Model Reference Adaptive Control (MRAC) Experiment Description

(Curt Hanson)

Flight Test Objectives

- **Flight Test a Simplified Adaptive Controller**
  – Investigate the relationship between the complexity and utility of adaptive controls
  – Demonstrate, in a flight environment, the strengths and weaknesses of a simple “textbook” model reference adaptive controller
  – Provide experimental evidence supporting the need for, and benefits of, additional complexity

- **Investigate Pilot Interaction with Adaptive Systems**
  – Gather evidence in support of the following questions:
    - Should an adaptive controller be active at all times or only in emergencies?
    - Should an adaptive controller be a “one size fits all” solution, or should it be tailored to the emergency situation?
  – Determine whether the pilot has sufficient information to customize the adaptive controller
  – Identify any potentially adverse interaction between the pilot and the adaptive controller

Experiment Background

Experiment Selection Process:

2009, Apr: The IRAC project disseminated a request for information (RFI) on potential flight experiments to the adaptive controls community

2009, Aug: The IRAC project hosted a workshop to discuss the RFI and responses from Industry, Academia and Government

2009, Sep: A decision letter was released outlining the IRAC project's research focus for flight experiments on the 853 testbed (FAST):

MRAC Objectives

Primary:
1. Experiments focused on the design and evaluation of <u>simple yet effective</u> adaptive algorithms, that may be more compatible with existing verification and validation techniques.

Secondary:
2. Experiments that investigate methods to include pilot control, awareness, and interaction with the adaptive control algorithm.

Out of Scope:
3. Experiments that address issues associated with the constraints imposed by both static load and dynamic structural interaction.

“simple yet effective” Adaptive Control

Nonlinear Dynamic Inversion *plus* **Model Reference Adaptive Control**

Nonlinear Dynamic Inversion

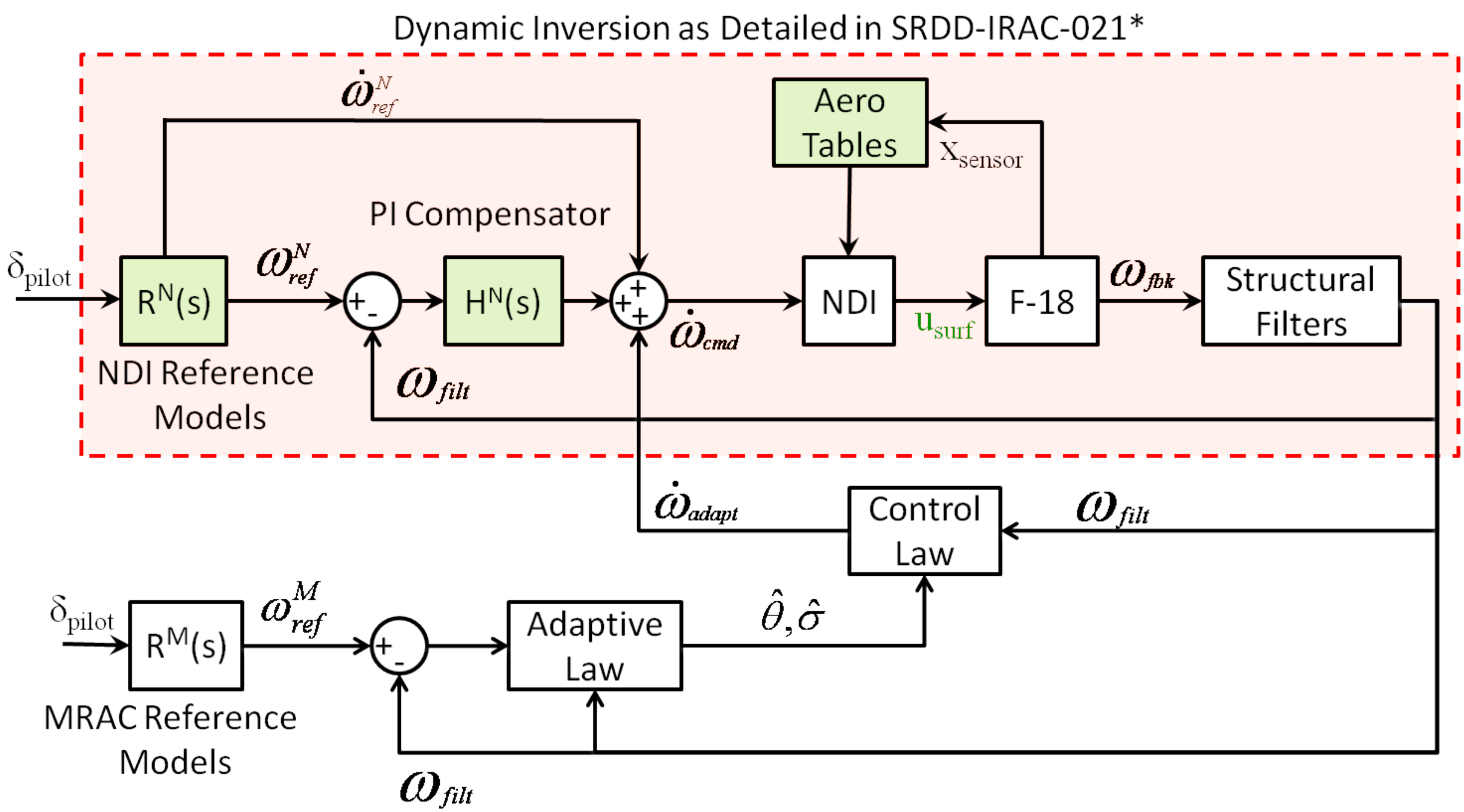
- Explicit Model Following
  - integrates nicely with many adaptive control techniques, such as model reference adaptive control
- Failure Modeling
  - The NDI controller can be used to model a variety of failure dynamics
- Analyzability
  - The NDI architecture is easy to analyze and include in stability proofs
- Open-Source Architecture
  - By specifying non-ITAR reference models, simulation and flight test data can be openly published
- Ease of Gain Scheduling
  - The NDI architecture implicitly accomplishes gain scheduling via its suite of aerodynamic coefficient lookup tables

Model Reference Adaptive Control

- Basic
  - easy to understand and implement
  - well-known throughout the community
- Generic and Extensible
  - forms the basis of more advanced algorithms
  - easy to add modification terms to the update laws
    - normalization, projection, e-mod, etc
- Aligns with NASA Experience Base
  - Past work on IFCS (T/N 837)
  - Recent work at ARC
- Meets Kalmanje Krishnakumar’s Directives:

1. Don’t showcase someone’s favorite adaptive controller, and
2. Don’t compare multiple control schemes

Control Architecture



* -Failure implementation capabilities have been add to the items in green which differ from the design in SRDD-IRAC-021

Theoretical Background

1. Desired (Reference Model) Dynamics

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

2. Uncertain Plant Dynamics

$$\dot{x} = Ax + Bu + \sigma$$

where $A = A_m + B_m \theta^T$

$B = B_m$

$$\dot{x} = \left(A_m + \underbrace{B_m \theta^T}_{\text{matched uncertainty}}\right)x + \underbrace{B_m u + \sigma}_{\text{unmatched uncertainty}}$$

