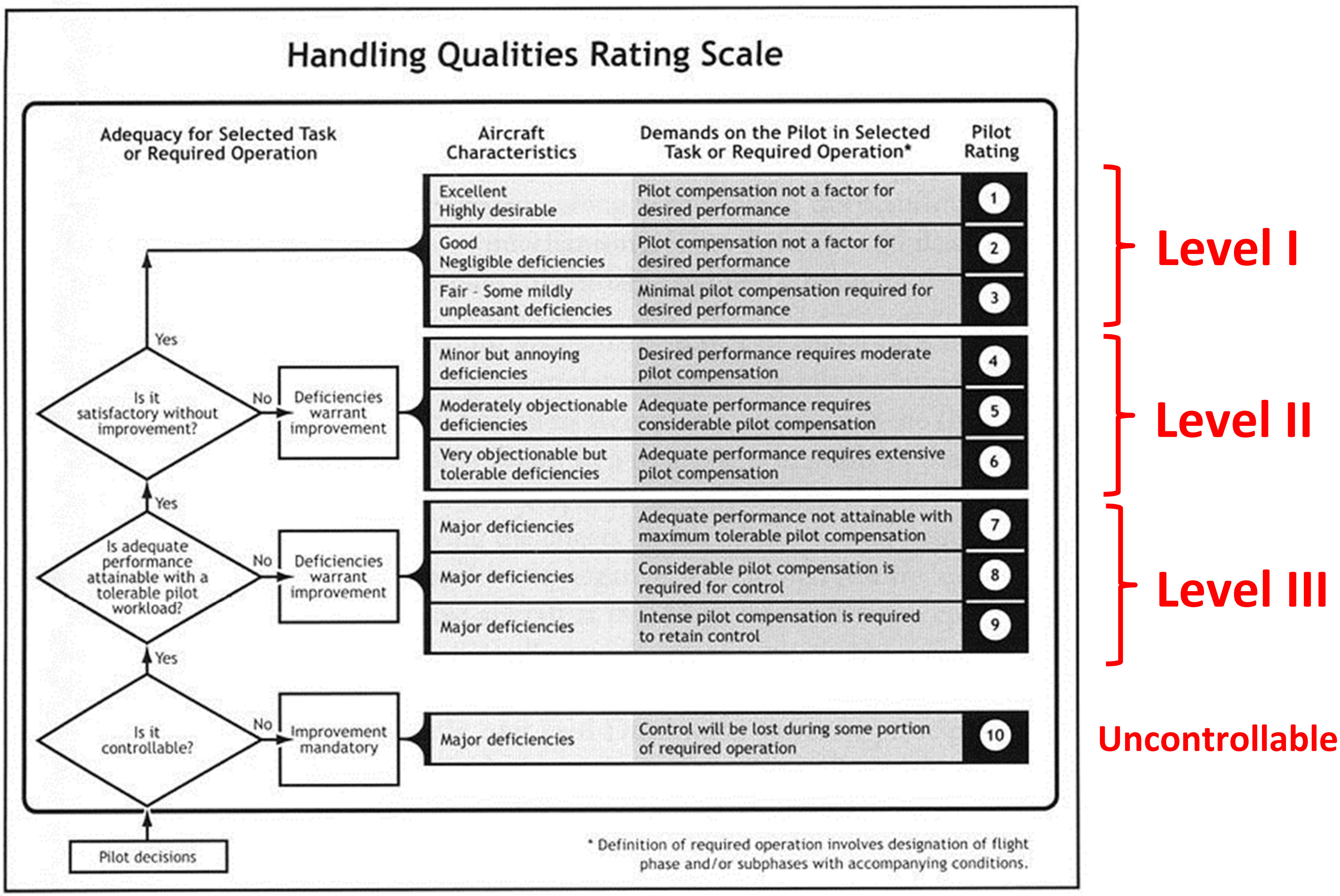
MIL-Standard requirements

Performance Specs

LEVEL I HANDLING QUALITIES

- **Aircraft characteristics**
- **Pilot compensation**

Handling Qualities :: Cooper Harper Rating Scale



L_1 Control Architecture

State predictor:

$$\dot{\hat{x}}(t) = A_m\hat{x}(t) + B_m(\omega_0 u(t) + \hat{\sigma}_1(t)) + B_{um}\hat{\sigma}_2(t), \quad \hat{x}(0) = x_0$$

Adaptive laws:

T_s: adaptive sampling time

$$\begin{bmatrix} \hat{\sigma}_1(t) \\ \hat{\sigma}_2(t) \end{bmatrix} = \begin{bmatrix} \hat{\sigma}_1(iT_s) \\ \hat{\sigma}_2(iT_s) \end{bmatrix}, \qquad t \in [iT_s, (i+1)T_s)$$

$$\begin{bmatrix} \hat{\sigma}_1(iT_s) \\ \hat{\sigma}_2(iT_s) \end{bmatrix} = -\begin{bmatrix} \mathbb{I}_m & 0 \\ 0 & \mathbb{I}_{n-m} \end{bmatrix} B^{-1}\Phi^{-1}(T_s)\mathrm{e}^{A_m T_s}\tilde{x}(iT_s)$$

$$\Phi(T_s) = A_m^{-1}\left(\mathrm{e}^{A_m T_s} - \mathbb{I}_n\right)$$

$$B = \begin{bmatrix} B_m & B_{um} \end{bmatrix}$$

Control law:

$$u(s) = -KD(s)\left(\omega_0 u(s) + \hat{\sigma}_1(s) + H_m^{-1}(s)H_{um}(s)\hat{\sigma}_2(s) - K_g(s)r(s)\right)$$

$$H_m(s) = C(s\mathbb{I} - A_m)^{-1}B_m$$
$$H_{um}(s) = C(s\mathbb{I} - A_m)^{-1}B_{um}$$

Sufficient Condition for Stability and Performance

The design of $D(s)$ and K needs to ensure that, $\forall\ \omega \in \Omega$:

1. $C(s) \triangleq \omega K D(s) \left(\mathbb{I}_m + \omega K D(s)\right)^{-1} \quad \in \quad \mathcal{RH}_\infty, \quad$ with DC gain $C(0) = \mathbb{I}_m$
2. $C(s) H_m^{-1}(s) \quad \in \quad \mathcal{RH}_\infty$

Moreover, the design of $D(s)$ and a K needs to ensure that, for given ρ_0, $\exists\ \rho_{x_r} > 0$ such that

$$\|G_m(s)\|_{\mathcal{L}_1} + \|G_{um}(s)\|_{\mathcal{L}_1} \ell_0 \quad < \quad \frac{\rho_{x_r} - \|H_{xm}(s)C(s)K_g(s)\|_{\mathcal{L}_1} \|r\|_{\mathcal{L}_\infty} - \left\|s(s\mathbb{I} - A_m)^{-1}\right\|_{\mathcal{L}_1} \rho_0}{L_{1\rho_{x_r}} \rho_{x_r} + B_0},$$

where $\ell_0 \triangleq L_{2\rho_{x_r}} / L_{1\rho_{x_r}}$, and $B_0 \triangleq \max\{B_{10},\ \frac{B_{20}}{\ell_0}\}$

$$\begin{aligned}
H_{xm}(s) &\triangleq (s\mathbb{I}_n - A_m)^{-1} B_m \\
H_{xum}(s) &\triangleq (s\mathbb{I}_n - A_m)^{-1} B_{um} \\
H_m(s) &\triangleq C H_{xm}(s) \ = \ C\,(s\mathbb{I}_n - A_m)^{-1} B_m \\
H_{um}(s) &\triangleq C H_{xum}(s) \ = \ C\,(s\mathbb{I}_n - A_m)^{-1} B_{um} \\
G_m(s) &\triangleq H_{xm}(s)\,(\mathbb{I}_m - C(s)) \\
G_{um}(s) &\triangleq \left(\mathbb{I}_n - H_{xm}(s) C(s) H_m^{-1}(s) C\right) H_{xum}(s)
\end{aligned}$$

- **Remark:**

$f_2(\cdot) = 0 \quad$ and $\quad f_1(\cdot)$ globally Lipschitz with constant L

$$\|G_m(s)\|_{\mathcal{L}_1} L \quad < \quad 1$$

Closed-Loop Reference System :: Feasible Control Objective

- **Closed-Loop Reference System (*non-adaptive version*):**

$$\begin{aligned}
\dot{x}_{\text{ref}}(t) &= A_m x_{\text{ref}}(t) + B_m \left(\omega u_{\text{ref}}(t) + f_1(x_{\text{ref}}(t), z(t), t)\right) + B_{um} f_2(x_{\text{ref}}(t), z(t), t), \qquad x_{\text{ref}}(0) = x_0 \\
u_{\text{ref}}(s) &= -\omega^{-1} C(s) \left\{ f_1(x_{\text{ref}}(t), z(t), t) \right\} + H_m^{-1}(s) H_{um}(s) \left\{ f_2(x_{\text{ref}}(t), z(t), t) \right\} - K_g(s) r(s)) \\
y_{\text{ref}}(t) &= C x_{\text{ref}}(t)\,,
\end{aligned}$$

If the stability (sufficient) conditions hold, and

$$\|z_t\|_{\mathcal{L}_\infty} \le L_z(\|x_{\text{ref}\,t}\|_{\mathcal{L}_\infty} + \gamma_x) \ + \ B_z\,,$$

then the closed-loop reference system is BIBO stable:

$$\|x_{\text{ref}\,t}\|_{\mathcal{L}_\infty} \ < \ \rho_{x_r}\,, \qquad \|u_{\text{ref}\,t}\|_{\mathcal{L}_\infty} \ < \ \rho_{u_r}\,.$$

where

$$\begin{aligned}
\rho_{u_r} \ \triangleq \ & \left\|\omega^{-1} C(s)\right\|_{\mathcal{L}_1} \left(L_{1\rho_{x_r}} \rho_{x_r} + B_{10}\right) + \\
& + \left\|\omega^{-1} C(s) H_m^{-1}(s) H_{um}(s)\right\|_{\mathcal{L}_1} \left(L_{2\rho_{x_r}} \rho_{x_r} + B_{20}\right) + \left\|\omega^{-1} C(s) K_g(s)\right\|_{\mathcal{L}_1} \|r\|_{\mathcal{L}_\infty}\,.
\end{aligned}$$

Guaranteed Performance Bounds

Let the adaptation sampling time T_s be chosen to satisfy

$$\gamma_0(T_s) \quad < \quad \bar{\gamma}_0 \,, \qquad (\lim_{T_s \to 0} \gamma_0(T_s) \; = \; 0)$$

Arbitrarily small

Given the adaptive closed-loop system with the $\mathcal{L}_1$ adaptive controller, subject to the $\mathcal{L}_1$-norm condition, and the closed-loop reference system, if

$$\|x_0\|_\infty \quad \le \quad \rho_0 \,,$$

then we have

$$\|x\|_{\mathcal{L}_\infty} \le \rho_x \,, \qquad \|u\|_{\mathcal{L}_\infty} \le \rho_u \,,$$

$$\|\tilde{x}\|_{\mathcal{L}_\infty} < \bar{\gamma}_0 \,,$$

$$\|x - x_{\mathrm{ref}}\|_{\mathcal{L}_\infty} < \gamma_x \,, \qquad \|u - u_{\mathrm{ref}}\|_{\mathcal{L}_\infty} < \gamma_u \,, \qquad \|y - y_{\mathrm{ref}}\|_{\mathcal{L}_\infty} < \|C\|_\infty \, \gamma_x \,,$$

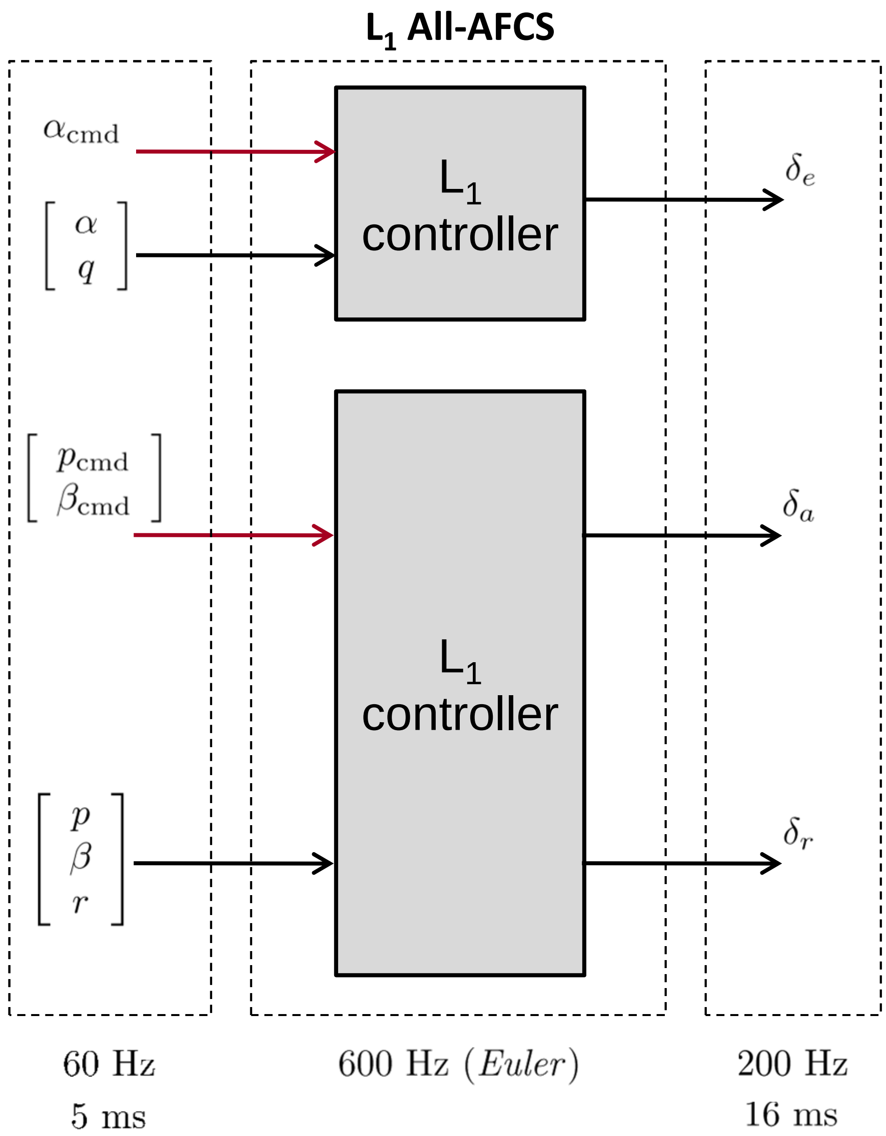
where γ_x and γ_u are defined as

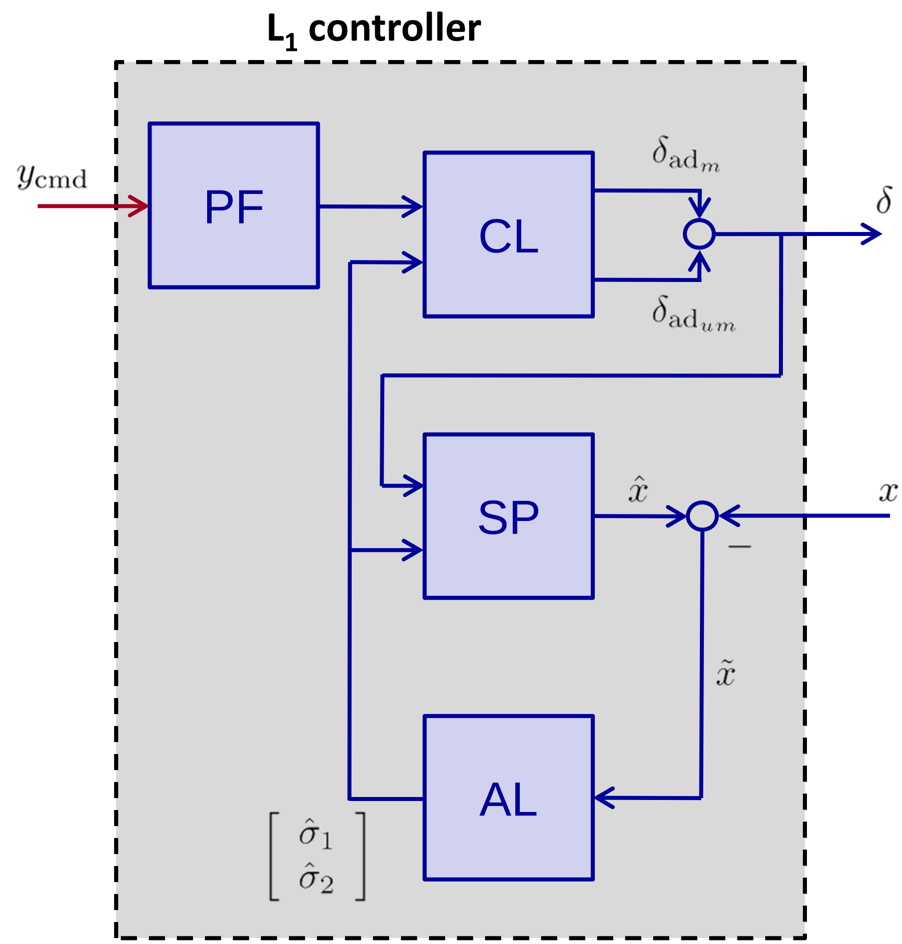
$$\gamma_x \triangleq \frac{\left\| H_{xm}(s) C(s) H_m^{-1}(s) C \right\|_{\mathcal{L}_1}}{1 - \|G_m(s)\|_{\mathcal{L}_1} L_{1\rho_{x_r}} - \|G_{um}(s)\|_{\mathcal{L}_1} L_{2\rho_{x_r}}} \bar{\gamma}_0 + \epsilon$$

