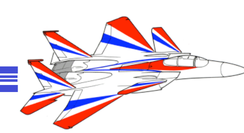
F-15 IFCS

Intelligent Flight Control System

John Bosworth
Project Chief Engineer

Project Participants

- **NASA Dryden Flight Research Center**
  - Responsible test organization for the flight experiment
    - Flight, range and ground safety
    - Mission success
- **NASA Ames Research Center**
  - Development of the concepts
- **Boeing STL Phantom Works**
  - Primary flight control system software (Conventional mode)
  - Research flight control system software (Enhanced mode)
- **West Virginia High Technology Consortium (formerly ISR)**
  - Neural Network adaptive software
- **Academia**
  - West Virginia University
  - Georgia Tech



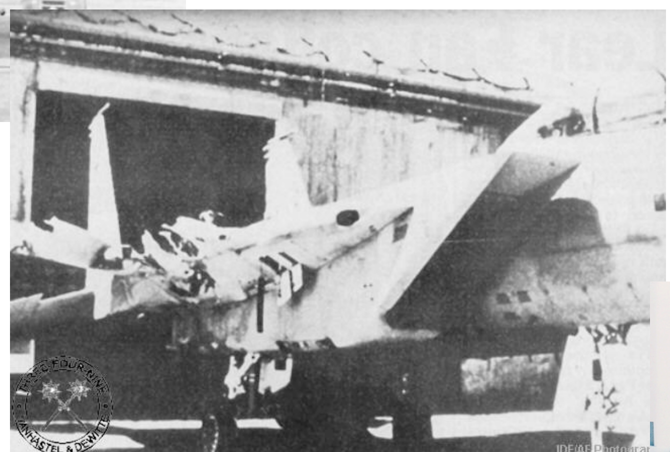
F-15 IFCS Project Goals

- **Demonstrate Revolutionary Control Approaches that can Efficiently Optimize Aircraft Performance in both Normal and Failure Conditions**

- **Advance Neural Network-Based Flight Control Technology for New Aerospace Systems Designs**