3. Adaptive Parameter Estimation

$$\left.\begin{aligned} \dot{\hat{\theta}} &= \Gamma_\theta e^T P B_m x \\ \dot{\hat{\sigma}} &= -\Gamma_\sigma e^T P B_m \end{aligned}\right\} \text{Lyapunov-based adaptive update laws}$$

where $e = x_m - x$

4. Control Signal

$$u = r + \hat{\theta}^T x - \hat{\sigma}$$

5. Closed-Loop Dynamics with Adaptive Control

$$\dot{x} = A_m x + B_m r + B_m\left(\theta^T + \hat{\theta}^T\right)x + \left(\sigma - B_m \hat{\sigma}\right) \Rightarrow \underbrace{\dot{x} = A_m x + B_m r}_{\text{if } \hat{\theta}^T \to -\theta^T \text{ and } B_m \hat{\sigma} \to \sigma}$$

Controller Configurations

Configuration*	Strengths	Weaknesses
Simple MRAC (sMRAC) $\begin{bmatrix} \cancelto{\sim 0}{\dot{\hat{\theta}}_1} \\ \dot{\hat{\theta}}_2 \end{bmatrix} = \Gamma_\theta \begin{bmatrix} \int e \\ e \end{bmatrix}^T PB_m \begin{bmatrix} \int q \\ q \end{bmatrix}$	one input and one adaptive parameter	over-adaptation, no unmatched uncertainty term
MRAC w/ Normalization and Optimal Control Modification (onMRAC) $\begin{bmatrix} \cancelto{\sim 0}{\dot{\hat{\theta}}_1} \\ \dot{\hat{\theta}}_2 \end{bmatrix} = \frac{\Gamma_\theta}{1 + R_\theta q^2} \left(\begin{bmatrix} \int e \\ e \end{bmatrix}^T PB_m \begin{bmatrix} \int q \\ q \end{bmatrix} - \nu \hat{\theta}_2 B_m^T P A_m^{-1} B_m q^2 \right)$	suppresses over-adaptation	no unmatched uncertainty term
onMRAC plus Unmatched Uncertainty (onMRAC+) $\dot{\hat{\sigma}} = \frac{-\Gamma_\sigma}{1 + R_\sigma q^2} \begin{bmatrix} \int e \\ e \end{bmatrix}^T PB_m$	suppresses over-adaptation, better performance with unmatched uncertainties	reduced performance with matched uncertainties

***Pitch-Axis Examples Shown**

Simulated In-Flight Failures

Failure	Failure Magnitude	Comments
1. Reduced pitch damping	80% reduction	not maneuverable in NDI due to slowly divergent, oscillatory instability
2. Reduced roll damping	117% reduction	PIO-prone with NDI
3. Reduced pitch static stability	60% reduction	slow pitch-up transient on failure insertion
4. Frozen left stabilator	100% failed	similar to RFCS right stabilator failure
5. Roll-to-pitch input coupling	dep+1.0*dap	prone to causing over-adaptation of sMRAC configuration

simulated failures are faded in/out over 2 seconds

Special Features, Part 1

Pedal Suppression Gain

Symptom: Sudden un-commanded rolls were observed following extended SSHS maneuvers

Cause: Over-adaptation due to non-zero roll stick accompanied by zero roll rate (i.e. high roll error)

Fix: Roll adaptation is linearly scaled from 100% to 0% over the first 50 lbs of rudder pedal, and held at zero out to max pedal

High-Pass Filtering of Pitch Rate to Adaptive Laws

Symptom: Over-adaptation of onMRAC and onMRAC+ configurations during 2.5g windup turns, reduced pitch damping failure

Cause: Oscillations about a non-zero pitch rate caused pitch adaptive parameter to “un-adapt”; exacerbated by normalization term

Fix: High-pass filtering of the pitch rate used in the adaptive update law

Special Features, Part 2

Time-Correlation of Error Calculation

Symptom: Poor performance and low time delay margins

Cause: Time delay differences between reference signals and measured feedback signals cause "phantom" error, leading to inappropriate adaptation

Fix: The reference signals to the error calculation are delayed by 8 minor (160 Hz) frames:

- 2: known system time delays
- 3: approximate phase loss due to anti-aliasing filter
- 3: an empirically-determined amount of additional delay

Nosewheel Steering (NWS) Logic

PVI Display

‘N’: NDI control

‘S’: simple MRAC

‘O’: MRAC with normalization / optimal modification term

‘+’: MRAC with normalization / optimal modification term and unmatched uncertainty term

‘=‘: adaptive parameters are frozen

‘X’: invalid DAG/CAT

Notes

1. when the failure is inserted, the PVI character will flash
2. removal of adaptation is rate-limited for transient suppression