Arbitrarily small

$$\gamma_u \triangleq \left(\|\omega^{-1} C(s)\|_{\mathcal{L}_1} L_{1\rho_{x_r}} + \|\omega^{-1} C(s) H_m^{-1}(s) H_{um}(s)\|_{\mathcal{L}_1} L_{2\rho_{x_r}} \right) \gamma_x + \|\omega^{-1} C(s) H_m^{-1}(s) C\|_{\mathcal{L}_1} \bar{\gamma}_0$$

All-Adaptive FCS

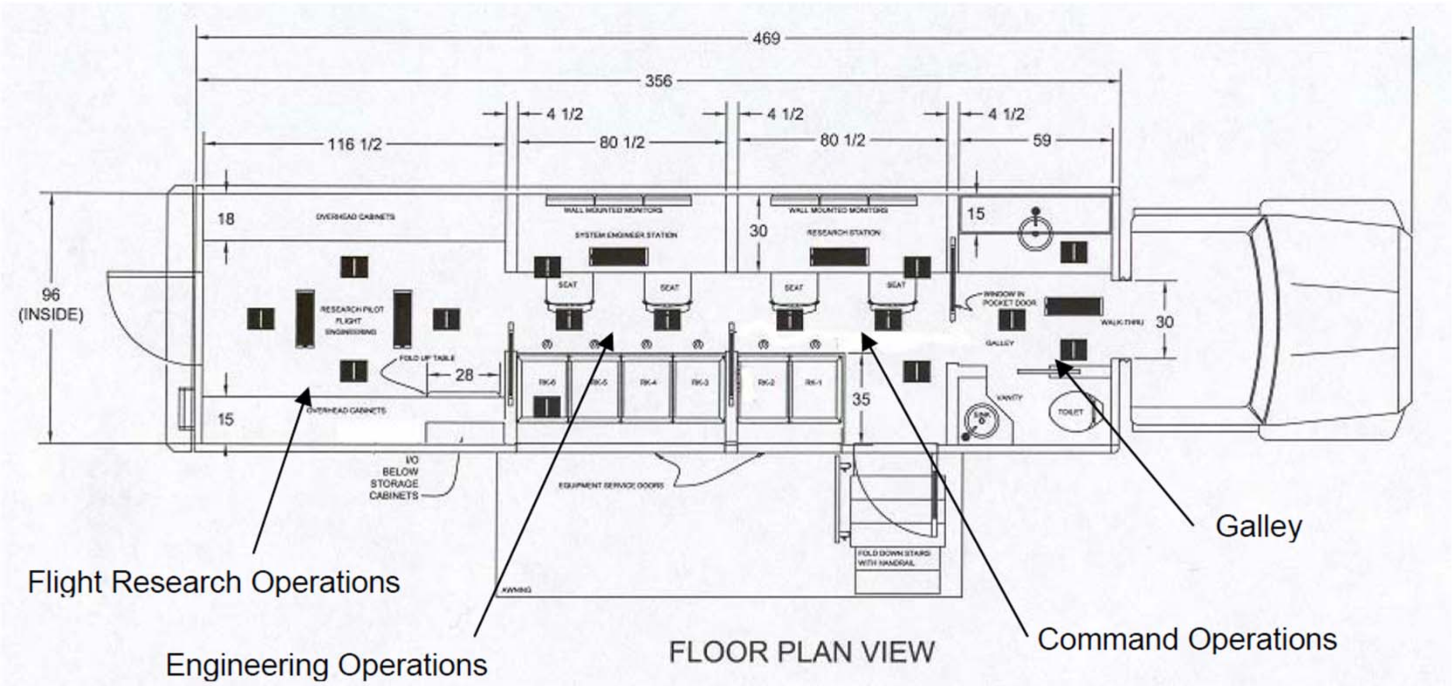


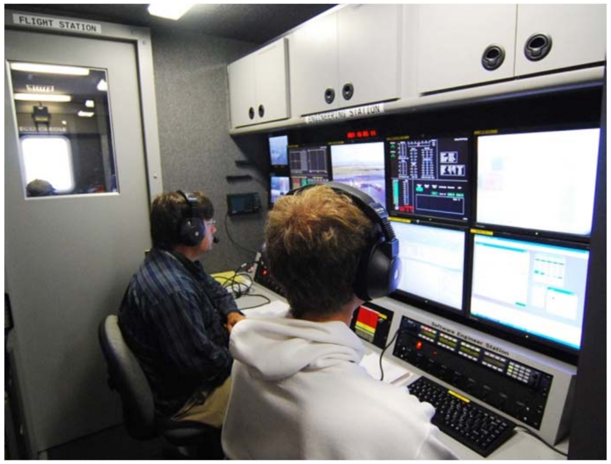


Flight Test Evaluations

Credit: NASA LaRC / Sean Smith / Irene M. Gregory

Mobile Operations Station





Flight Control Law Evaluation Matrix (I)

Evaluation Task	1st straight leg	2nd straight leg	Turns	Scope
Latency injection *(5msec / 5sec)*	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Fault Engaged	Nominal Stability
Δ(Cmα & Clp) ≈ 0%	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault	Nominal Stability
Δ(Cmα & Clp) ≈ -50%	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault	Robust Stability
Δ(Cmα & Clp) ≈ -75%	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault	Robust Stability
Δ(Cmα & Clp) ≈ -100% *(neutrally stable)*	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault	Robust Stability
Δ(Cmα & Clp) ≈ -125% *(unstable)*	Fault Engaged Roll Doublet	Fault Engaged Pitch Doublet	Disengage Fault	Robust Stability
Post-stall α tracking	No Fault No Doublet	No Fault No Doublet	N/A	Robust Performance

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

Flight Control Law Evaluation Matrix (and II)

Evaluation Task	Downwind straight leg	Upwind straight leg	Turns	Scope
Offset-to-landing *(nominal)*	Achieve good trim	No fault 1st: Practice landing 2nd: Evaluation landing	N/A	Nominal Performance
Offset-to-landing *$\Delta(C_{m\alpha}$ & $C_{lp}) \approx -100\%$* *(neutrally stable)*	Achieve good trim	Fault Engaged Evaluation landing	Disengage Fault	Robust Performance
Offset-to-landing $\Delta(C_{m\alpha}$ & $C_{lp}) \approx -125\%$ *(unstable)*	Achieve good trim	Fault Engaged Evaluation landing	Disengage Fault	Robust Performance

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

March 2010 Flight Test Evaluation

L1 all-adaptive CAS: provides performance/stability for nominal and impaired aircraft

- ✓ **Not an augmentation** to a baseline controller that provides nominal aircraft performance, like other adaptive controllers implemented

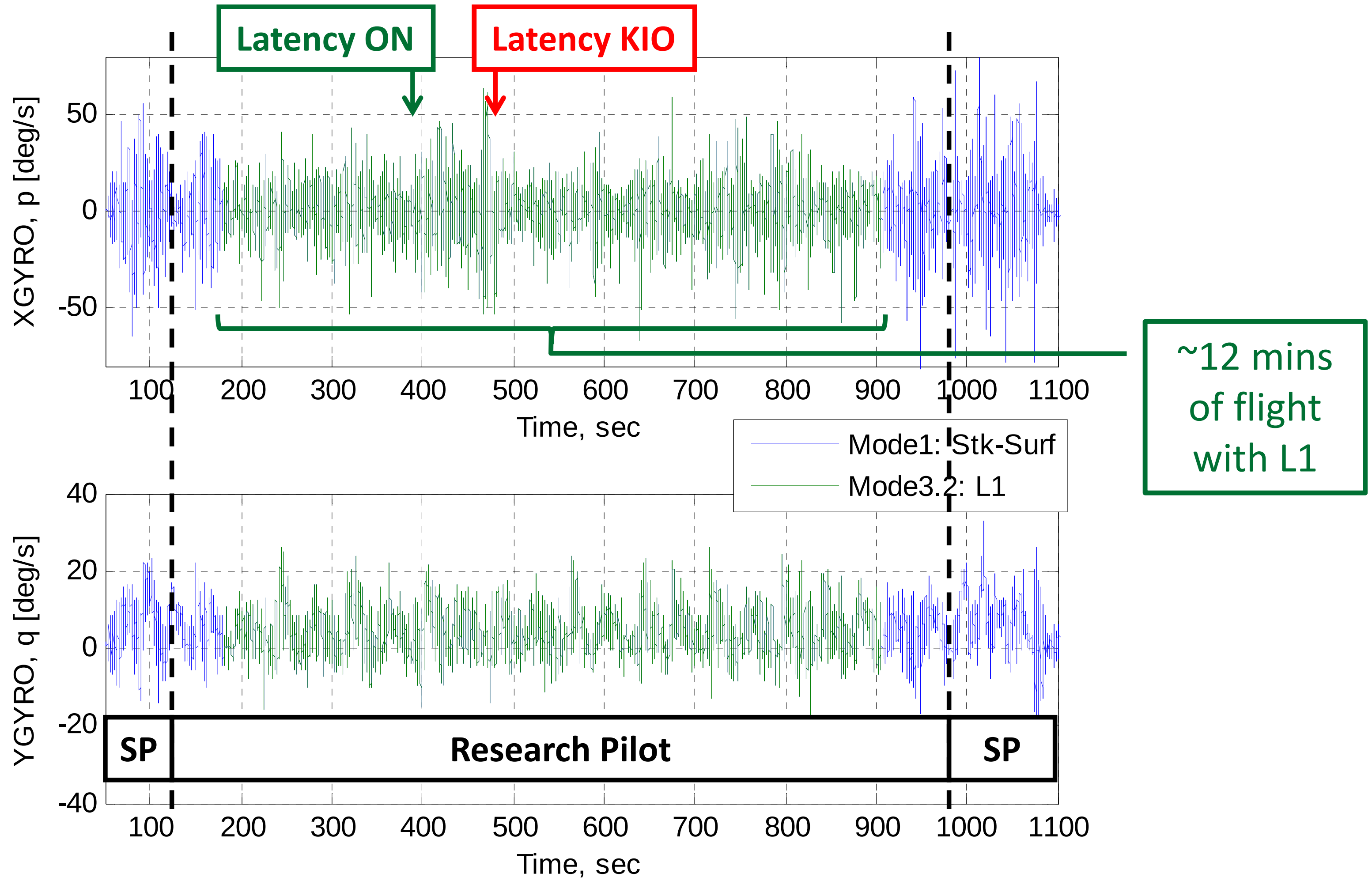
Flight Control Law related tasks during March 2010 deployment:

➢ Flight Control Law Block :

- Injected longitudinal and lateral stick doublets for each fault, continuous stick doublets on straight legs during latency fault
- **Latency fault**: starting at 20msec, continuously increase in latency (5msec every 5sec) through the turns, etc until aircraft is neutrally stable or unstable – want graceful performance degradation
    - ✓ **Robust to 105msec of additional time delay**
- **Simultaneous** longitudinal and lateral **stability degradation ($C_{m\alpha}/C_{lp}$)**:
    - ✓ 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
- **Left elevator inboard and outboard segments locked-in-place failure (<2deg):** **nonevent** for the adaptive controller

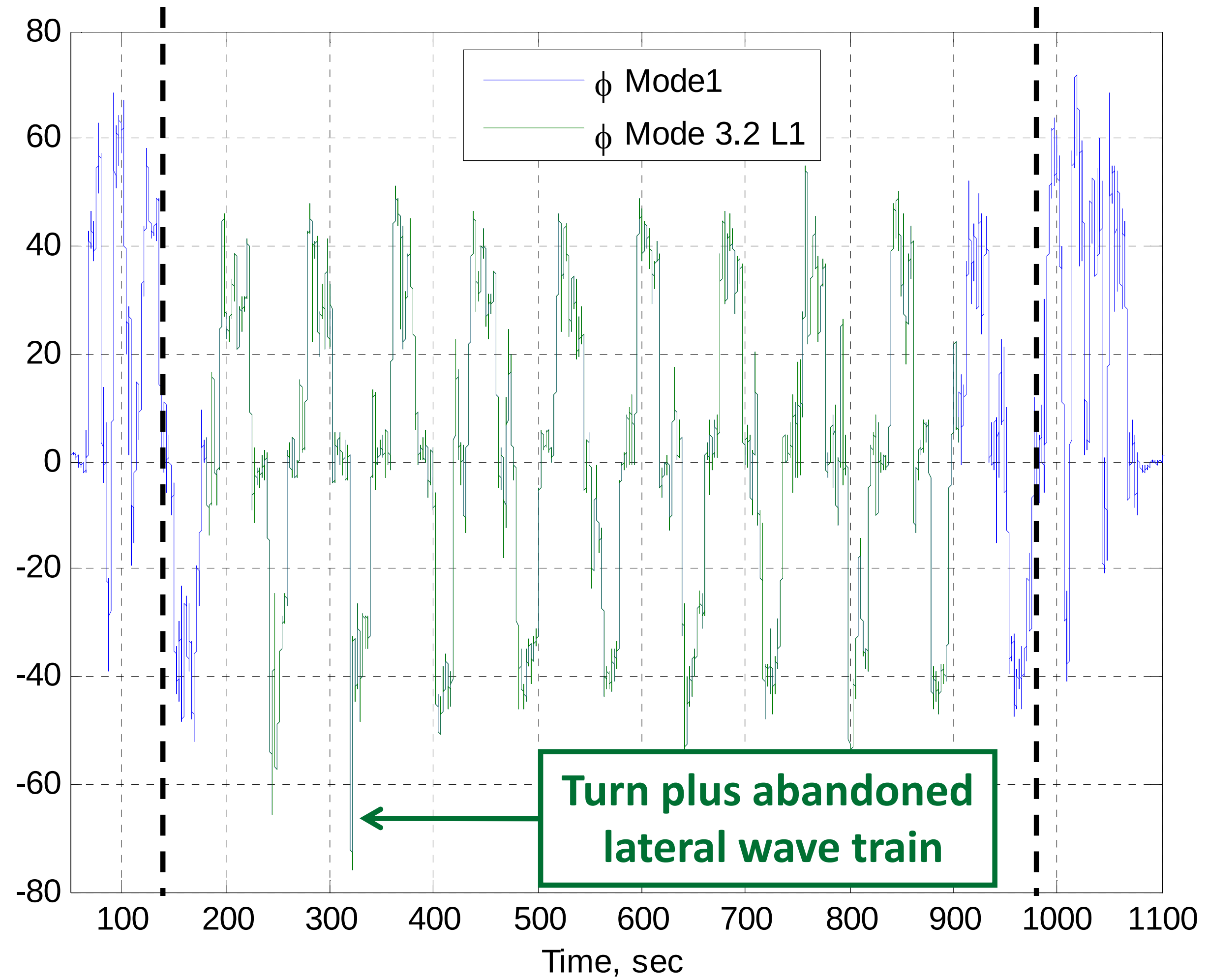
Flight Test Evaluation (March 2010)