Motivation

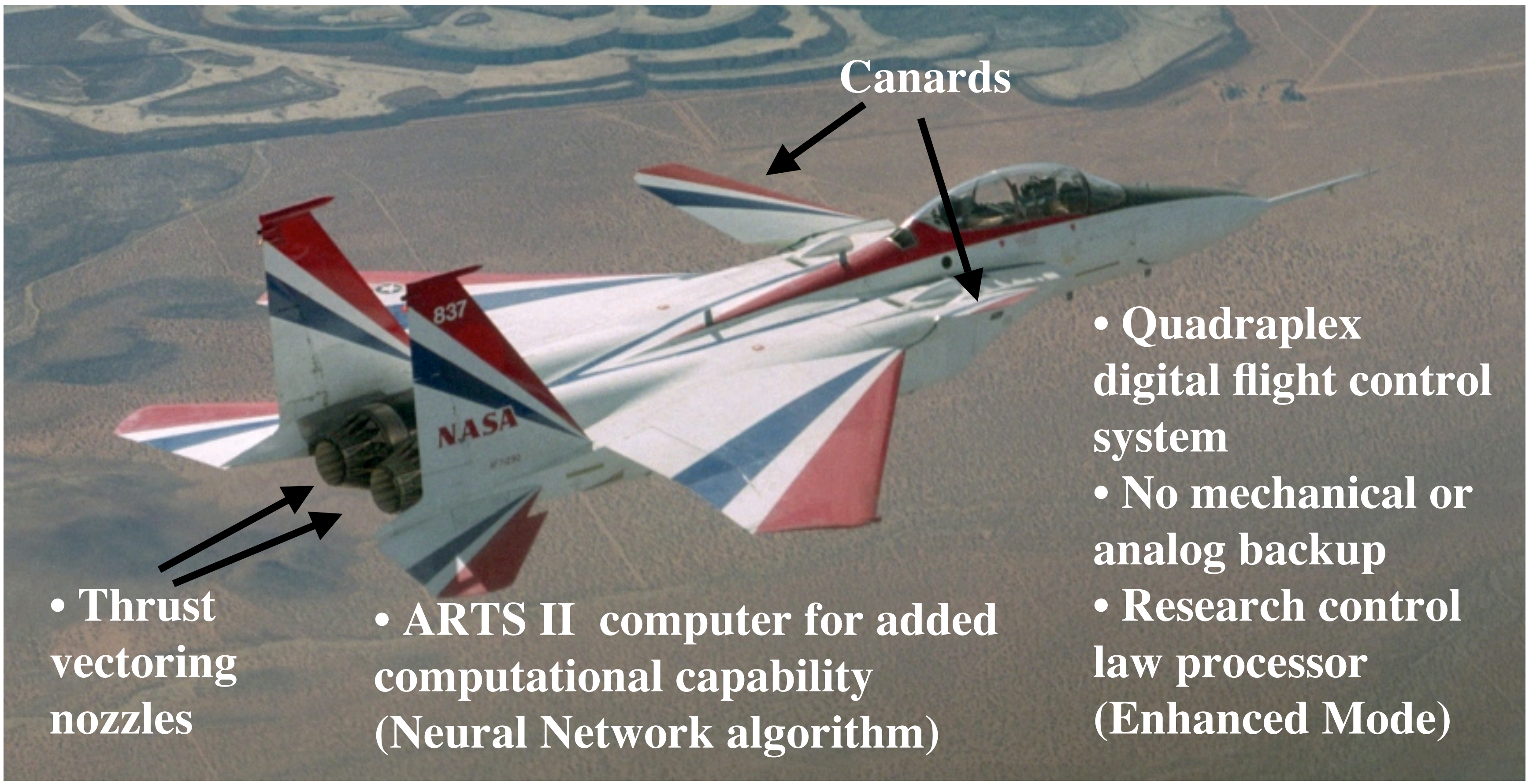
These are survivable accidents



IFCS has potential to reduce the amount of skill and luck required for survival

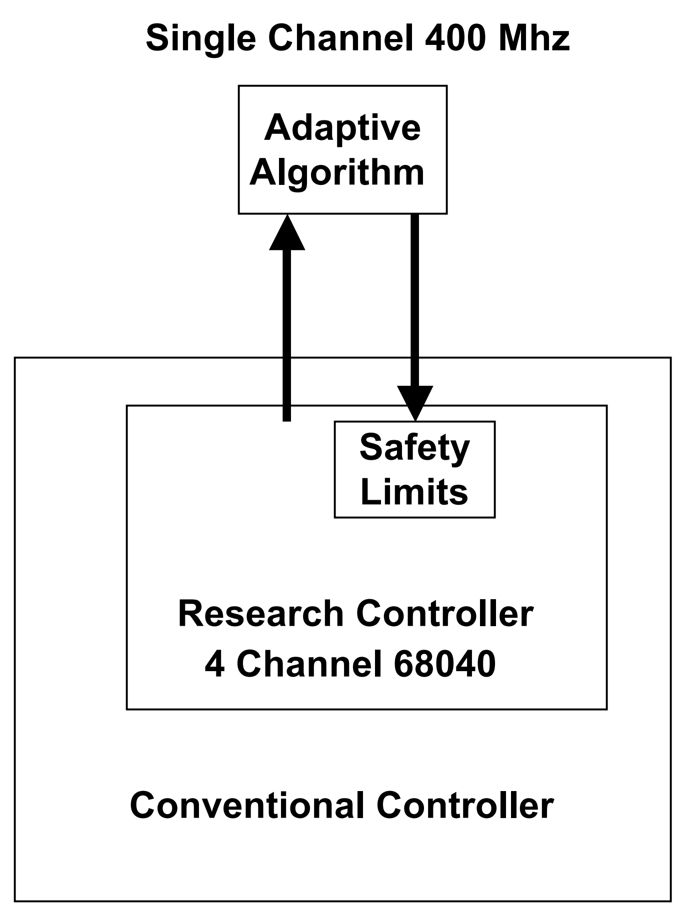
NASA NF-15B Tail Number 837

Extensively modified F-15 airframe

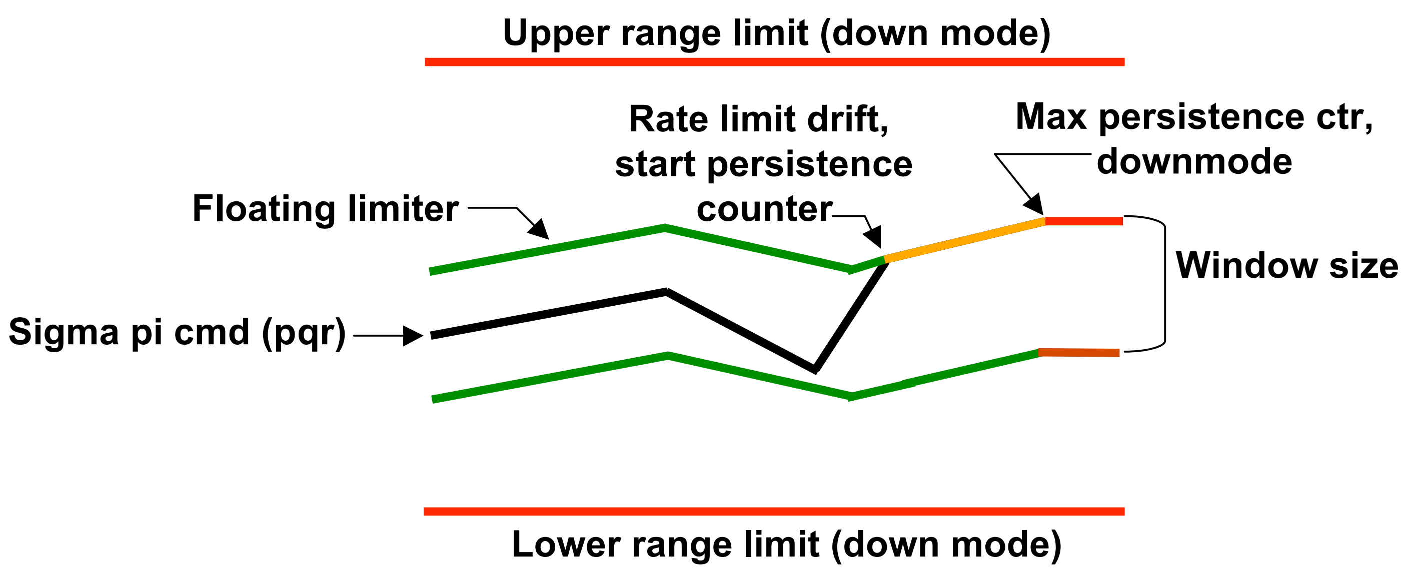


Limited Authority System

- Adaptation algorithm implemented in separate processor
  - Class B software
  - Autocoded directly from Simulink block diagram
  - Many configurable settings
    - Learning rates
    - Weight limits
    - Thresholds, etc.
- Control laws programmed in Class A, quad-redundant system
- Protection provided by floating limiter on adaptation signals