ARTS is Engaged

1st Press: Inserts Failure

2nd Press : Turns on Adaptation

3rd Press: Freezes Adaptation

4th Press: Unfreezes Adaptation

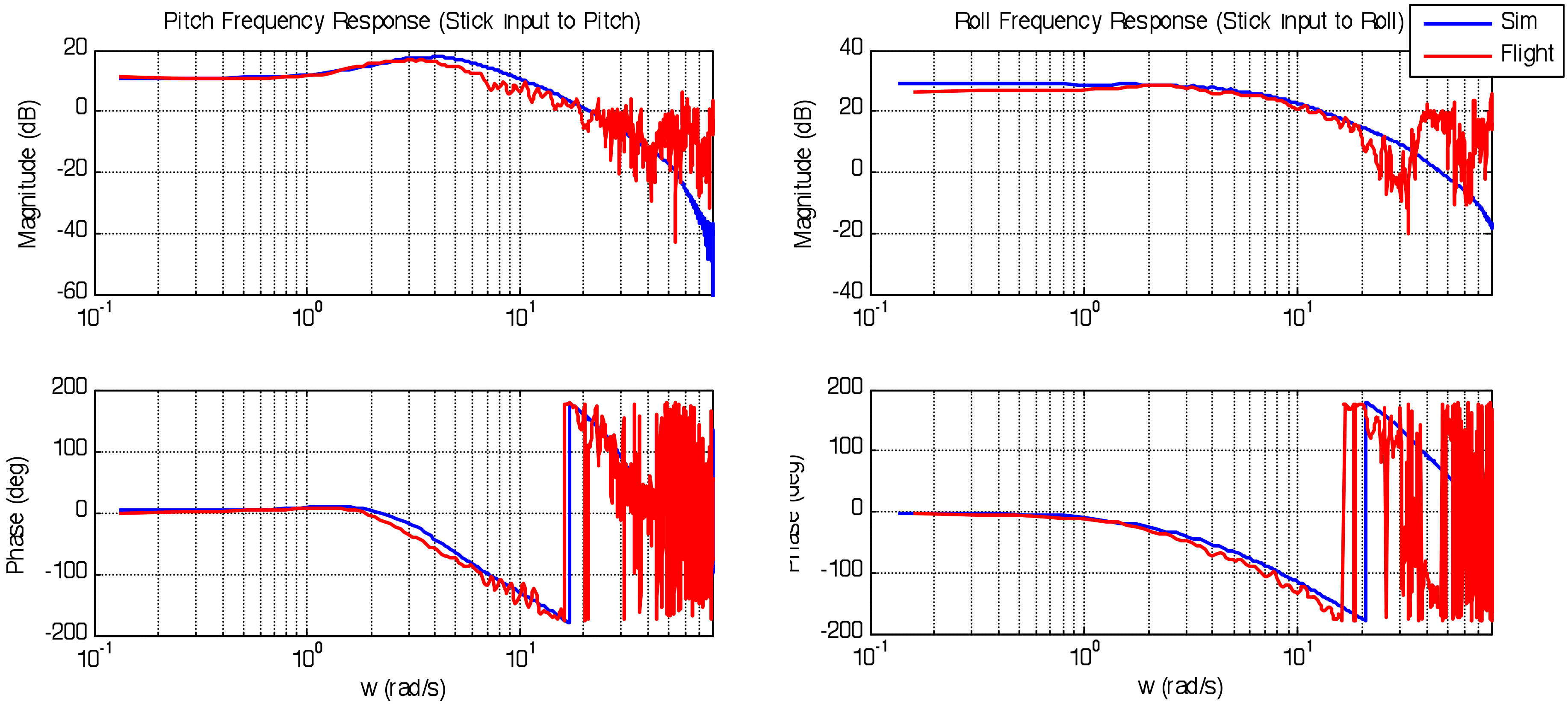
5th Press: Removes Failure

6th Press: Turns off Adaptation (reset counter)

De-bounce:
The NWS logic contains a 400ms de-bounce to avoid repetitive annunciations of the NWS button

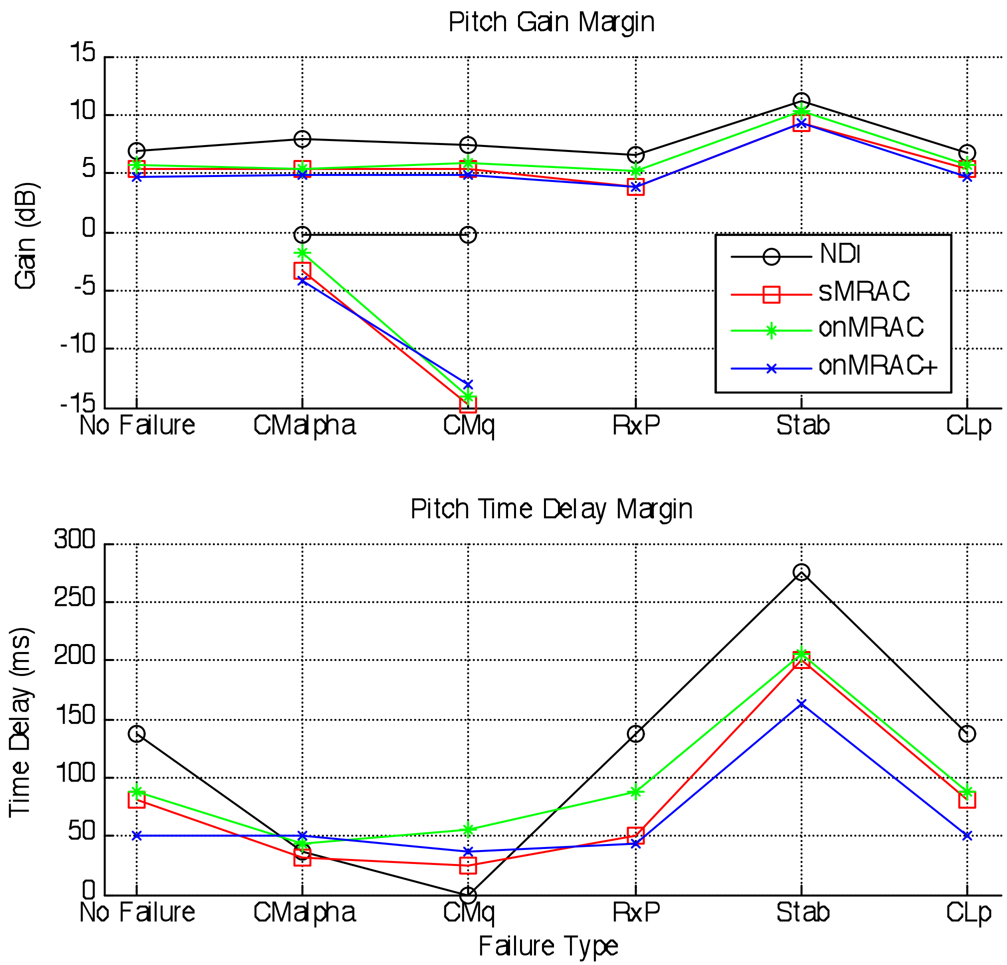
Simulink Toolset

Comparison of flight data to the Simulink toolset that was used for analysis.



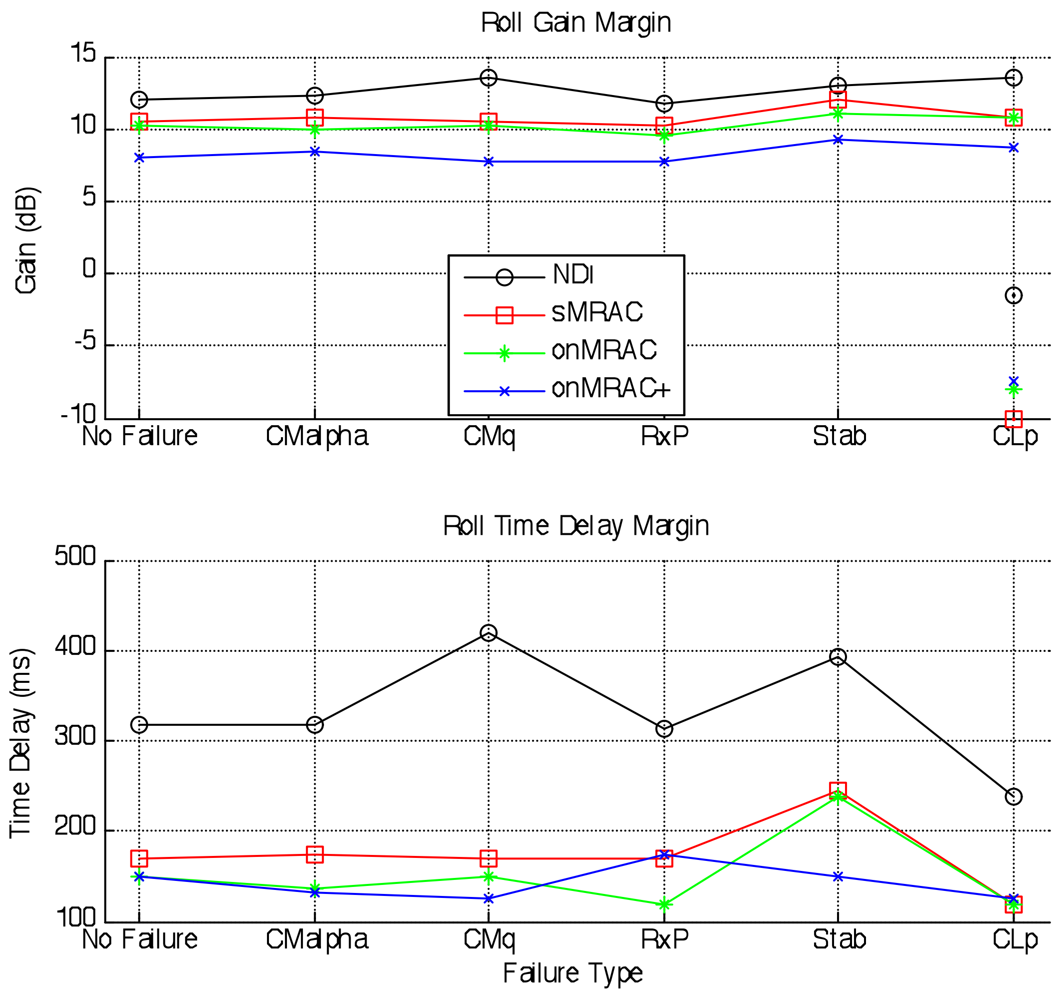
*** Flight Data: NDI v1.4 at FC6 (Flight 112)**