- FLT14: Mode 3.2 (L1 all-adaptive) FCL under moderate (+) turbulence
  - Reduction in turbulence response with all-adaptive flight controller engaged
  - Immediate return to nominal controller performance as soon as fault disengaged



Flight Test Evaluation (March 2010)

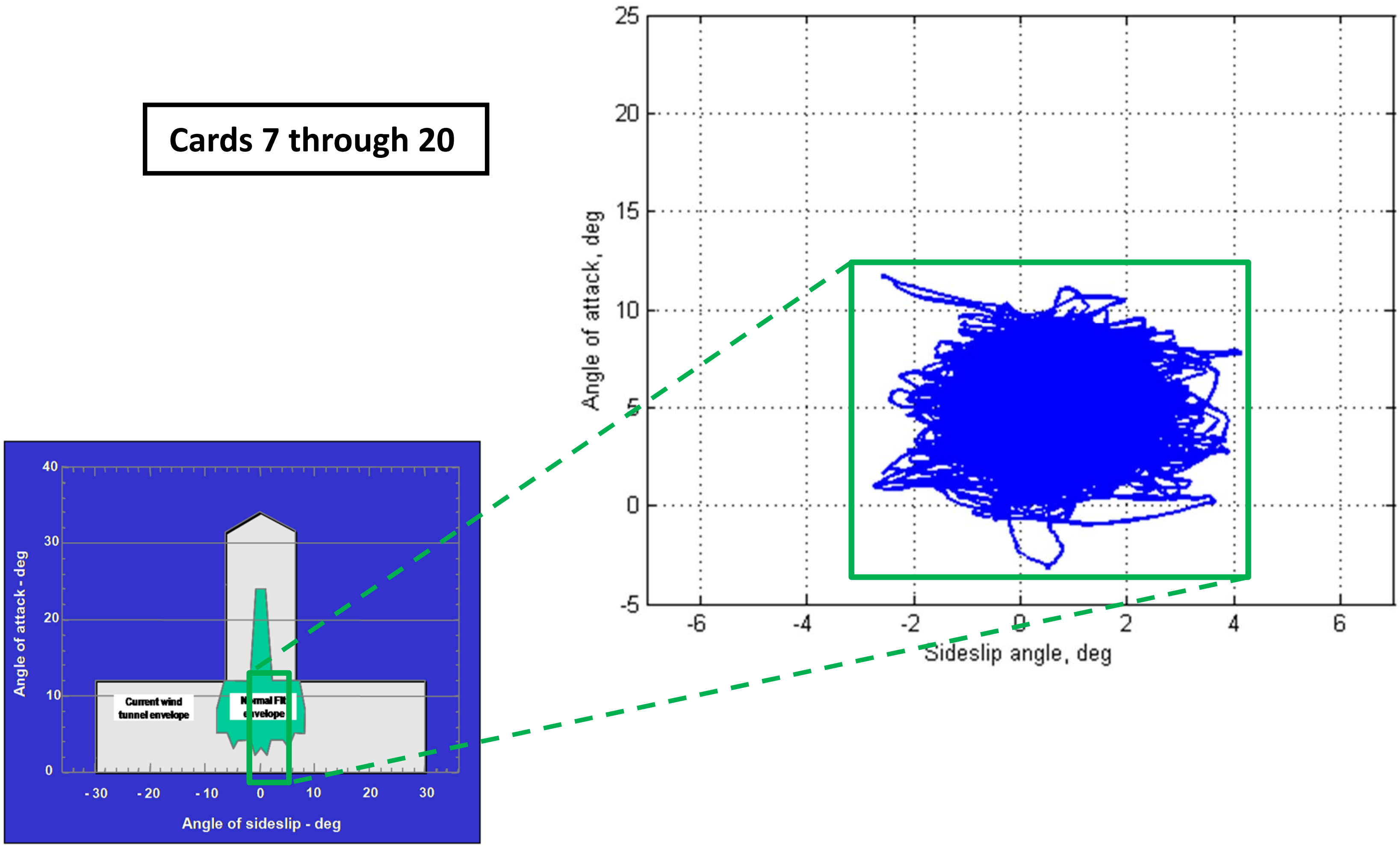
- FLT14: Mode 3.2 (L1 all-adaptive) FCL under moderate (+) turbulence
  - Consistency in bank angle throughout the flight



Flight Test Evaluation (March 2010)

- FLT14: Mode 3.2 (L_1 all-adaptive) FCL under moderate (+) turbulence
  - **α-β data:**

Cards 7 through 20



Flight Test Evaluation (March 2010)

*"…this is the first successful flight of an **all-adaptive** control law that deals with aircraft stability degradation as well as actuator failures…"*

*"…it is the first flight of a direct **all-adaptive** controller with a pilot in the loop…"*

NASA RTD weekly key activities report

Dr. Irene M. Gregory

June 2010 Flight Test Evaluation

L1 all-adaptive CAS: provides performance/stability for nominal and impaired aircraft

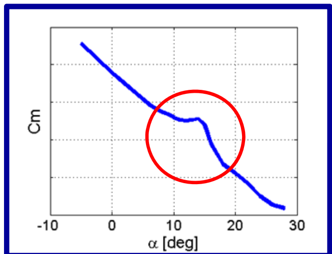
- ✓ **Not an augmentation** to a baseline controller that provides nominal aircraft performance, like other adaptive controllers implemented

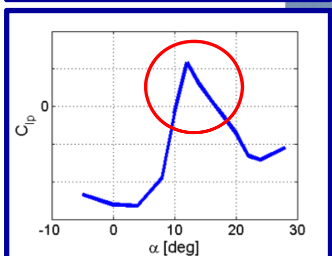
Flight Control Law related tasks during June 2010 deployment:

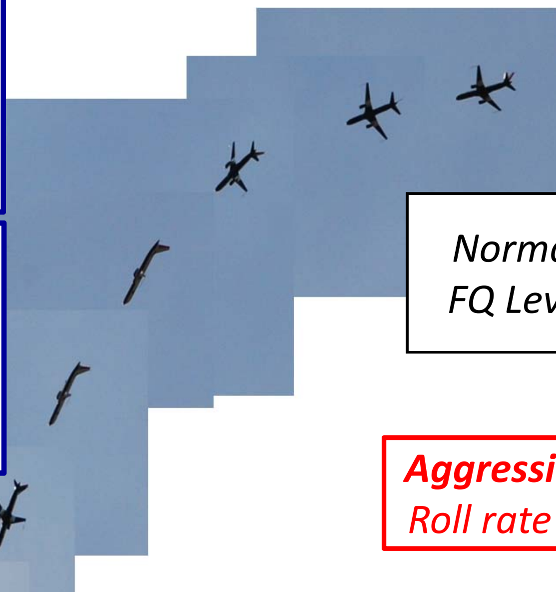
- ➢ Flight Control Law Block :
  - Injected longitudinal and lateral stick doublets for each fault, continuous stick doublets on straight legs during latency fault
  - **Latency fault**: starting at 20msec, continuously increase in latency (5msec every 5sec), carried through the turns, until aircraft is neutrally stable or unstable – want graceful performance degradation
    - ✓ **Robust to 125msec of additional time delay [147ms total time delay]**
  - **Simultaneous** longitudinal and lateral **stability degradation (Cmα/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
  - **Left elevator inboard and outboard segments locked-in-place failure (<2deg): nonevent** for the adaptive controller
- ➢ Modeling Tasks:
  - L1 used for **β-sweep in flat turn maneuver**

High AOA Flight :: Aggressive Roll-Off (June 2010)

- **Open-loop aircraft** tends to aggressively **roll off** between 13deg and 15deg AOA and exhibits significant degradation in pitch stability





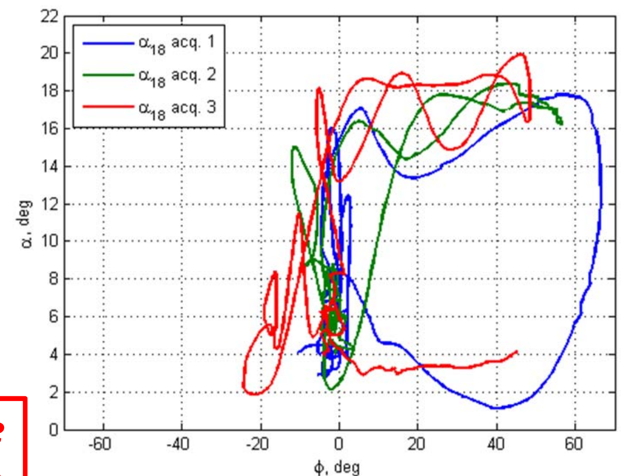


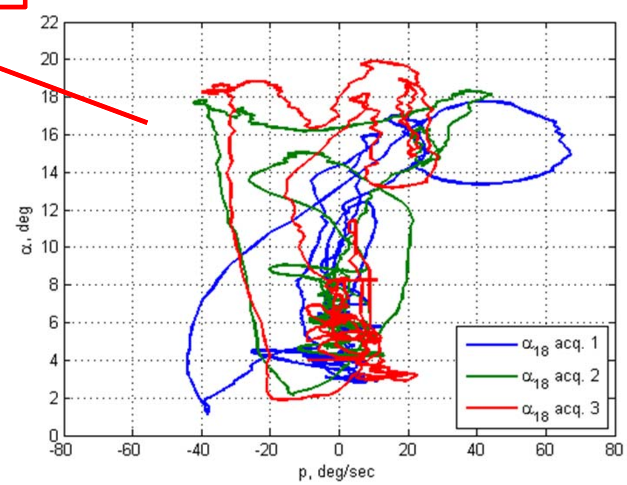
Normal flight
FQ Level I A/C

Aggressive departure
Roll rate above 60dps

FLT 25

Stick to surface

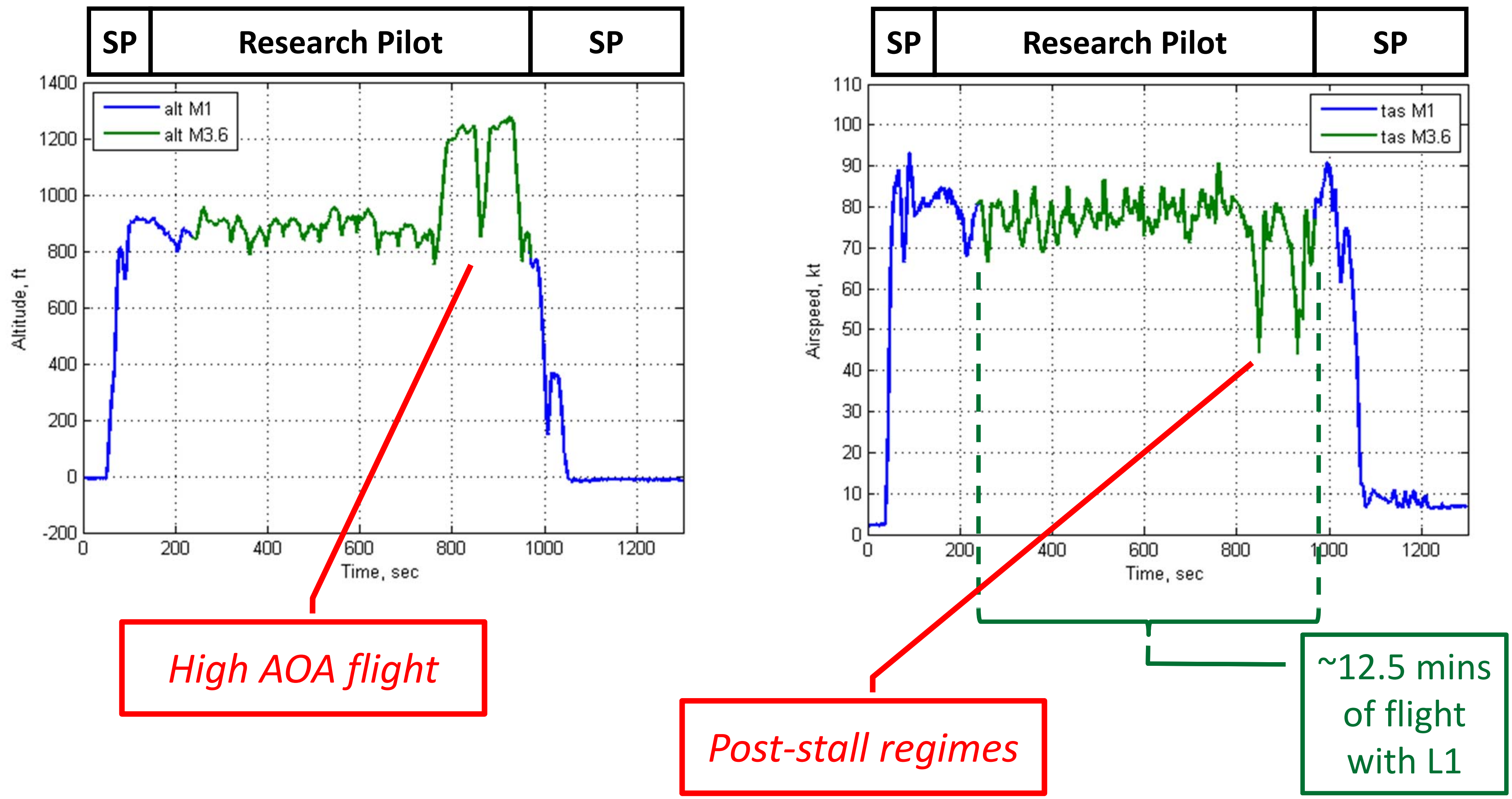




All 3 stick-to-surface attempts in maintaining ***controlled flight*** *at AOA=18deg were* ***unsuccessful***

Flight Test Evaluation (June 2010)

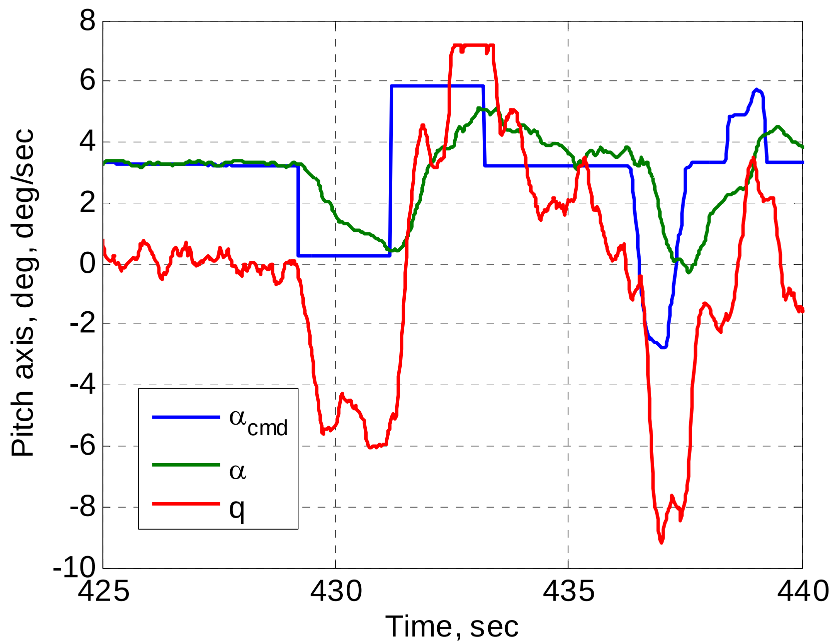
- FLT23: Mode 3.6 (L1 all-adaptive) FCL under light turbulence