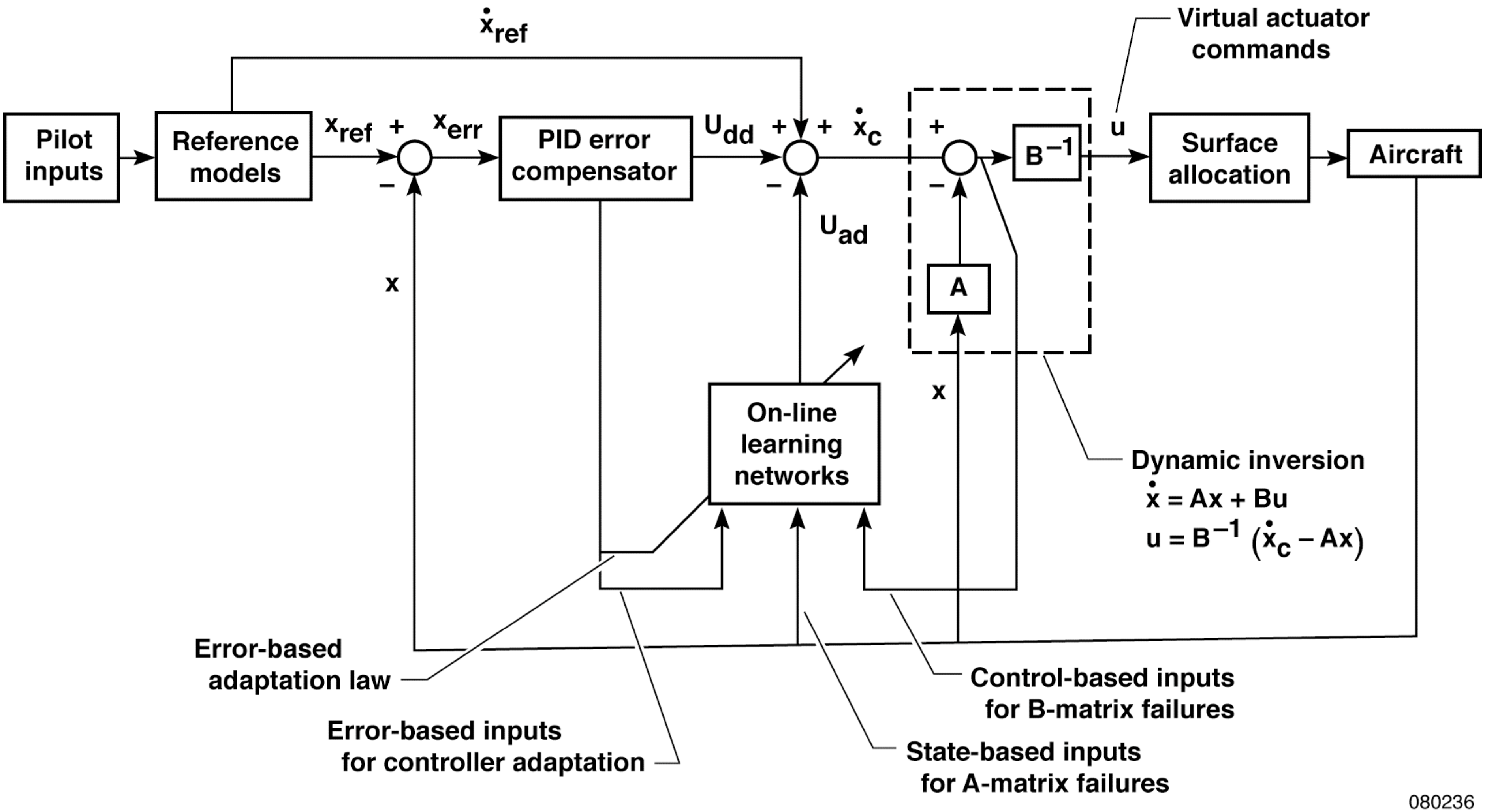
NN Floating Limiter



Black – sigma pi cmd
Green – floating limiter boundary
Orange – limited command (fl_drift_flag)
Red – down mode condition (fl_dmode_flag

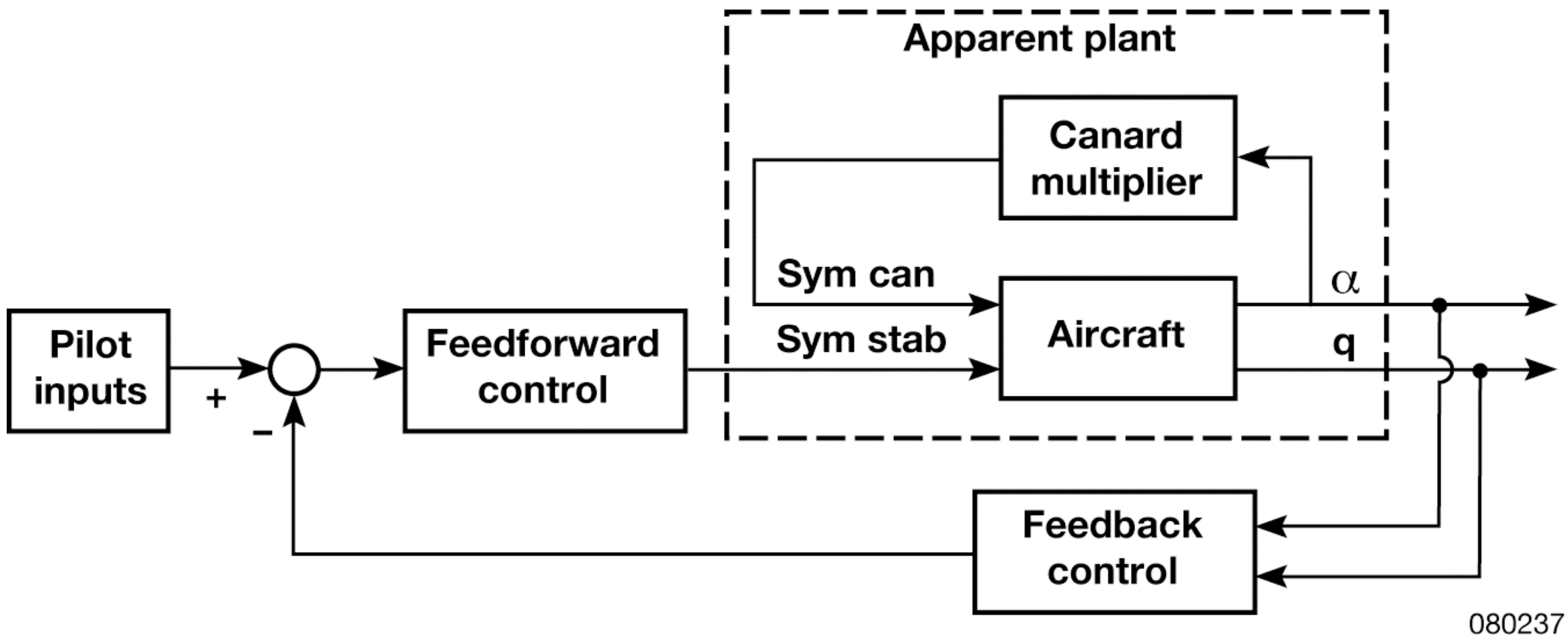
Tunable metrics
- Window delta
- Drift rate
- Persistence limiter
- Range limits