Results – Robustness (Pitch)



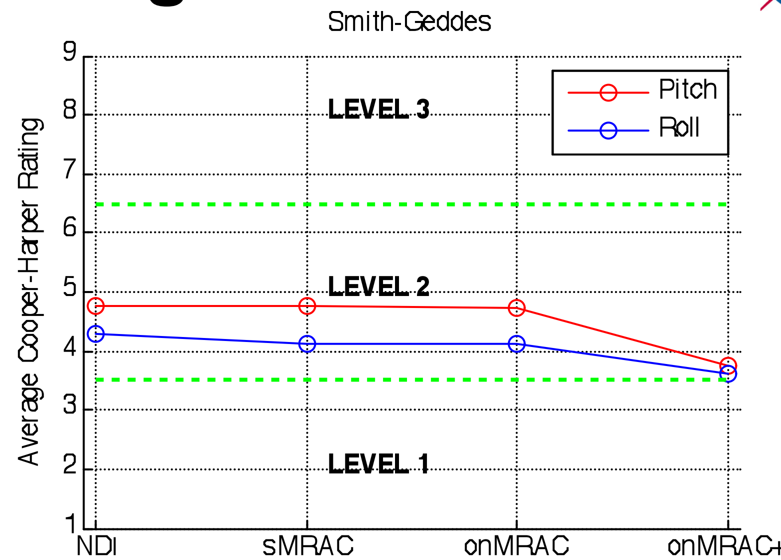
*** Includes all known delays**

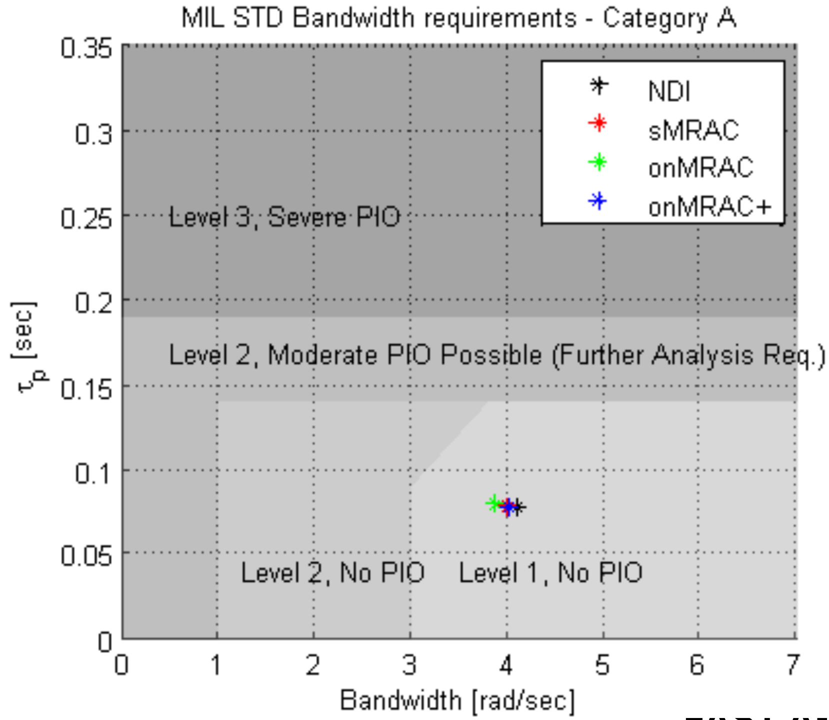
Results – Robustness (Roll)