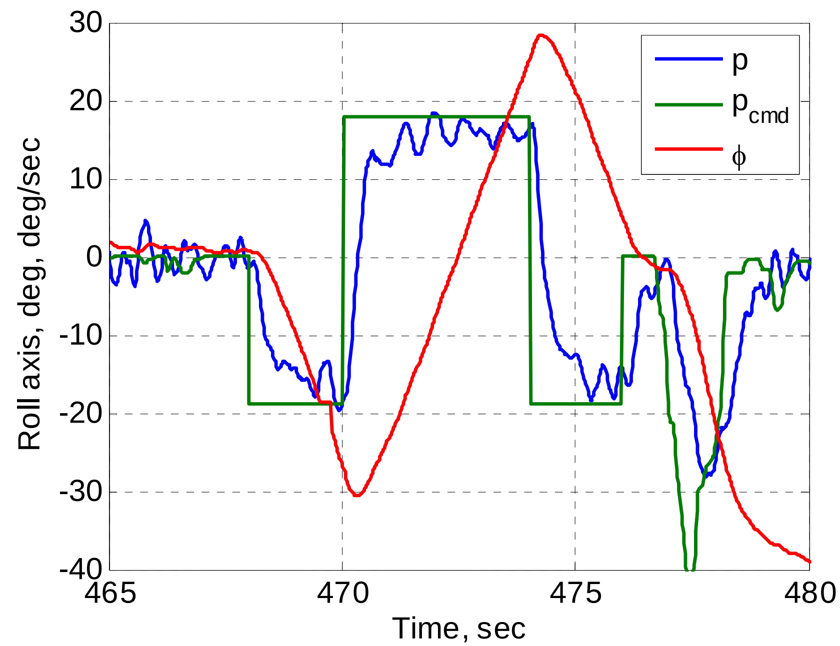
Nominal A/C Wave Train Response (June 2010)

- 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



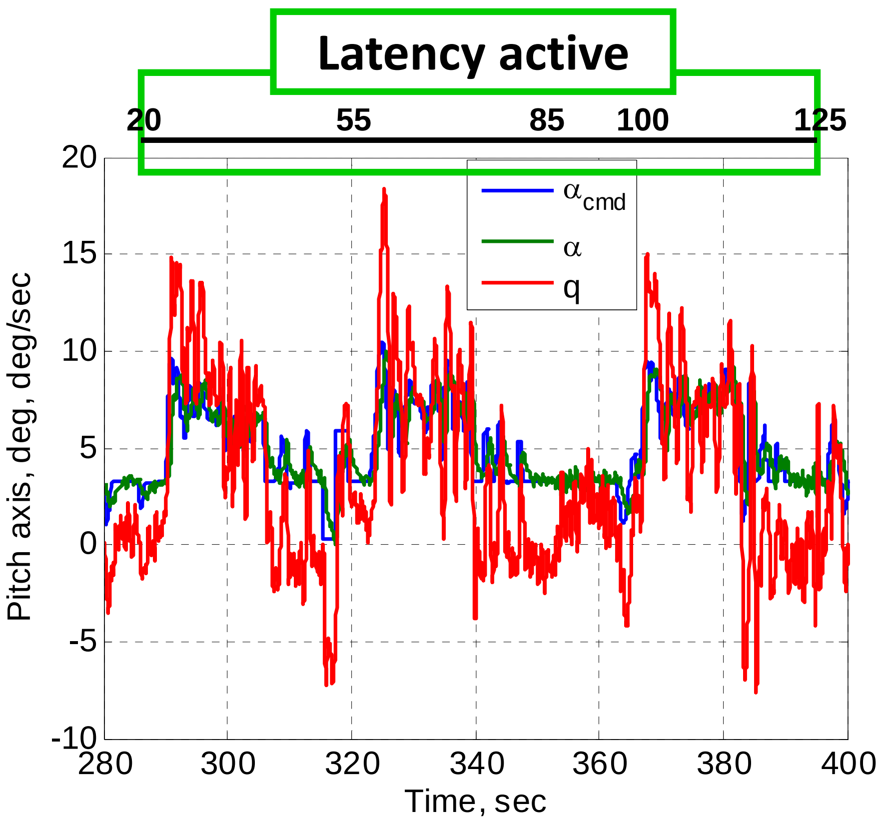
Roll axis – p_cmd doublet

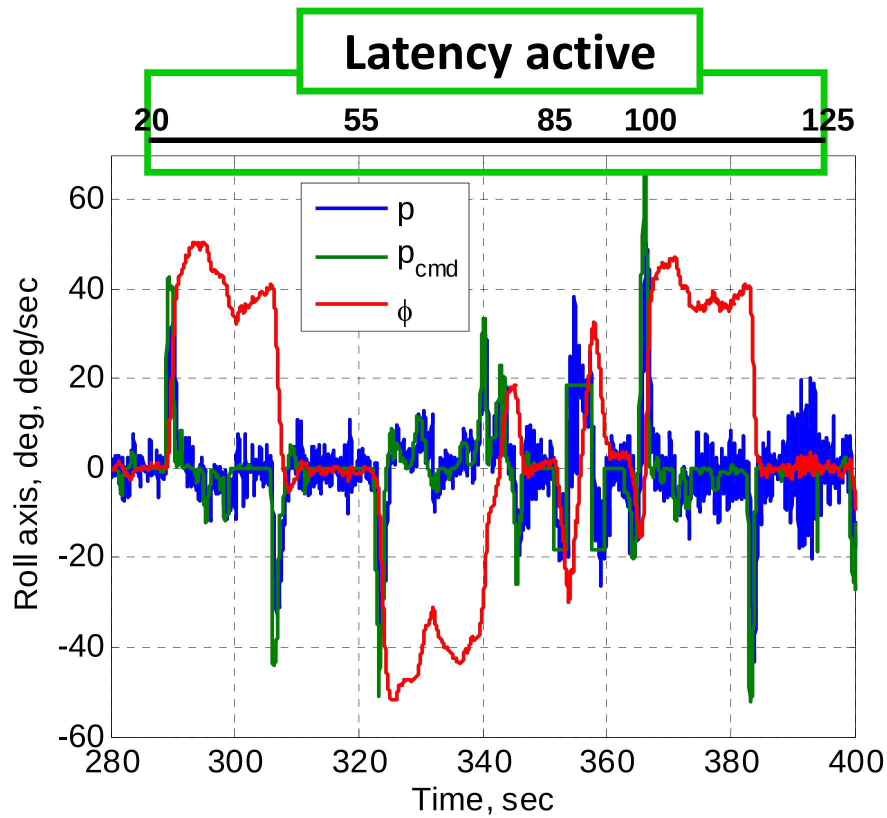


- α-cmd response designed for pilot, not to the maximum potential of the control law [tracking doublet faster – too sensitive for the pilot]
- Roll rate is a very fast and challenging response [with no turbulence – smooth, fast response tracking the p_cmd doublet]

Latency Response (June 2010)

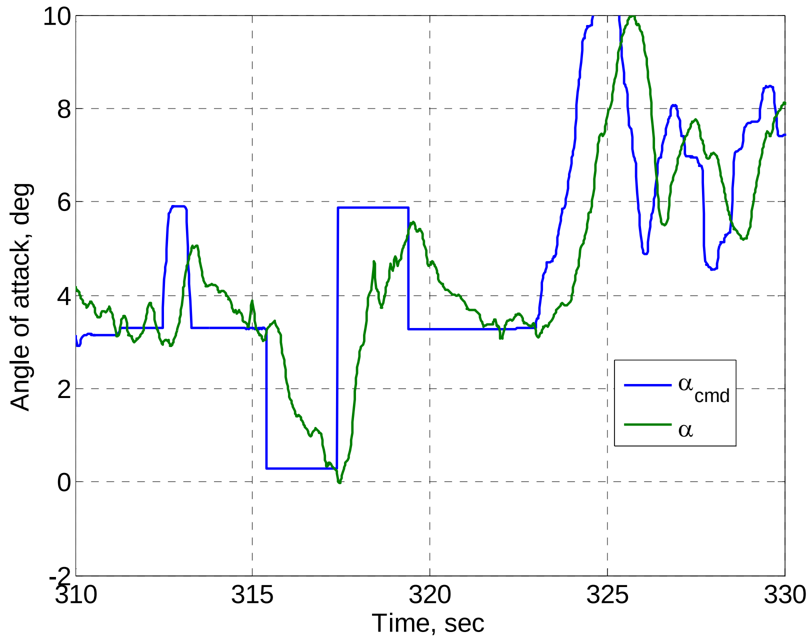
- Latency fault
  - Carried through the turns
  - Engaged around 286 seconds
  - The maneuver was abandoned at 394 seconds due to persistent roll rate oscillations of ± 20 deg/sec

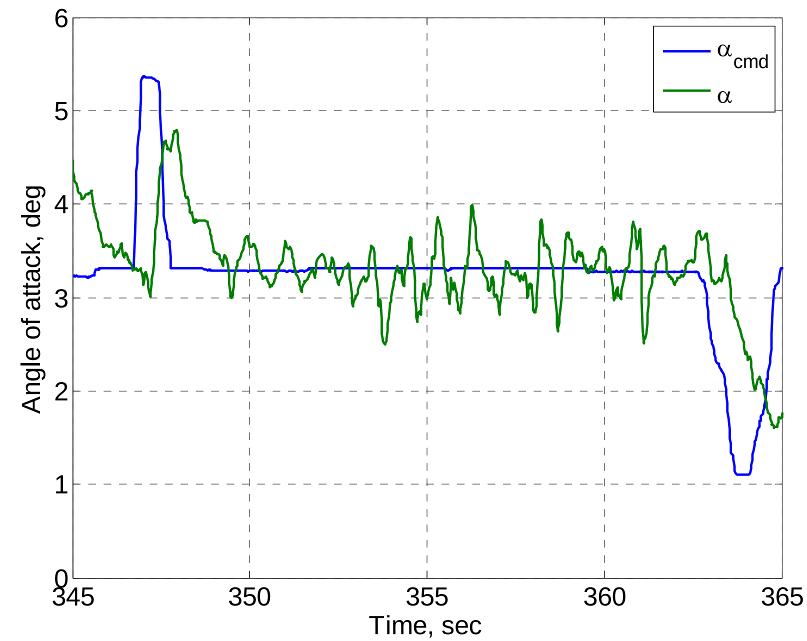




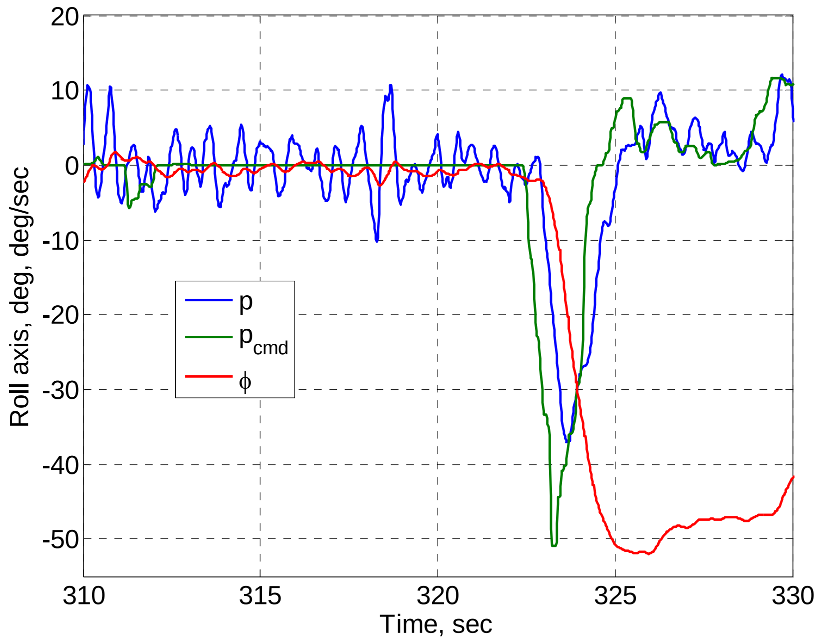
Latency Fault Doublet Response (June 2010)

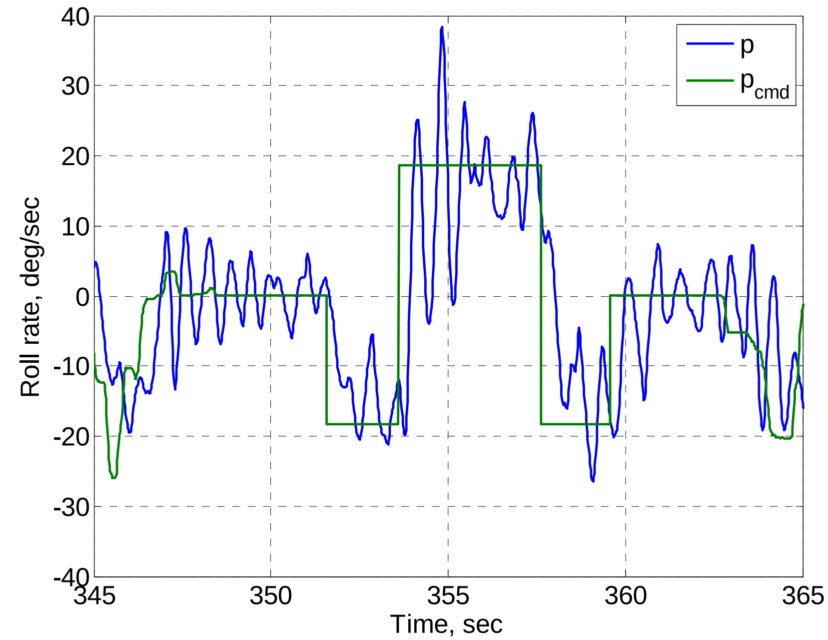
Angle of Attack





Roll rate

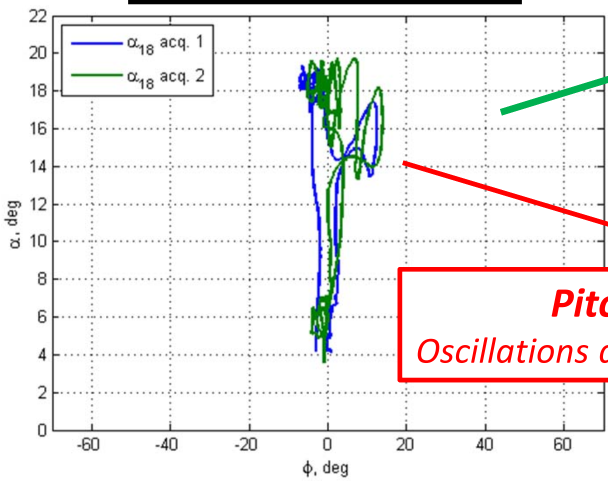




High AOA Flight :: L1 Adaptive FCL (June 2010)

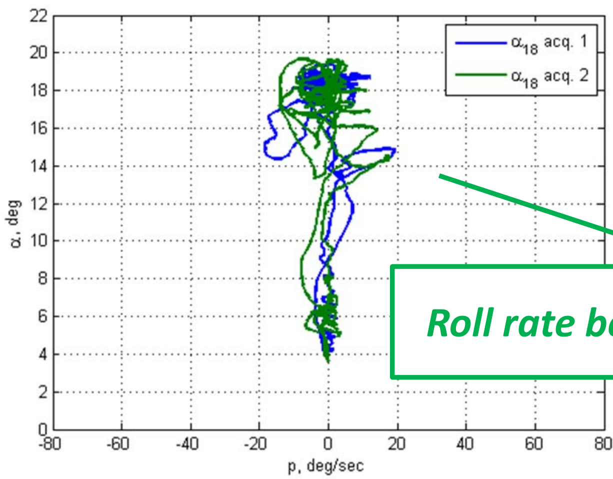
- **L1 provides departure resilient control for aircraft in post-stall flight**
  - ✓ L1 adaptive controller significantly improved pilot's ability to fly the aircraft at high angles of attack and decreased his workload

L1 AFCS



Repeatable results
Two AOA=18deg acquisitions with L1 AFCS

Pitch break
Oscillations around 15deg AOA



"A well controllable aircraft during stall and post-stall flight"
Dan Murri
AirSTAR GTM T2 research pilot