Direct Adaptive Control Architecture

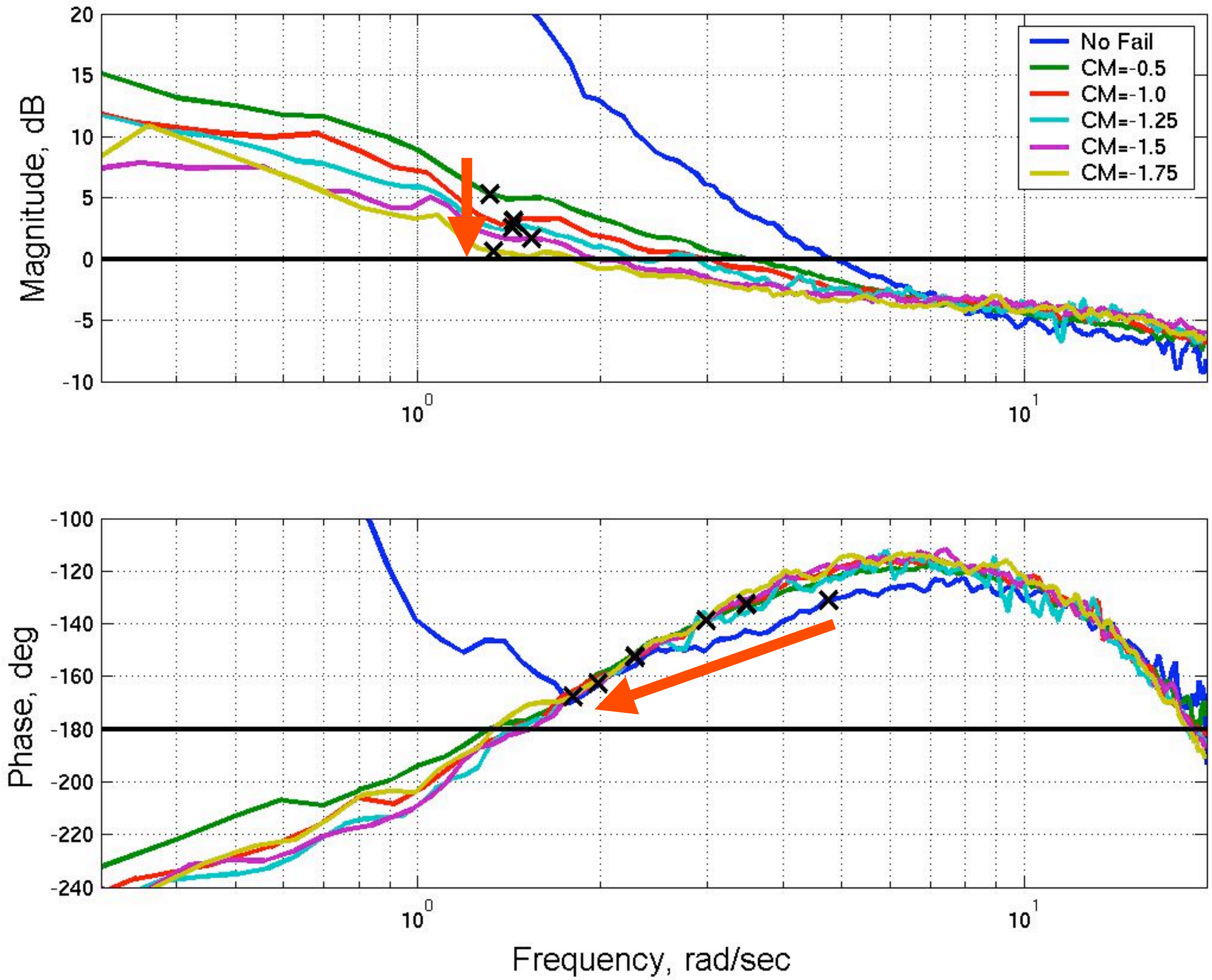


Effect of Simulated Longitudinally Destabilizing Failure