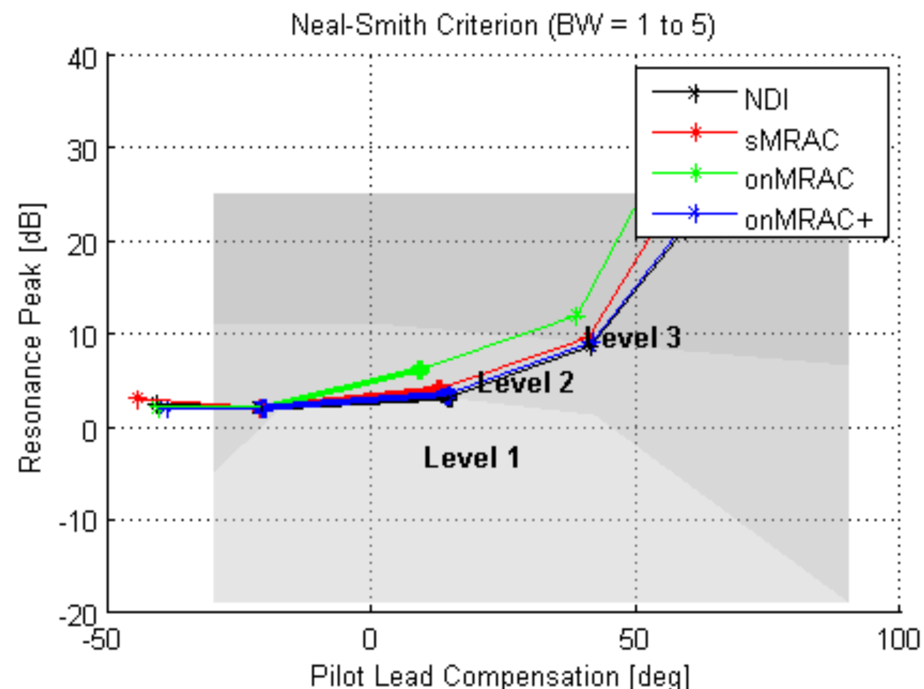


No Failure Handling Qualities

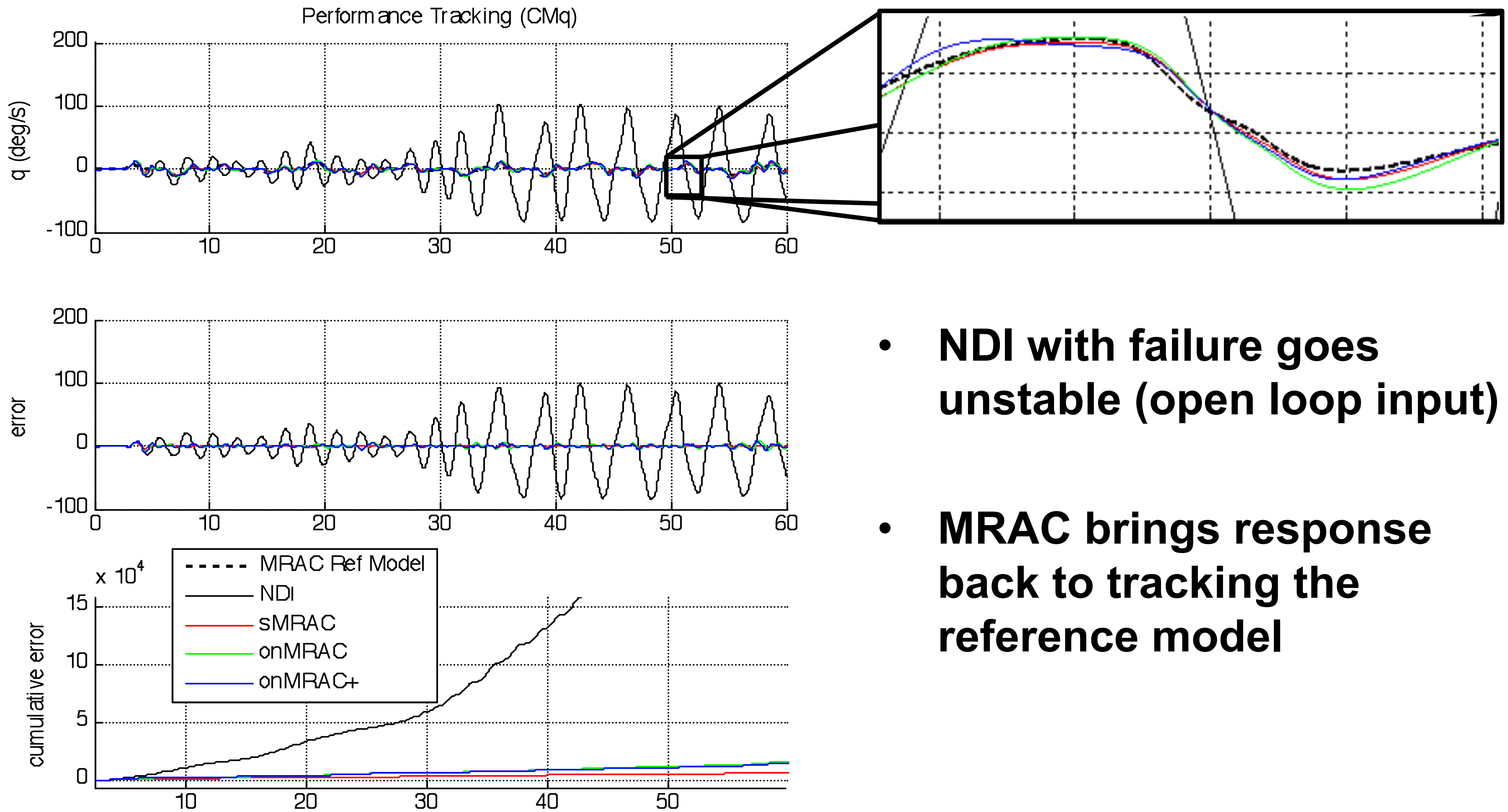
- **Level 1 to 2**
- **MRAC remains near baseline NDI handling qualities.**