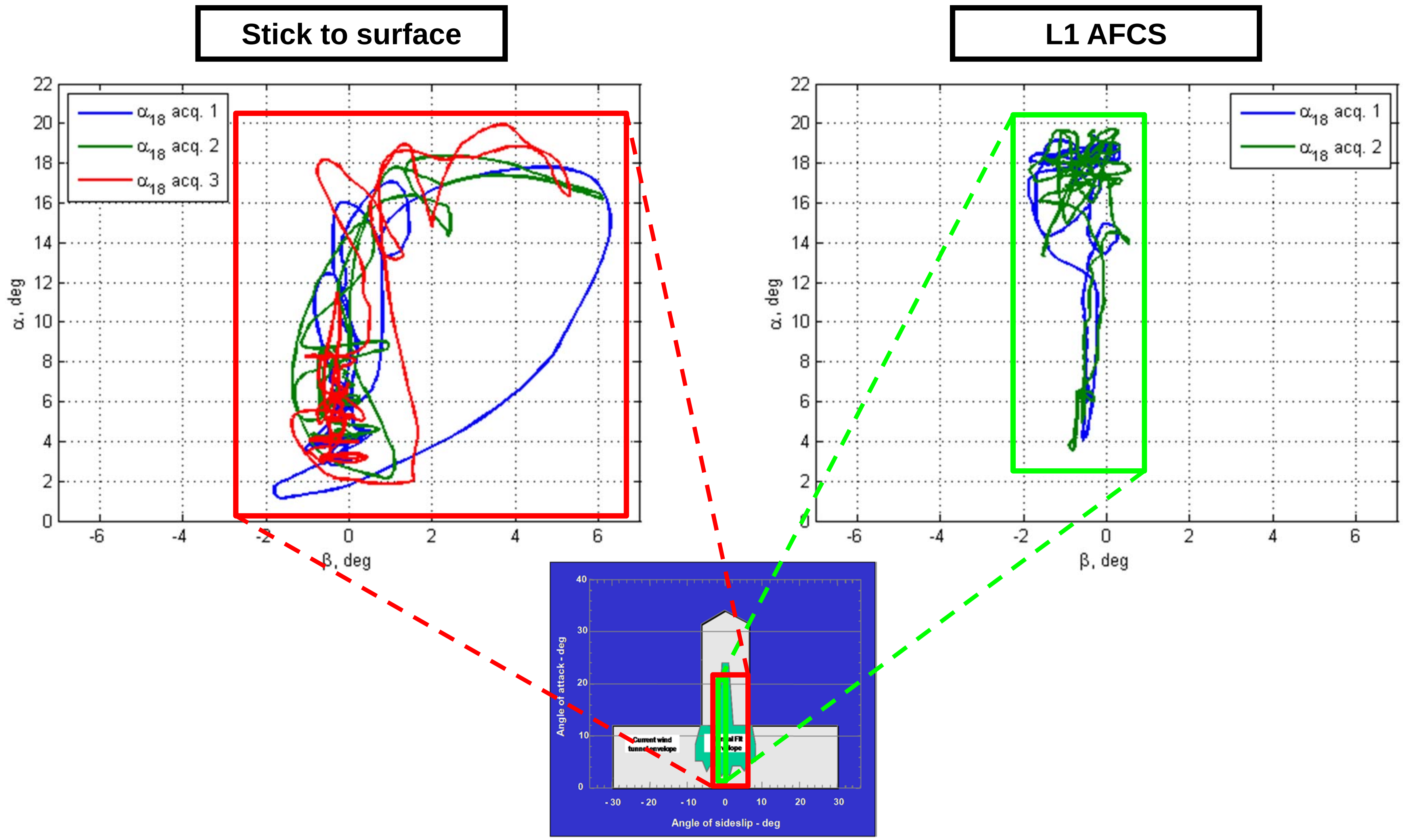
Roll rate below 20dps

FLT 23

High AOA Flight :: α-β Excursion (June 2010)

Post-stall, high angle of attack flight

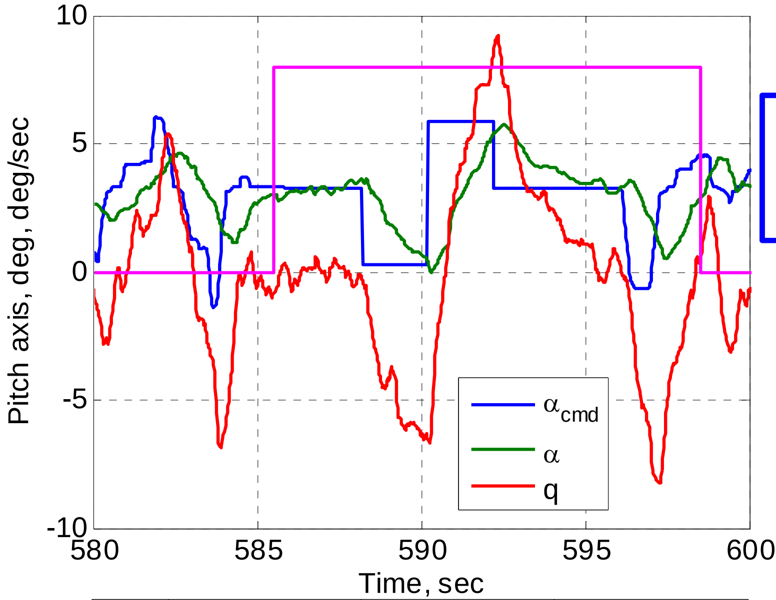
- **L1 provides departure resilient control for aircraft in post-stall flight**



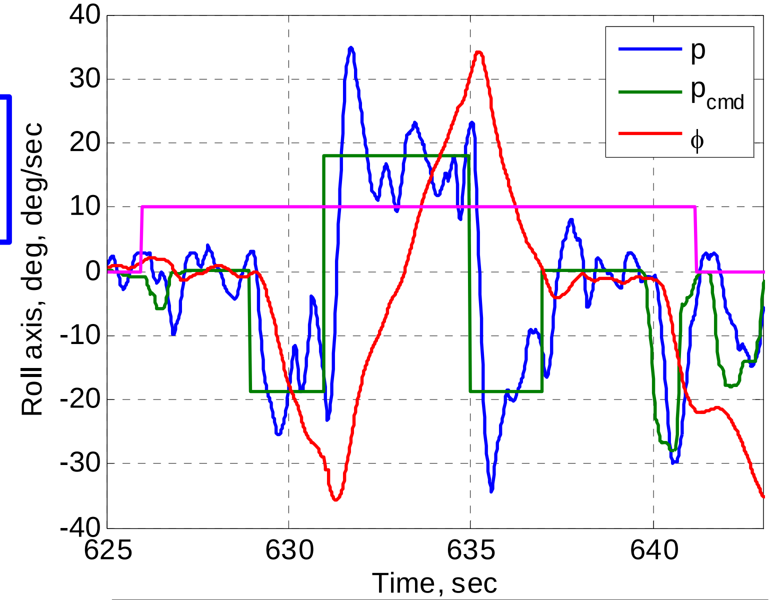
Cmα/Clp Degradation WT Response (June 2010)

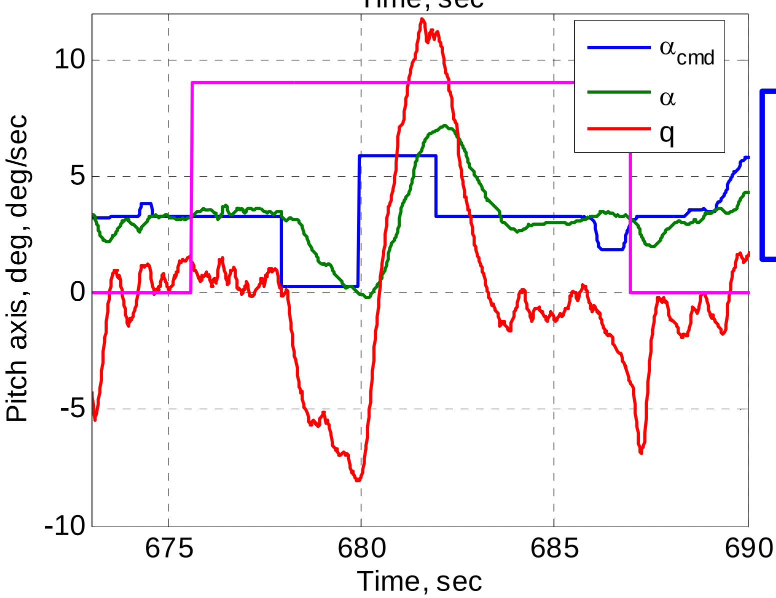
Pitch axis – α_cmd doublet

Roll axis – p_cmd doublet

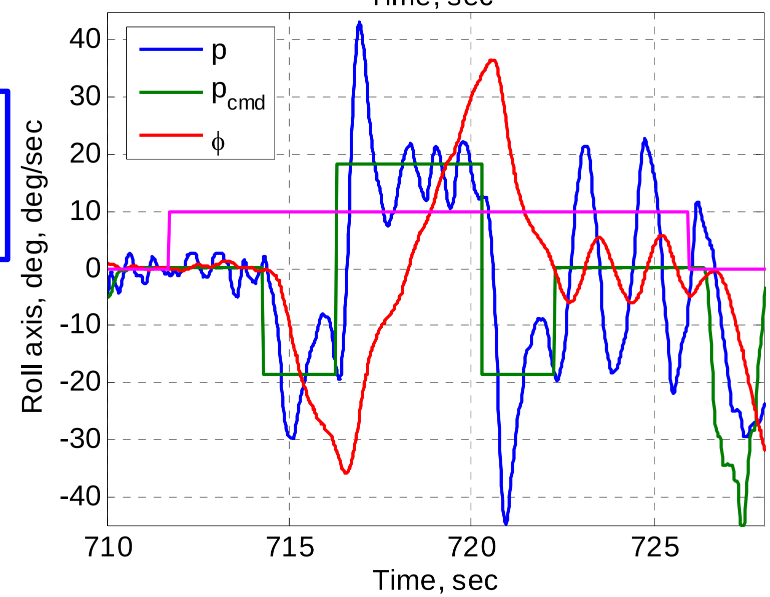


Cmα/Clp ↓75%
↓50% long cntrl



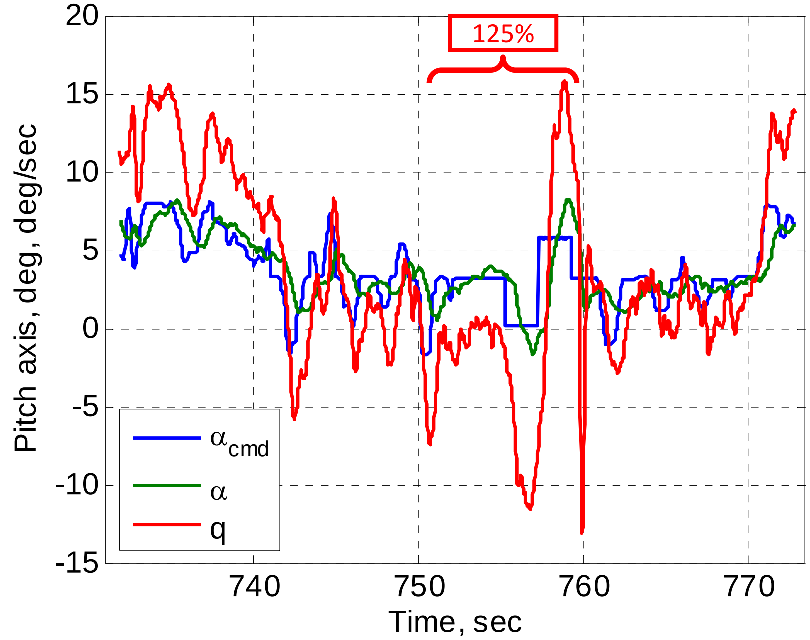


Neutrally stable
Cmα/Clp ↓100%
↓50% long cntrl

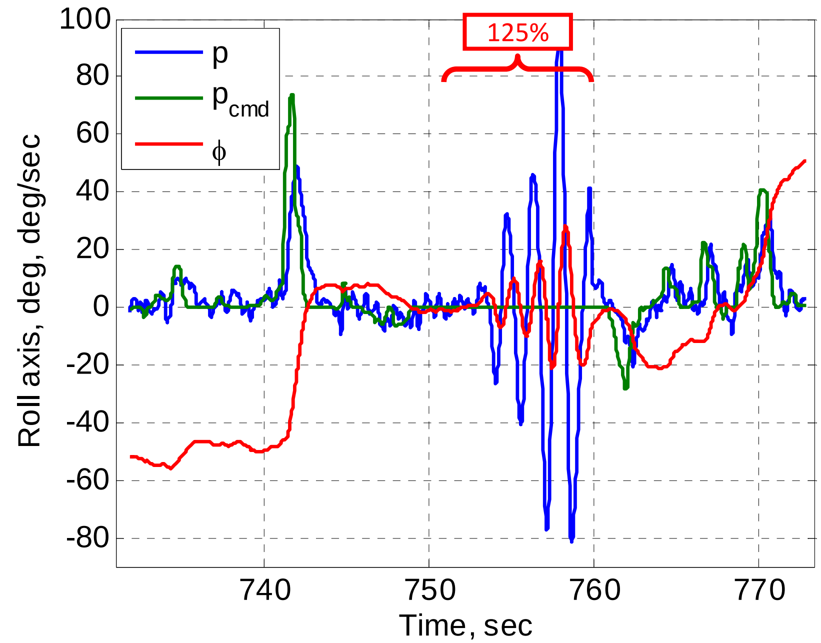


125% Cmα/Clp Degradation WT Response (June 2010)

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)

September 2010 Flight Test Evaluation

L1 all-adaptive CAS: provides performance/stability for nominal and impaired aircraft

- ✓ **Not an augmentation** to a baseline controller that provides nominal aircraft performance, like other adaptive controllers implemented

Flight Control Law related tasks during September 2010 deployment:

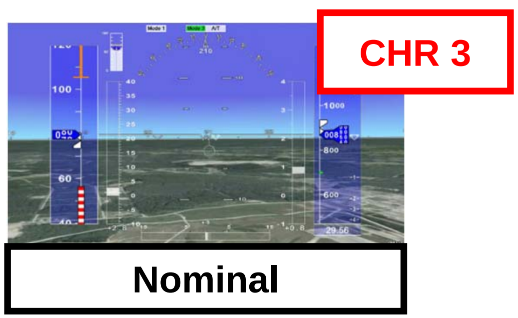
- ➢ Flight Control Law Block :
  - **Offset-to-landing with simultaneous** longitudinal and lateral **stability degradation ($C_{m\alpha}$/C_{lp})**:
    - ✓ Nominal: **CHR 3**
    - ✓ 100%: **CHR 5**
    - ✓ 125%: **CHR 7**

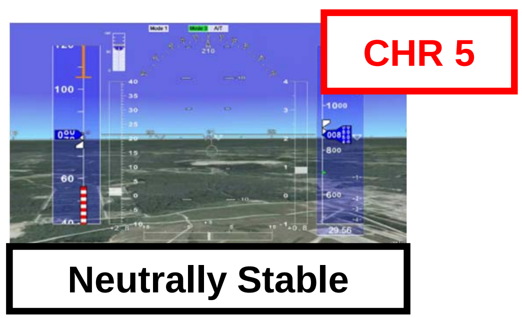
- ➢ L1 support on Modeling Tasks:
  - **β-vane calibration (flat turn maneuvers)**
  - **α-vane calibration (variable and constant AOA strategies)**
  - **Unsteady Aerodynamics Modeling (Stall and post-stall high AOA tracking)**

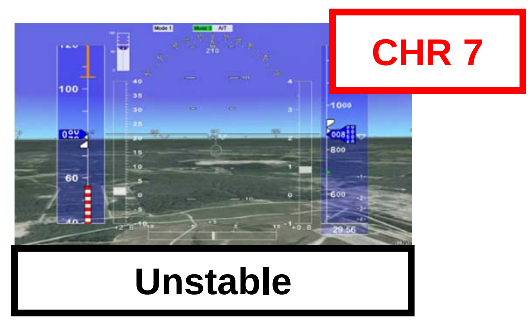
High Workload Task :: Offset-to-Landings (September 2010)