Longitudinally Destabilized Plant

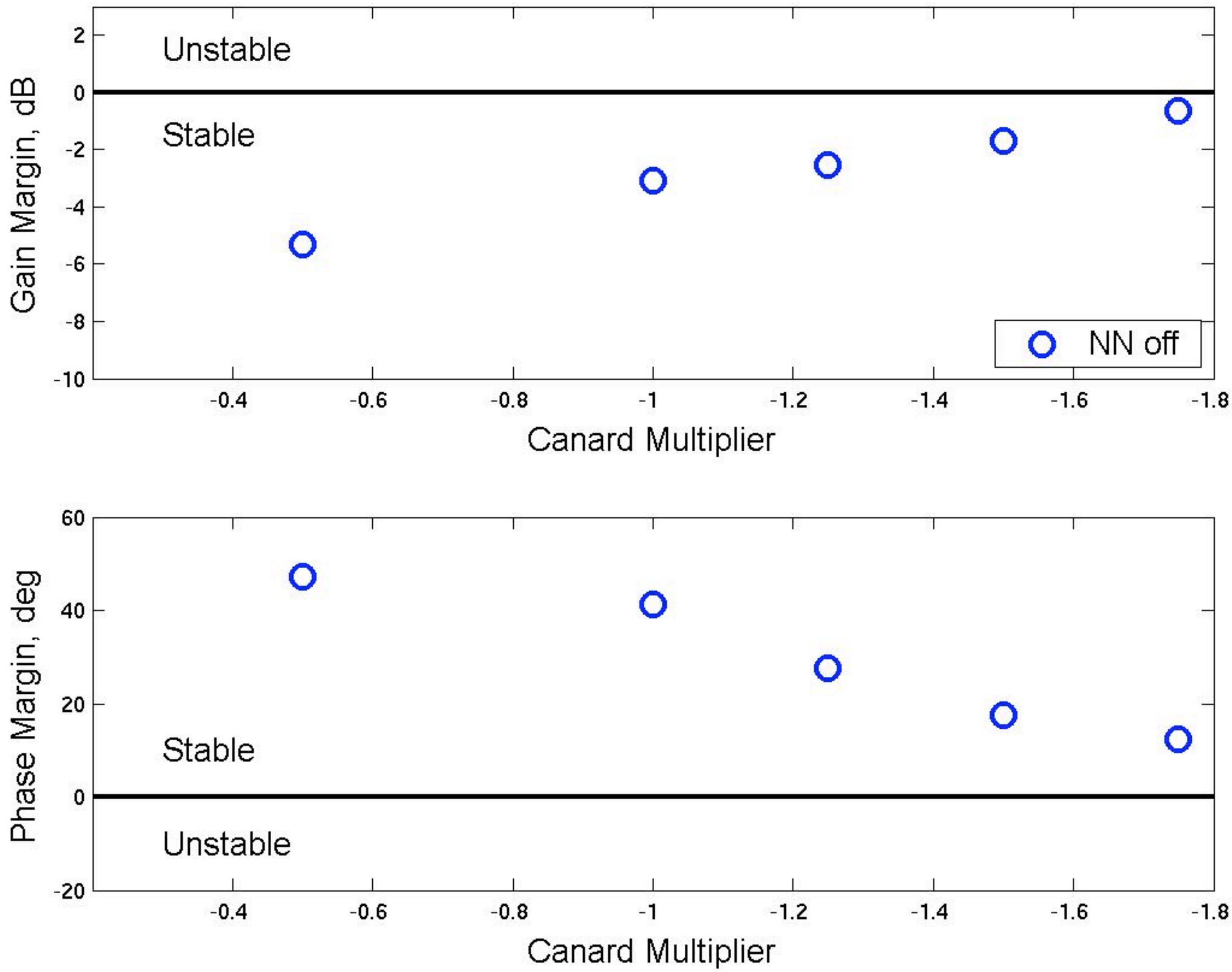


Open Loop Frequency Response