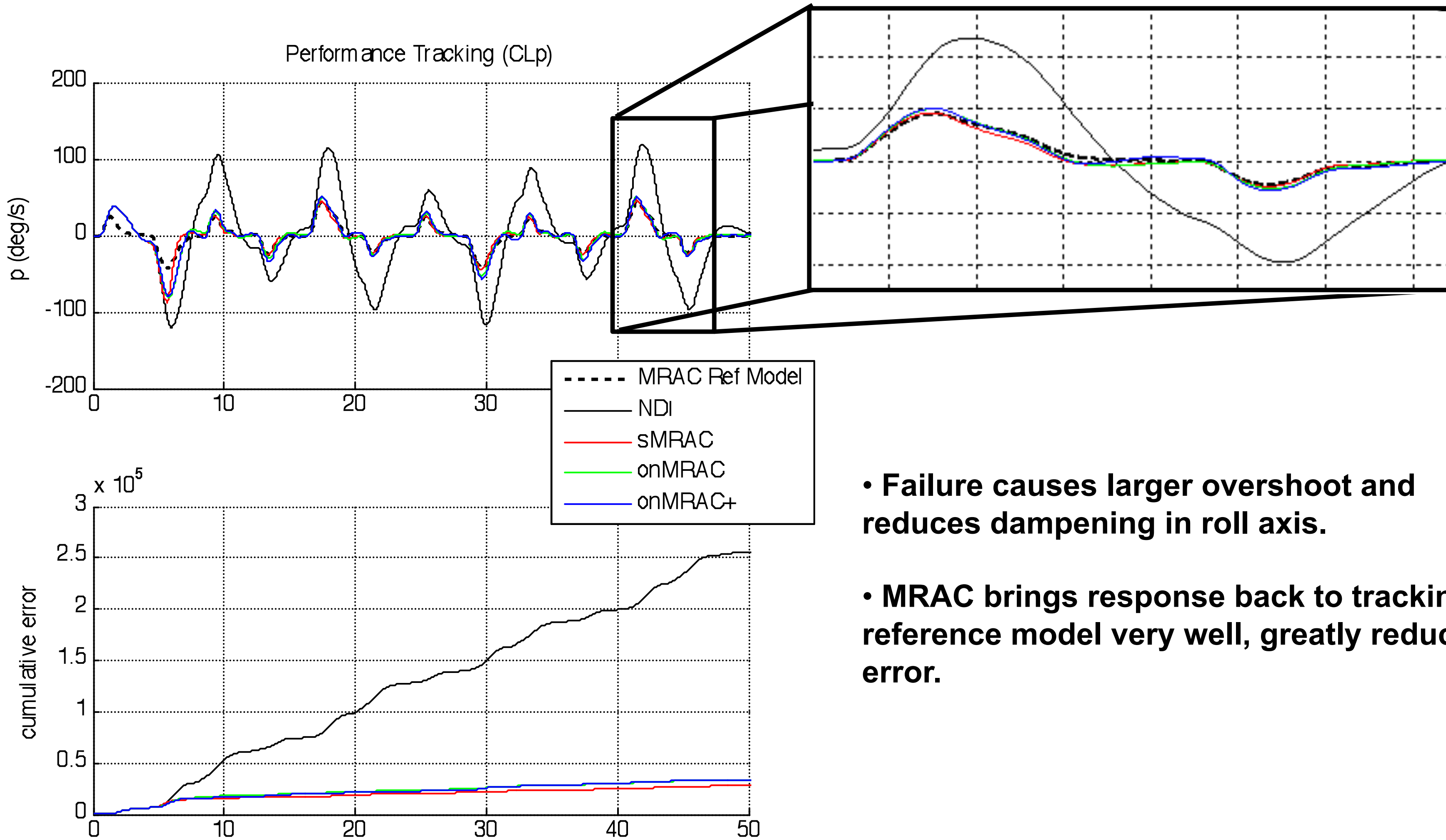


C_{Mq} Failure Performance



- **NDI with failure goes unstable (open loop input)**
- **MRAC brings response back to tracking the reference model**

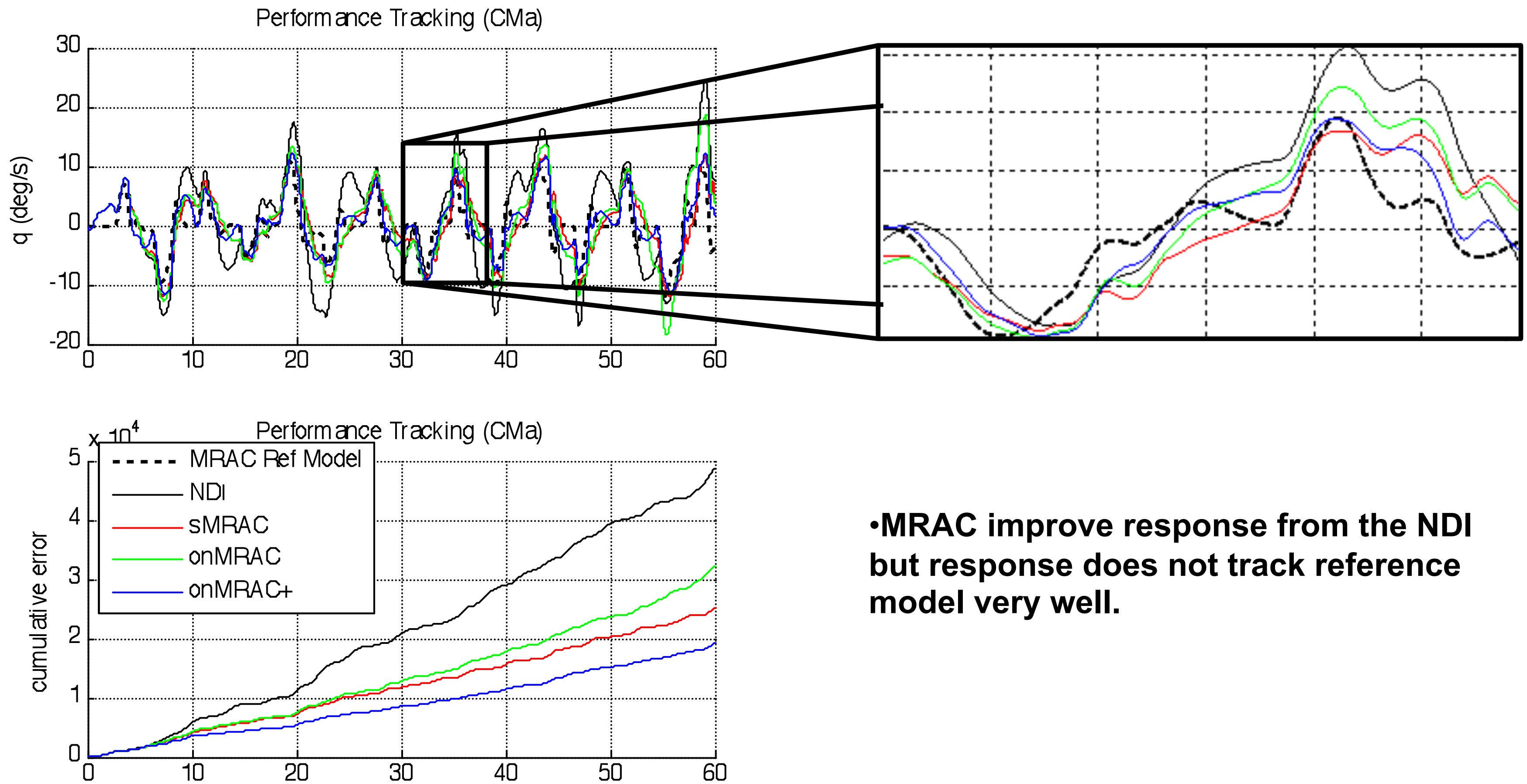
C_{Lp} Failure Performance



- Failure causes larger overshoot and reduces dampening in roll axis.