- **Initial offset:**
  - 90 ft. lateral, 1800 ft. downrange, 100 ft. above the runway
- **Performance boundaries:**
  - Desired: $|\phi| < 10$ deg; $|\gamma| < 1$ deg; landing box = 164’ x 12’
  - Adequate: $|\phi| < 20$ deg; $|\gamma| < 3$ deg; landing box = 363’ x 24’
- Flying qualities ratings taken for **nominal, neutrally stable, unstable airplane**

	S2S	L1 AFCS
Nominal	*CHR*4 (HQ L2)	*CHR*3 (HQ L1)
Neutral Stability	*CHR*10 (uncontrollable)	*CHR*5 (HQ L2)
Unstable	--	*CHR*7 (HQ L3)

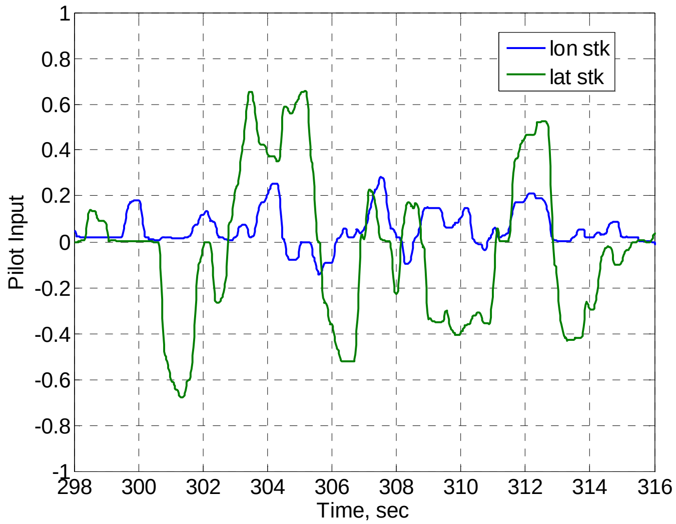


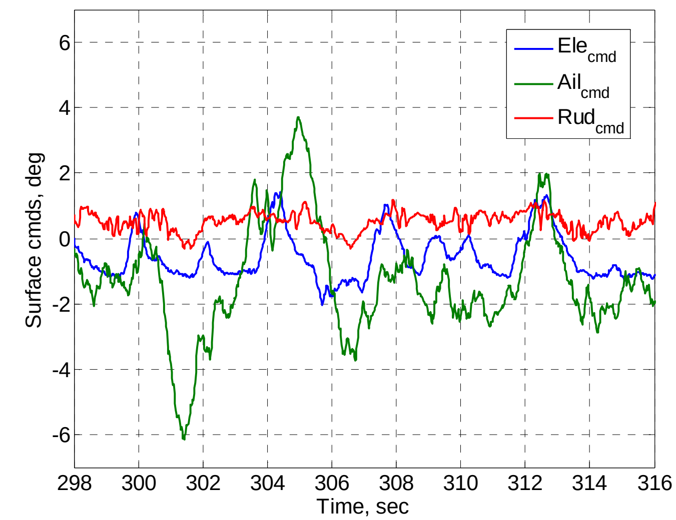


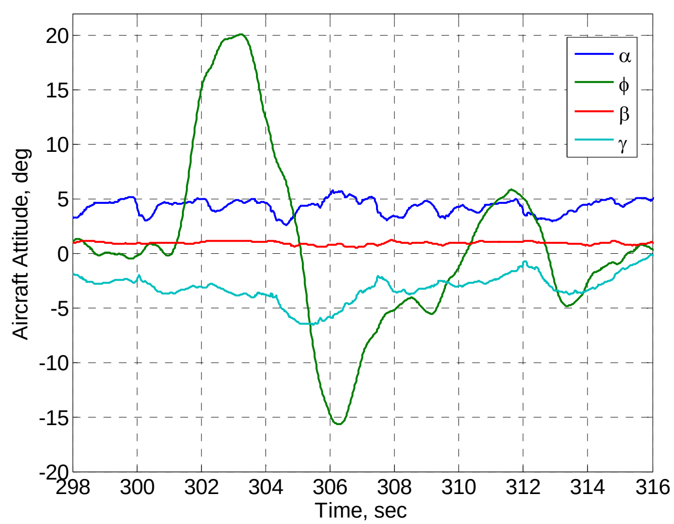


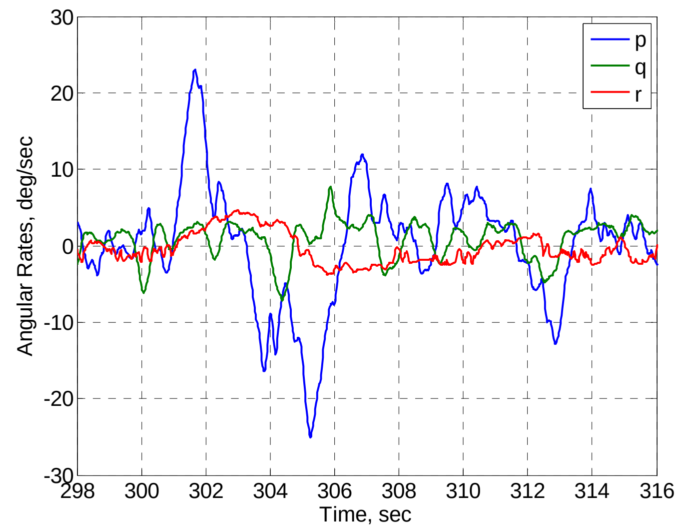
Offset-to-Landings (September 2010)

- Nominal airplane – CHR 3



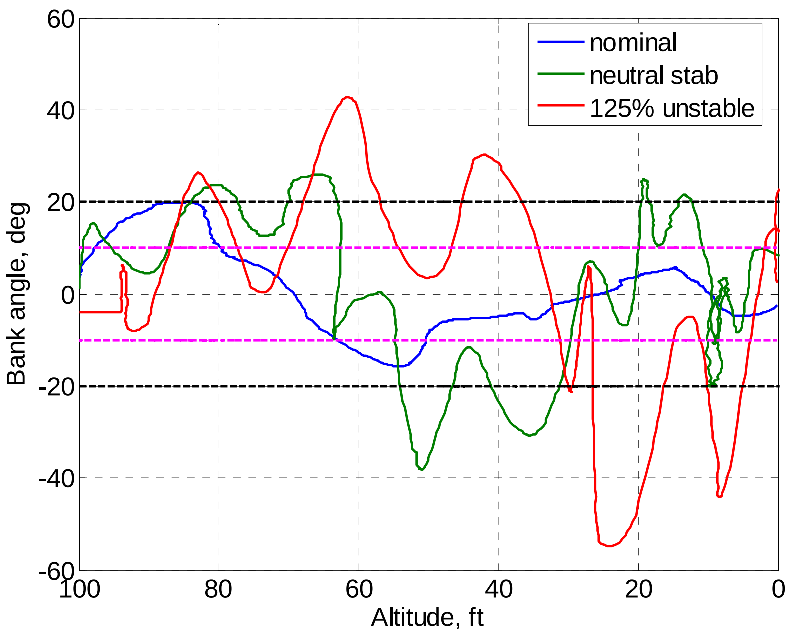


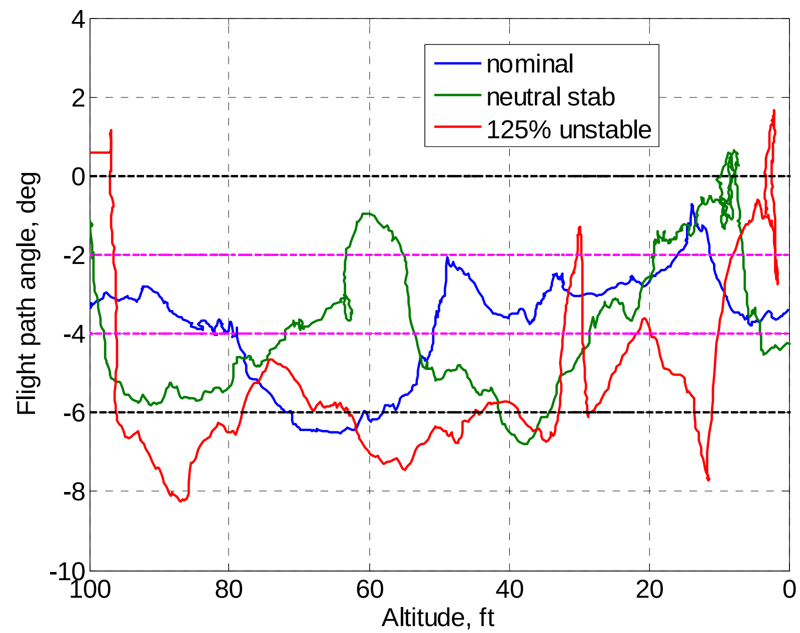




Offset-to-Landings (September 2010)

- **Aircraft response during offset landing task for nominal and stability degraded dynamics.**
- **Performance boundaries:**
  - Desired: |ϕ| < 10 deg; |γ|< 1 deg; landing box = 164' x 12'
  - Adequate: |ϕ| < 20 deg; |γ|< 3 deg; landing box = 363' x 24'



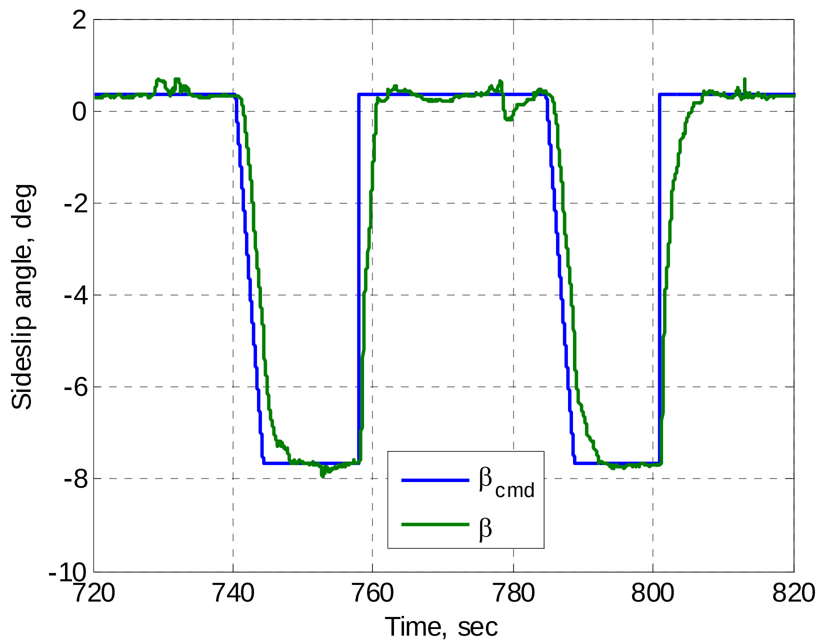


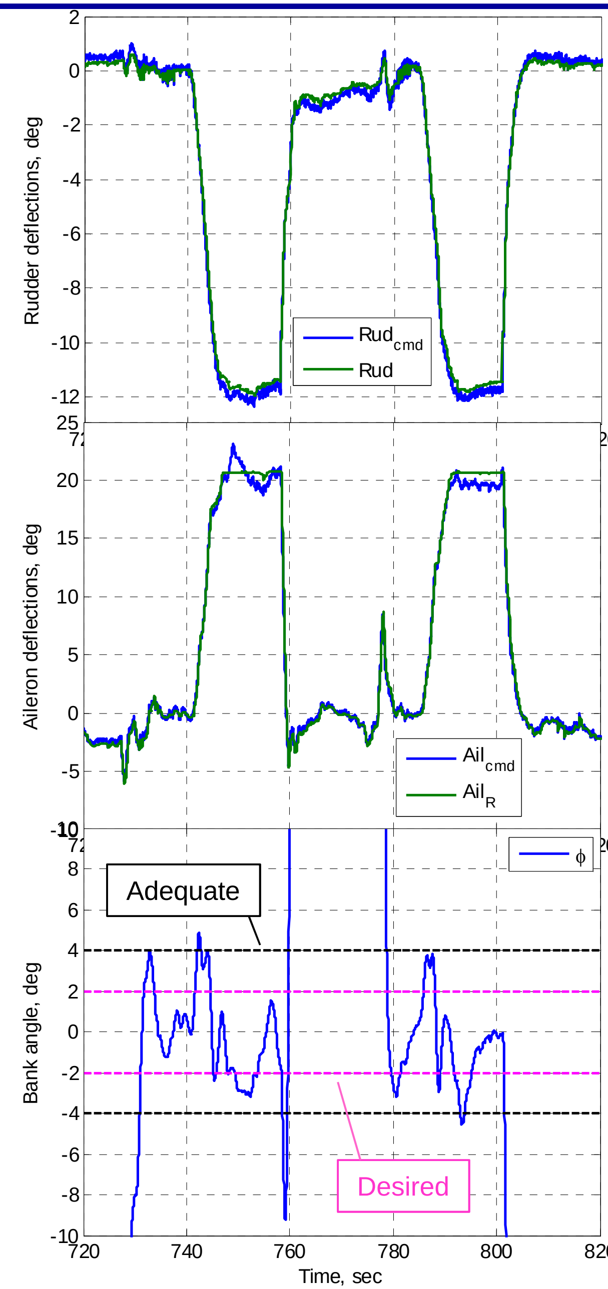
L1 Support Tasks on Modeling

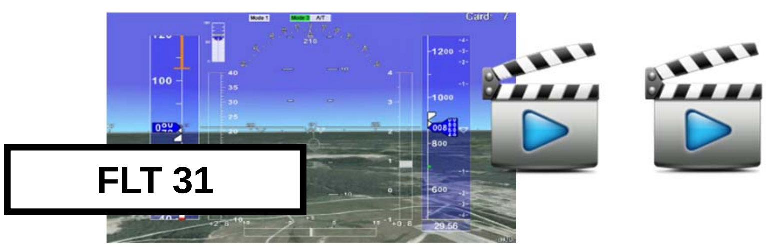
Research Task	Subtask	1st straight leg	2nd straight leg	Deployment	Flights
Air-data vane calibration	α-vane calibration	Variable α Constant α	Repeat	Sep 2010 May 2011	28, 56
	β-vane calibration	Flat turn	Repeat	Sep 2010 May 2011	29, 31, 56
Unsteady aerodynamic modeling work	Post-stall α tracking	Multi-step Schroeder sweep Multi-sine	Regain altitude	Sep 2010	31, 35, 52
	Roll forced oscillations	Roll wavetrain	Regain altitude	May 2011	49, 50, 53, 56, 57
Exploration of departure-prone edges	α-sweep from low angles, through stall, to departure	Control-surface wavetrains	Regain altitude	May 2011	54, 55, 58

β – Vane Calibration (September 2010)

- Flat turn:
  - 2deg/s (or 1deg/s) ramp up to desired β value
  - hold target sideslip (0, ±2, ±4, ±6, ±8 deg)
  - Minimize lateral axis excursions