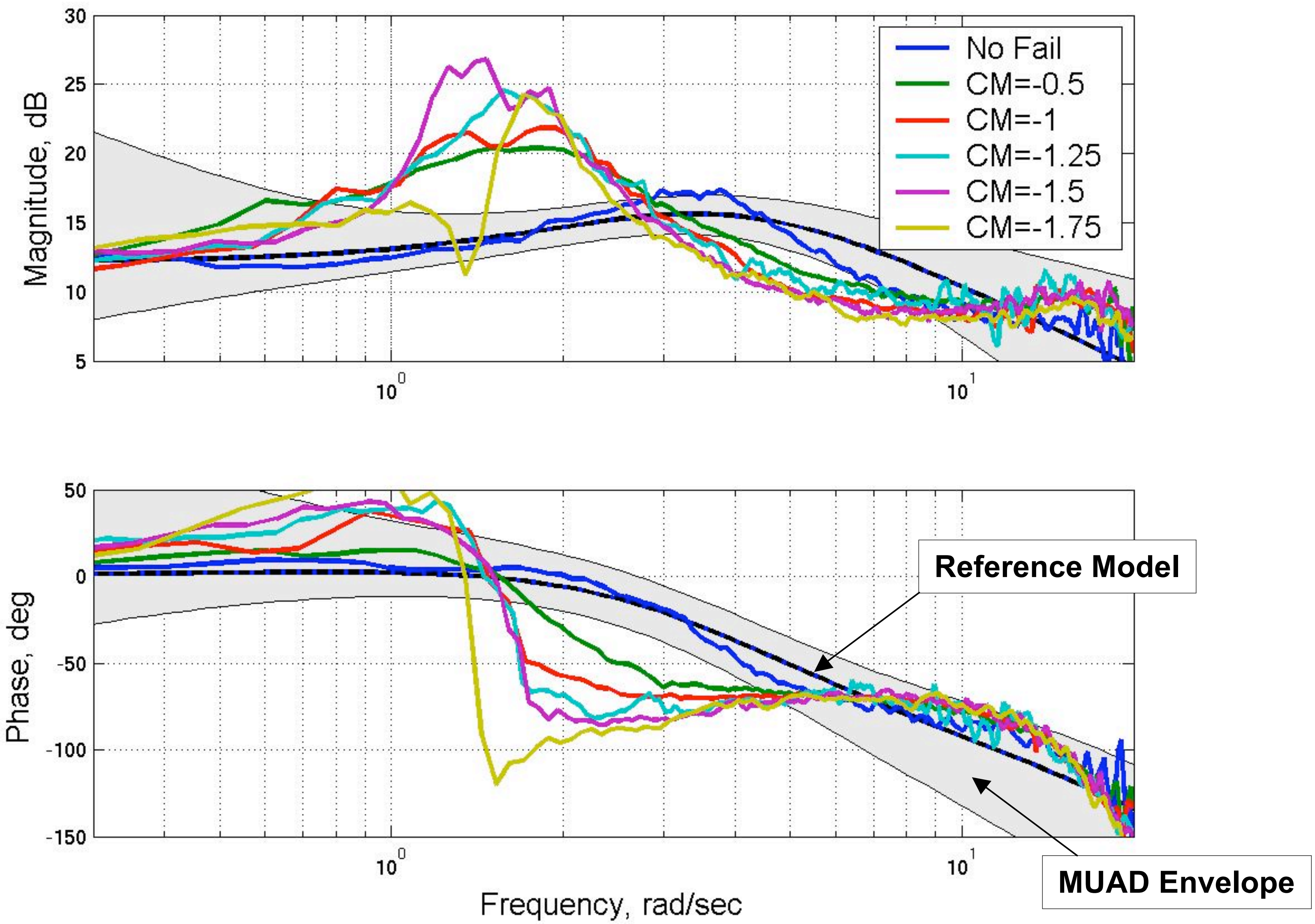


Stability Margins

No Adaptation



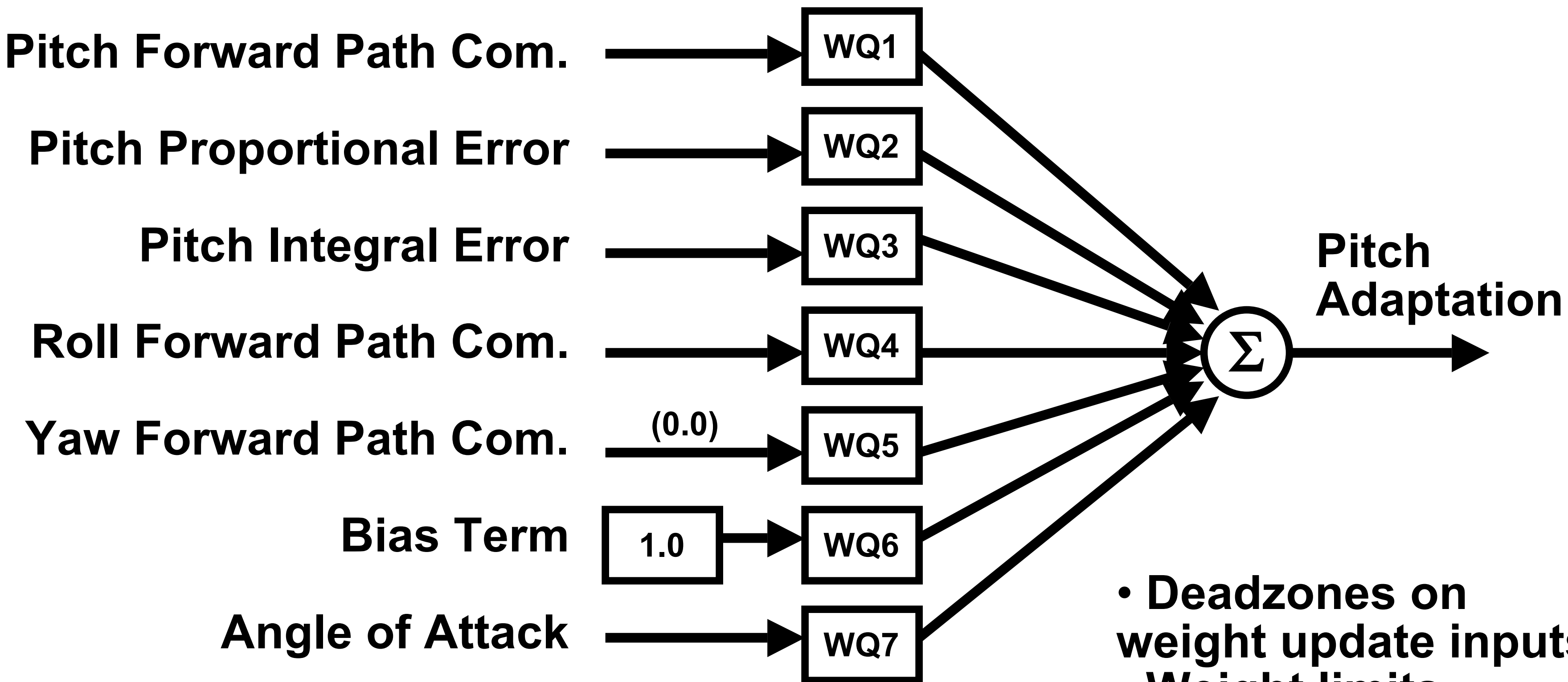
Closed Loop Frequency Resp.