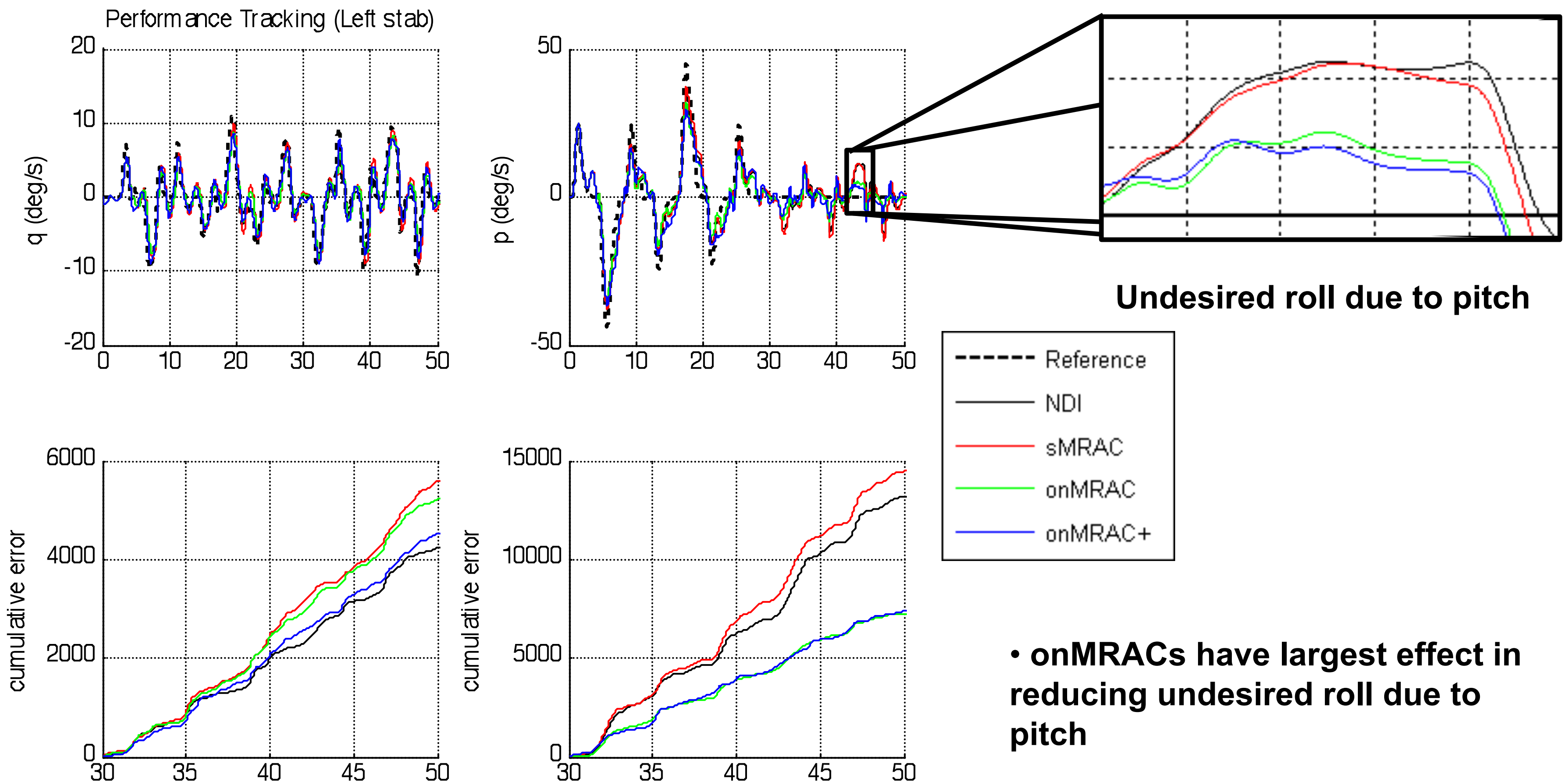
- MRAC brings response back to tracking reference model very well, greatly reduces error.

$C_{M\alpha}$ Failure Performance



- MRAC improve response from the NDI but response does not track reference model very well.

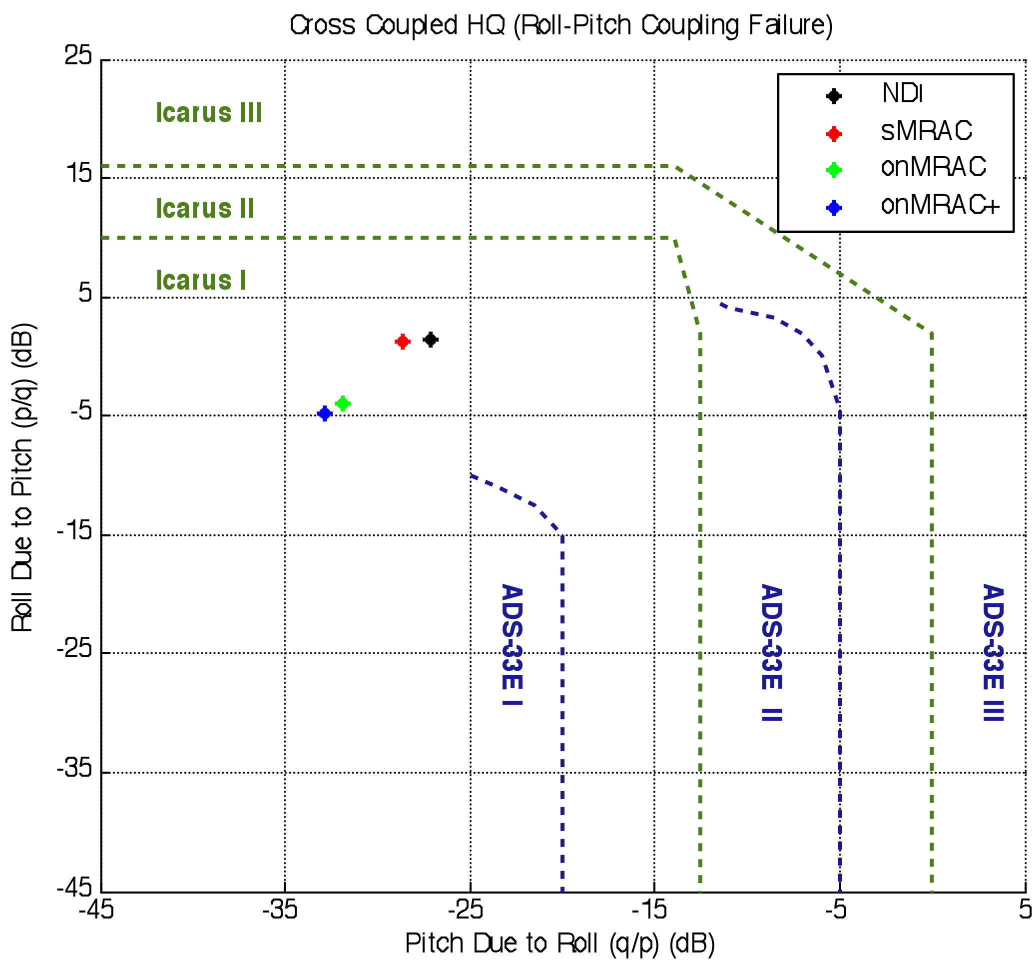
Stab Failure Performance



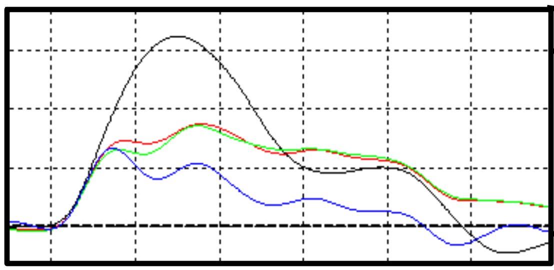
Undesired roll due to pitch

- **onMRACs have largest effect in reducing undesired roll due to pitch**
- **Slightly worse pitch performance but in line with nonfailed performance.**