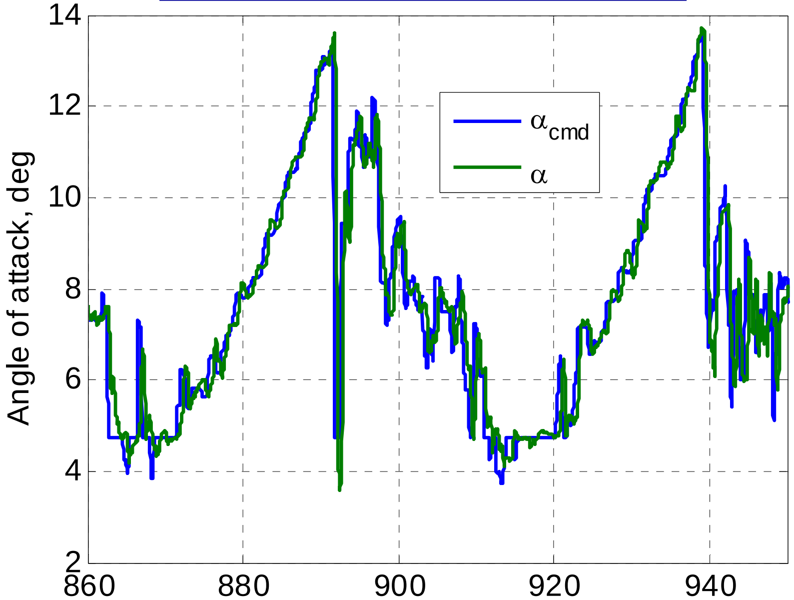


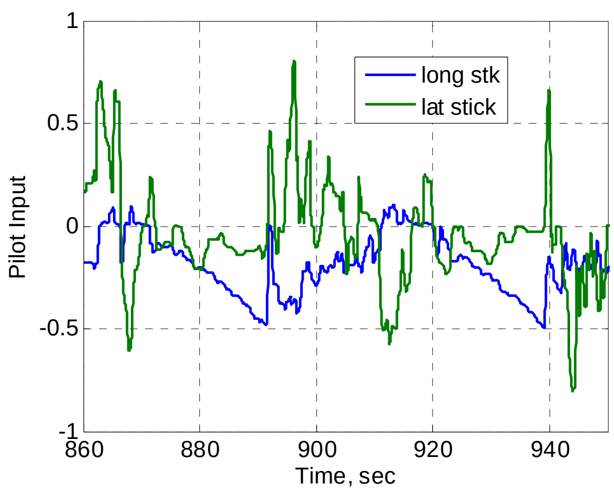


α – Vane Calibration (September 2010)

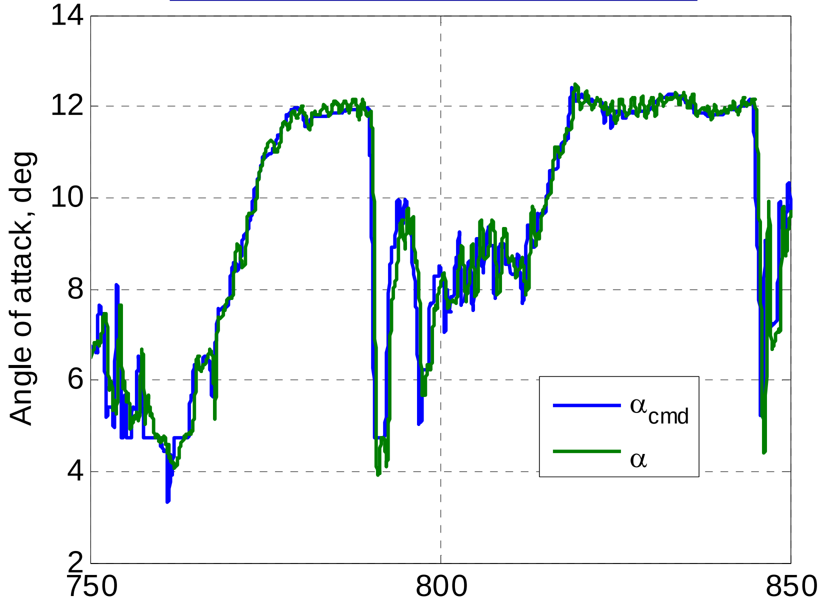
- Stall occurs between 12 and 13 deg AOA

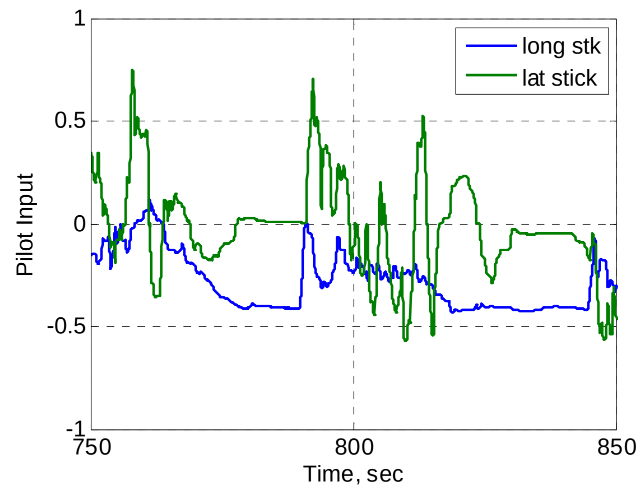
Variable AOA Strategy





Constant AOA Strategy

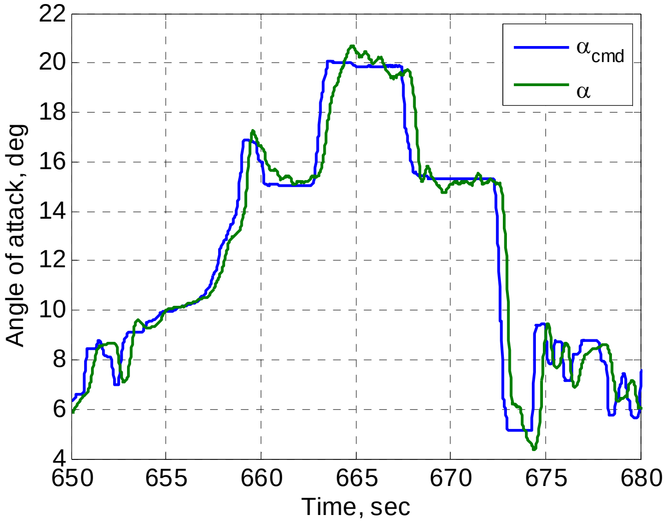




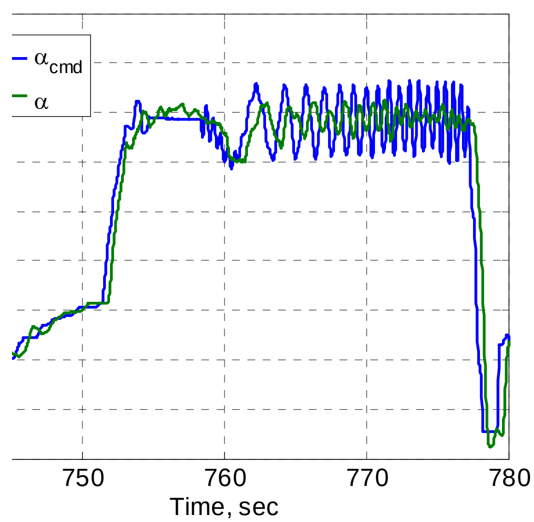
Unsteady Aero :: High AOA Tracking (September 2010)

- 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

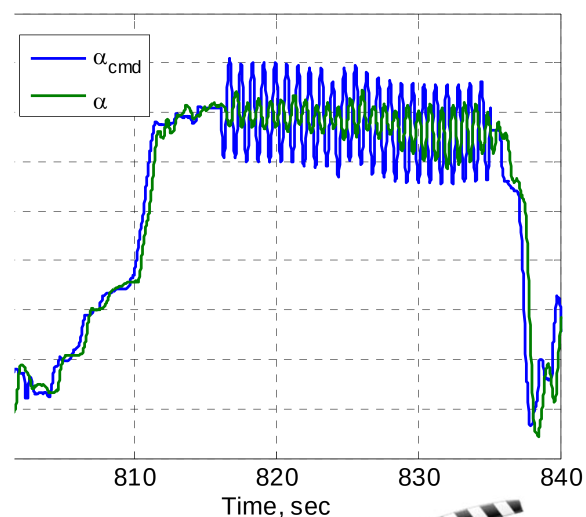
Step Input



Schroeder Input



Sinusoids Input



May 2011 Flight Test

L1 all-adaptive CAS: provides performance/stability for nominal and impaired aircraft

- ✓ **Not an augmentation** to a baseline controller that provides nominal aircraft performance, like other adaptive controllers implemented

Flight Control Law related tasks during September 2010 deployment:

➢ L1 support on Modeling Tasks:

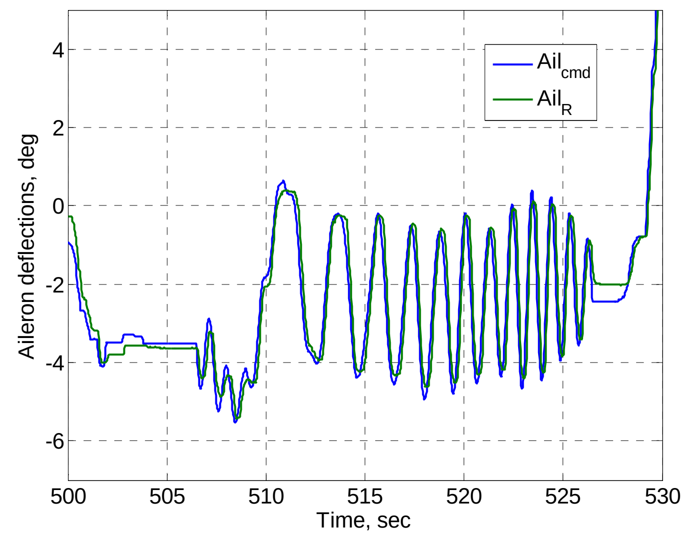
- **Continuation of Unsteady Aerodynamics Modeling**
- **Real-time System Identification in approach to stall and departure**

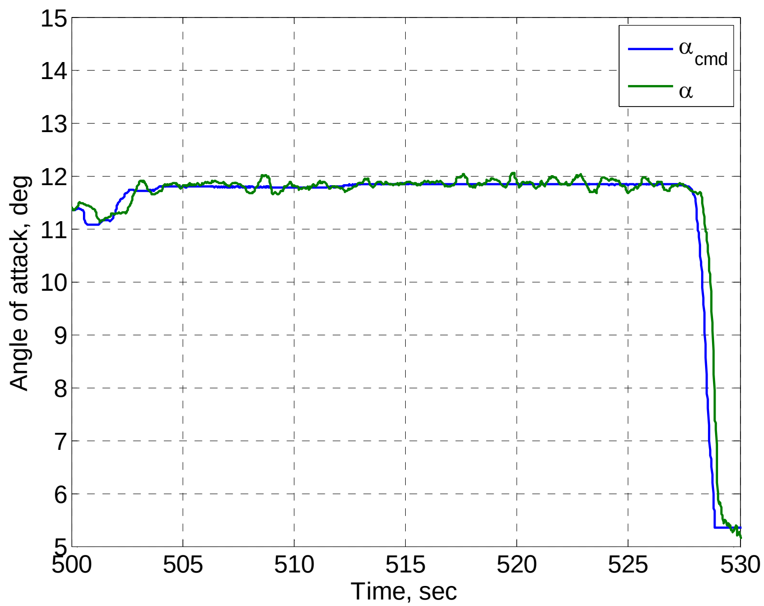
Applied L1 adaptive control to **lengthen time on condition**
with stabilization that allowed slow transition through stall boundary
and **improved stall/departure recovery**

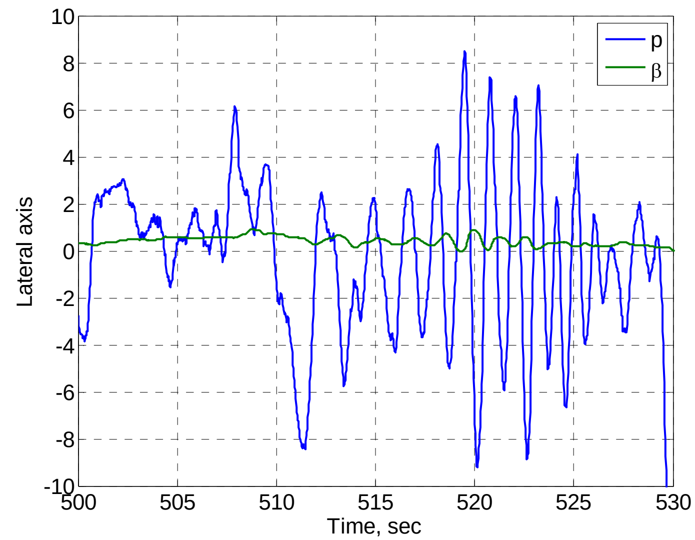
Unsteady Aero :: Roll Forced Oscillations (May 2011)

- **Roll forced oscillations at α=12 deg**:
  - Precise tracking of α=12 deg (*L1 longitudinal*)
  - Allow *free* β response to roll wavetrain
    - ✓ Step doublet, Schroeder sweep, variable frequency Sinusoid