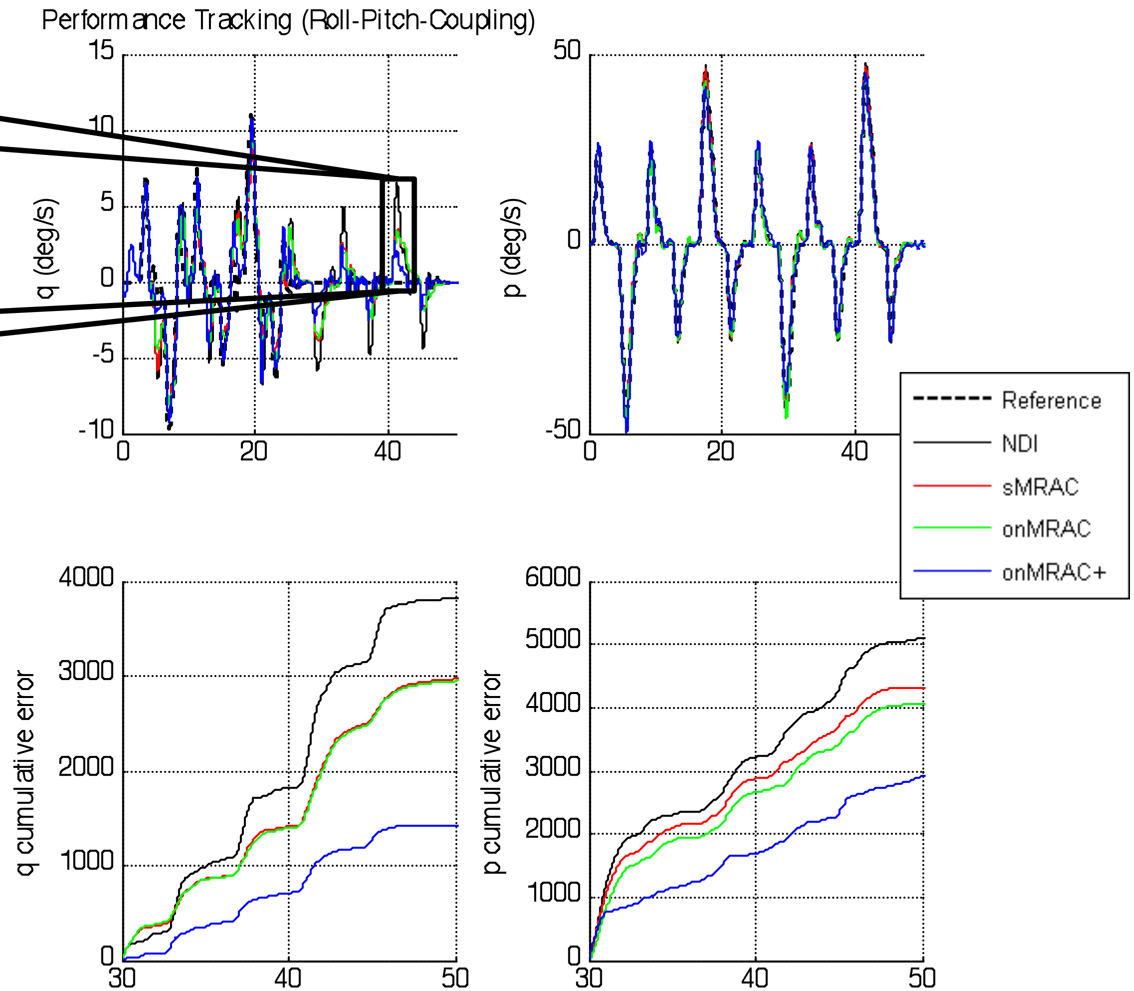
Stab Failure Handling Qualities



Roll to Pitch Coupling Performance



Undesired pitch due to roll

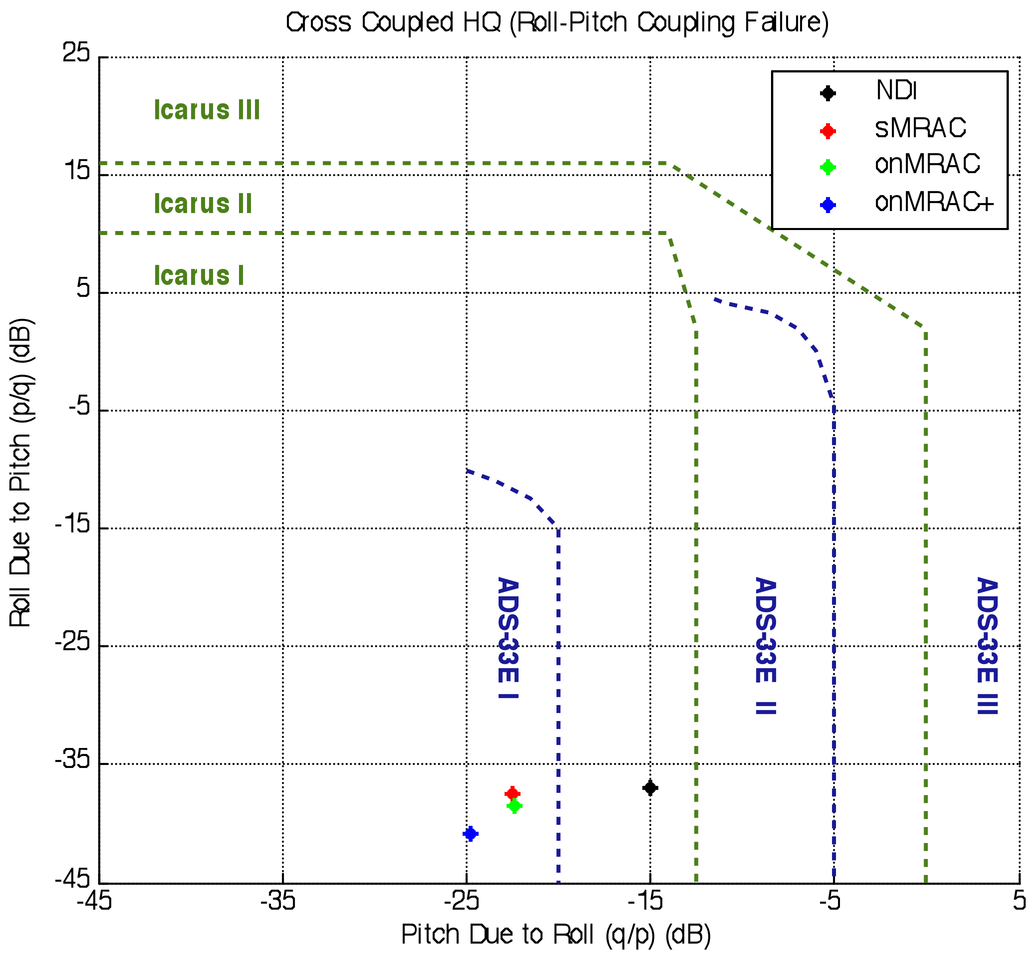


- MRAC reduces the pitch response due to roll.
- Also improves roll tracking.

Roll to Pitch Coupling Handling Qualities

• sMRAC and onMRAC reduce (q/p) by nearly half.

• onMRAC+ reduces undesired pitch due to roll down to 1/3 of that of the NDI



Summary

- **Experiment Meets Requirements**
  - Minimal impact in the no-failure cases
  - The minimal gain and time delay margins are met for all adaptive controllers with no failures
  - The adaptive controller improves tracking response with failures
  - Without adaptation, failures are either controllable by the pilot or slowly divergent
- **Adaptation meets the experiment objectives**
  - Failures are sufficiently aggressive to show the benefits of adaptation
  - Demonstrates a tradeoff between simplicity and versatility