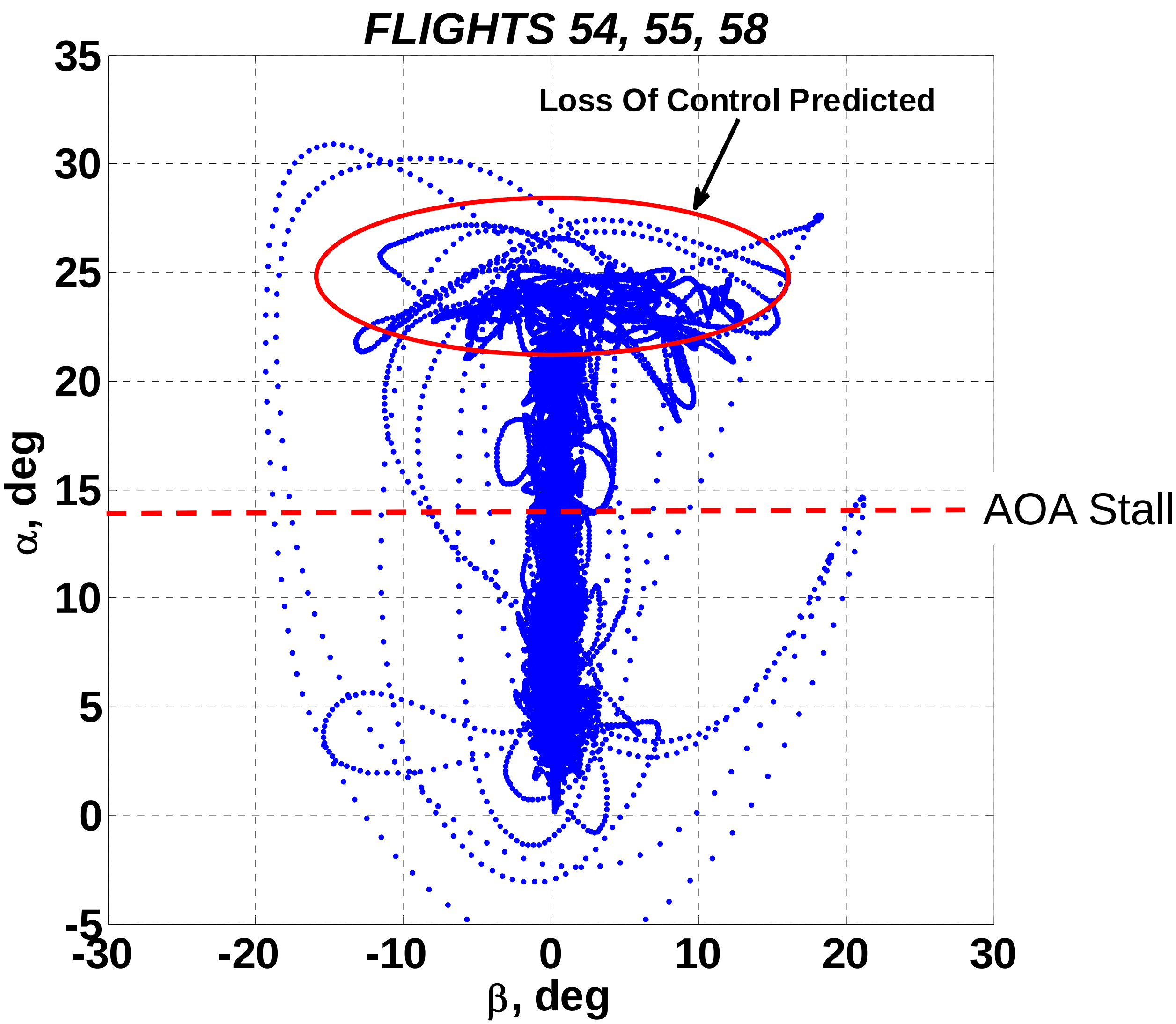
Schroeder Input





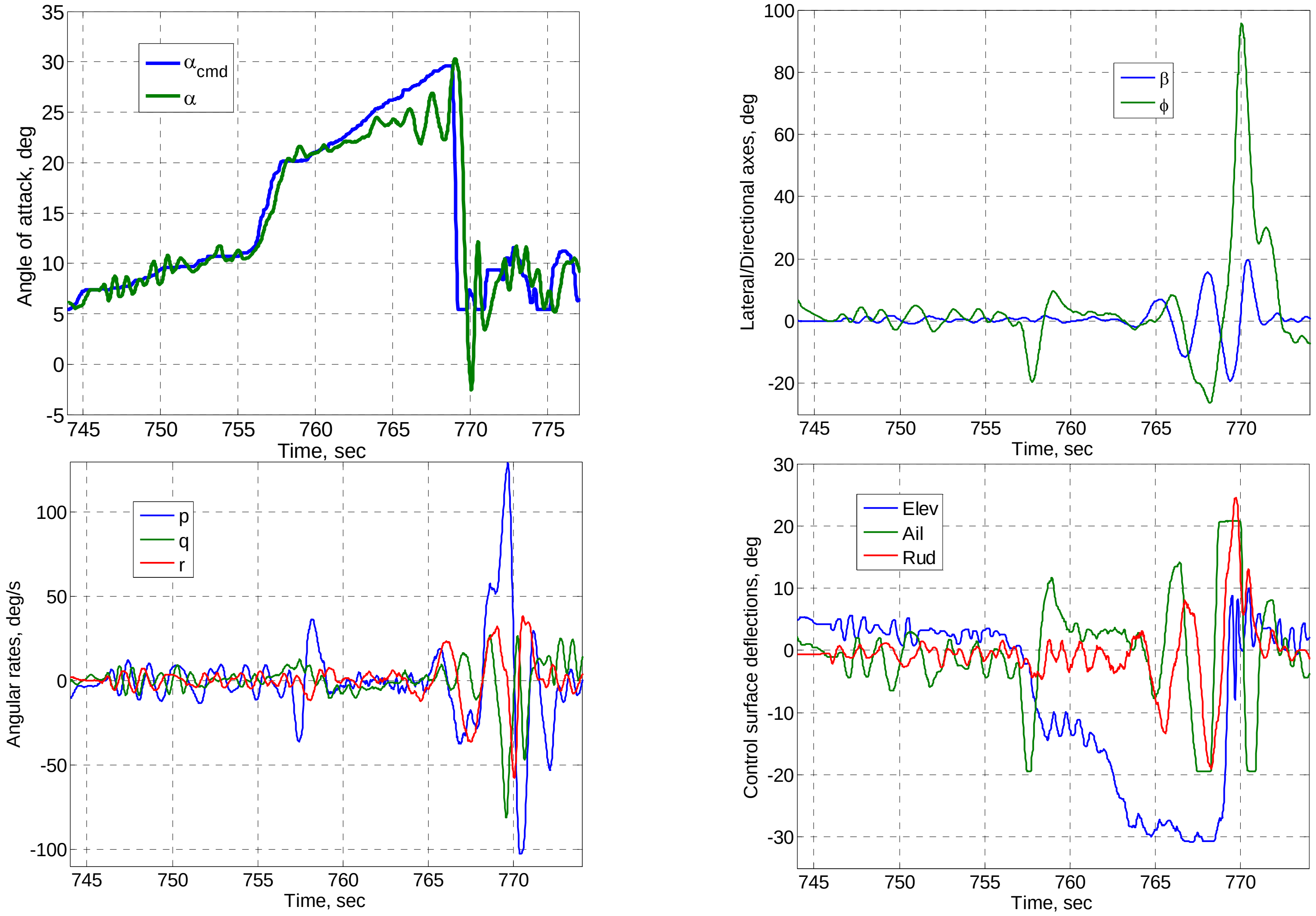


L1 Supports Large Flight Envelope Modeling (May 2011)



AoA Pull Through Stall and Departure (May 2011)

- Flight 58 – active wavetrain through stall, departure, and recovery, L1 adaptive control law in the feedback loop
- Reached departure conditions; aircraft <u>not fully controllable</u>



GTM T2 :: Flight Test Evaluation Summary

- **All-adaptive FCS** that provides nominal aircraft performance and takes care of large changes in aircraft dynamics
  - ✓ **No baseline to assist**
- A **single controller design** at a nominal flight condition (4deg AOA) to provide satisfactory FQ and robustness
  - ✓ **No gain scheduling of control parameters (adaptation rate, filter)**
- **Predictable response** to the pilot under stability degradation and *graceful performance degradation* once nominal response was unachievable
- **Departure resistant in post-stall flight:** L1 provides a **controllable aircraft** to the pilot and facilitates **safe** return to normal flight
- The classical **trade-off between robustness** (to system latency) **vs. performance** was found to be **consistent with the theory**
- **Protected against input control saturation** (persistent control surface saturation occurred during high AOA flight and vane calibration)

GTM T2 :: Modeling Support Summary

- Aerodynamic modeling in highly nonlinear regimes and real-time dynamic modeling of the **departure-prone edges of the flight envelope**.
- L1 control law used to support modeling of **unsteady aerodynamics at stall conditions**.
- Post-stall aerodynamic test **envelope expanded** to 28 degrees angle of attack (in closed-loop).
- The L1 flight control law:
  - ✓ enabled operation near stall and departure for **longer periods of time**, allowing for data collection for a wide range of flight conditions
  - ✓ provided **safe recovery**

<u>**L1 adaptive control law provides:**</u>

- ➢ tighter acquisition of target flight conditions
- ➢ precision tracking capability across the flight envelope
- ➢ graceful performance degradation
  - target flight conditions are beyond achievable values
  - control surfaces are persistently saturated

Source: NASA LaRC (internal reviews)

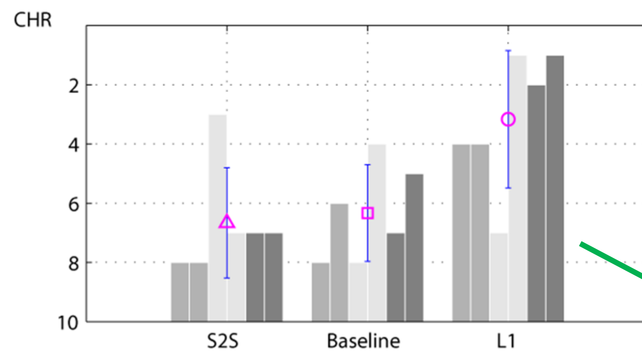
TU Delft :: Cessna Citation II

Objective:

- *Improve handling qualities and maneuverability margins for* ***safe landing*** *in the presence of failures.*

L_1 AFCS:

- *Augmentation of a nonadaptive (dynamic) baseline controller.*
- *Baseline controller is gain-scheduled.*
- *No gain-scheduling of the adaptation sampling rate or the law-pass filters.*
- *Adaptation working at 200Hz.*



Noticeable improvement of L_1 over S2S and BL configurations.

Stroosma, Damveld, Mulder, Choe, Xargay, & Hovakimyan, "A Handling Qualities Assessment of a business Jet Augmented with an L_1 Adaptive Controller," in AIAA GNC 2011

DA-42 & Gripen-like Fighter

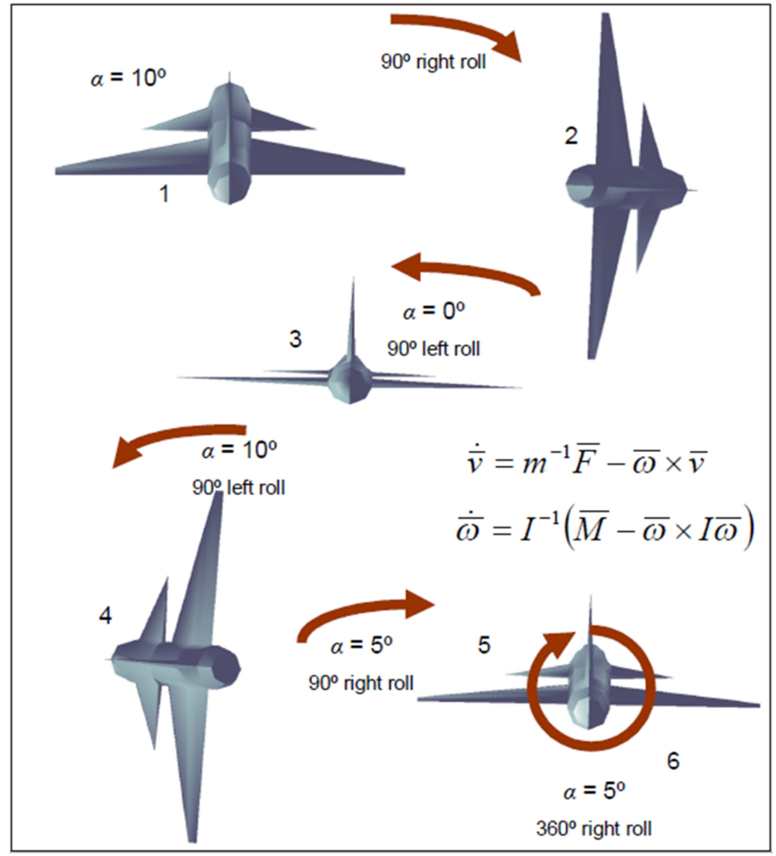
Gripen-like fighter

SAAB & Lund University, Sweden

DA-42

Twin seat, propeller-driven aircraft

TUM, Germany

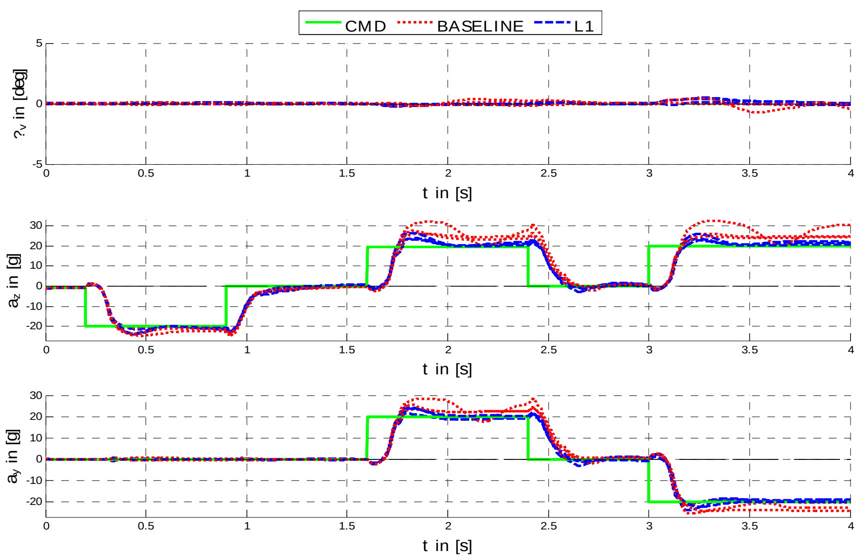


Generic Missile Model *(industry contract)*

Highly agile, tail-controlled missile

TUM, Germany (industry contract)

- **Baseline controller vs. L_1 Augmentation:**



Uniform tracking response for all tested (admissible) uncertainty combinations

Variable	UC 1	UC 2	UC 3
I_{xx}, I_{yy}, I_{zz}	$+5\%$	-5%	$+5\%$
m	-1%	-1%	-1%
x_{cg}	$-50mm$	$+50mm$	$+50mm$
$(C_{x,0})_B, (C_{y,0})_B, (C_{z,0})_B$	-10%	-10%	-10%
$(C_{L,0})_B, (C_{M,0})_B, (C_{N,0})_B$	-20%	-20%	-20%
$(C_{x,\xi})_B, (C_{y,\zeta})_B, (C_{z,\eta})_B, (C_{L,\xi})_B, (C_{M,\eta})_B, (C_{N,\zeta})_B$	-20%	$+20\%$	-20%
$(C_{L,p})_B, (C_{M,q})_B, (C_{N,r})_B$	-20%	$+20\%$	$+20\%$
α_K, β_K	$-2.5deg$	$-2.5deg$	$-2.5deg, +2.5deg$
$\bar{q}$	-5%	-5%	-5%
Ma	-10%	-10%	$+10\%$

26% improvement wrt other tested adaptive approaches

L_1 Augmentation Loops on Multirotors

Hexarotor

The Netherlands

"Did the maiden L_1 flight with the hexa. Perfect weather for testing the L_1 controller; lots of wind, changes in directions, rain clouds… The controller countered everything, unbelievable Bill!!"

Quadrotor

TUM, Germany

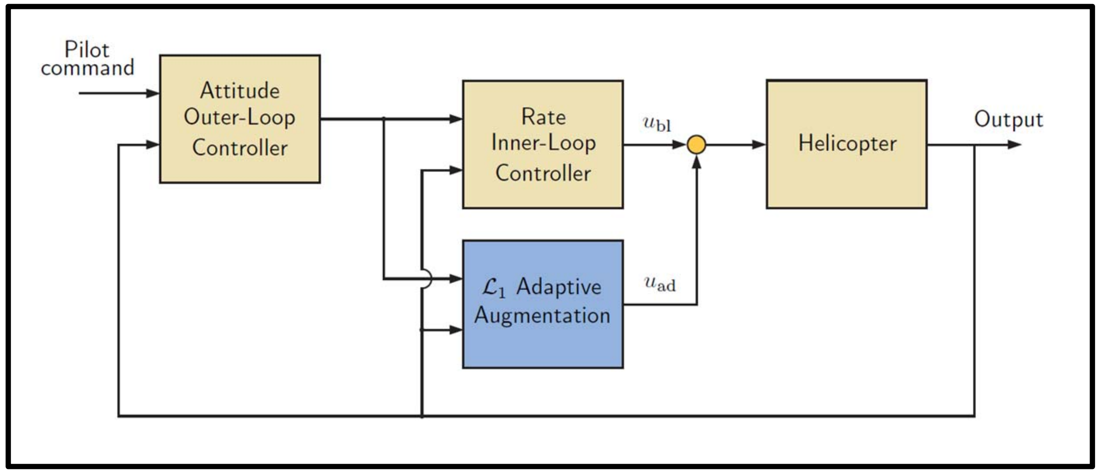
'Spider' Hexarotor

US

"Here is a craft that couldn't be stabilized or controlled with a PID. Once we did some bench tests to determine propeller thrust, motor torque, and moment of inertia, tuning L_1 was a piece of cake."

Generic Helicopter Model *(industry contract)*

Light-utility helicopter
TUM, Germany



Remarks:

- ***Rate inner-loop augmentation****;*
- *Augmented state predictor with* ***controller states****;*
- *Known nonlinearities, nominal actuator dynamics, saturations, & input delays included in the* ***state predictor****;*
- ***Fictitious uncertainty*** *added to derive estimation laws;*
- *PWC estimation laws with* ***integral modification term****;*
- ***Notch filter*** *added to the L_1 low-pass filter so as not to excite the* ***blade lead-lag mode****;*
- *Multi-rate controller (baseline 50Hz – L_1 200Hz)*

Conclusions

- **L_1 adaptive control architectures**:
  - ✓ Performance and robustness guarantees
  - ✓ Systematic design guidelines
  - ✓ Computationally predictable characteristics

- **Design of robust adaptive flight control systems:**
  - ✓ Single design for the **entire flight envelope** (including stall and post-stall conditions) **without**…
    - **Gain-scheduling/Persistency of excitation/Control reconfiguration/High-gain feedback**
  - ✓ Compensation for structural damage and actuator failures **without FDI methods**
  - ✓ **Consistent results** from platform to platform, *as predicted by theory*
  - ✓ Implementation as an **all-adaptive controller** or as an **augmentation loop** for baseline controllers
  - ✓ **10+ successful flights with NASA's GTM T2 and 100+ successful flights with NPS**

Suitable for development of **theoretically justified Verification & Validation tools** for feedback systems

Acknowledgements

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  - Irene M. Gregory (NASA Langley)

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Questions?