Desired Adaptation Response to Failure

- Regain Stable Platform
  - Typically measured in terms of stability margin
  - Stability margin not explicitly fed into adaptation
- Ability to re-establish good handling qualities
  - Measured in terms of model following
    - Response should fall within MUAD envelope
    - If successful should provide good handling qualities
- Provide ability to safely land airplane
  - Stay within maneuver constraints
  - Respect structural limitations

Simplified Sigma-Pi Neural Network
Pitch Axis

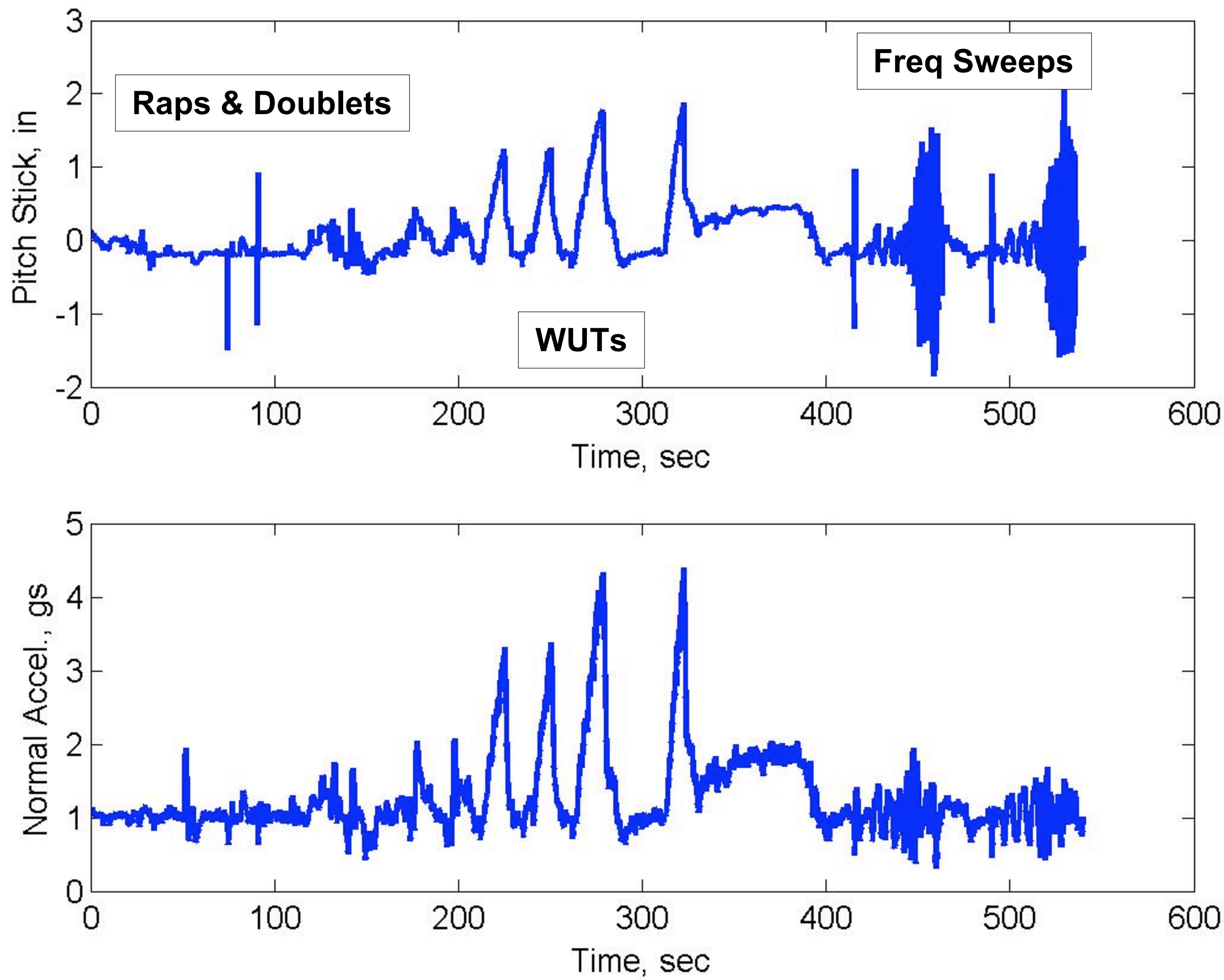


- Deadzones on weight update inputs
- Weight limits

Weight Update Law: $\dot{W} = -G(U_{err} B_a + L|U_{err}|W)$

Adaptive System Training

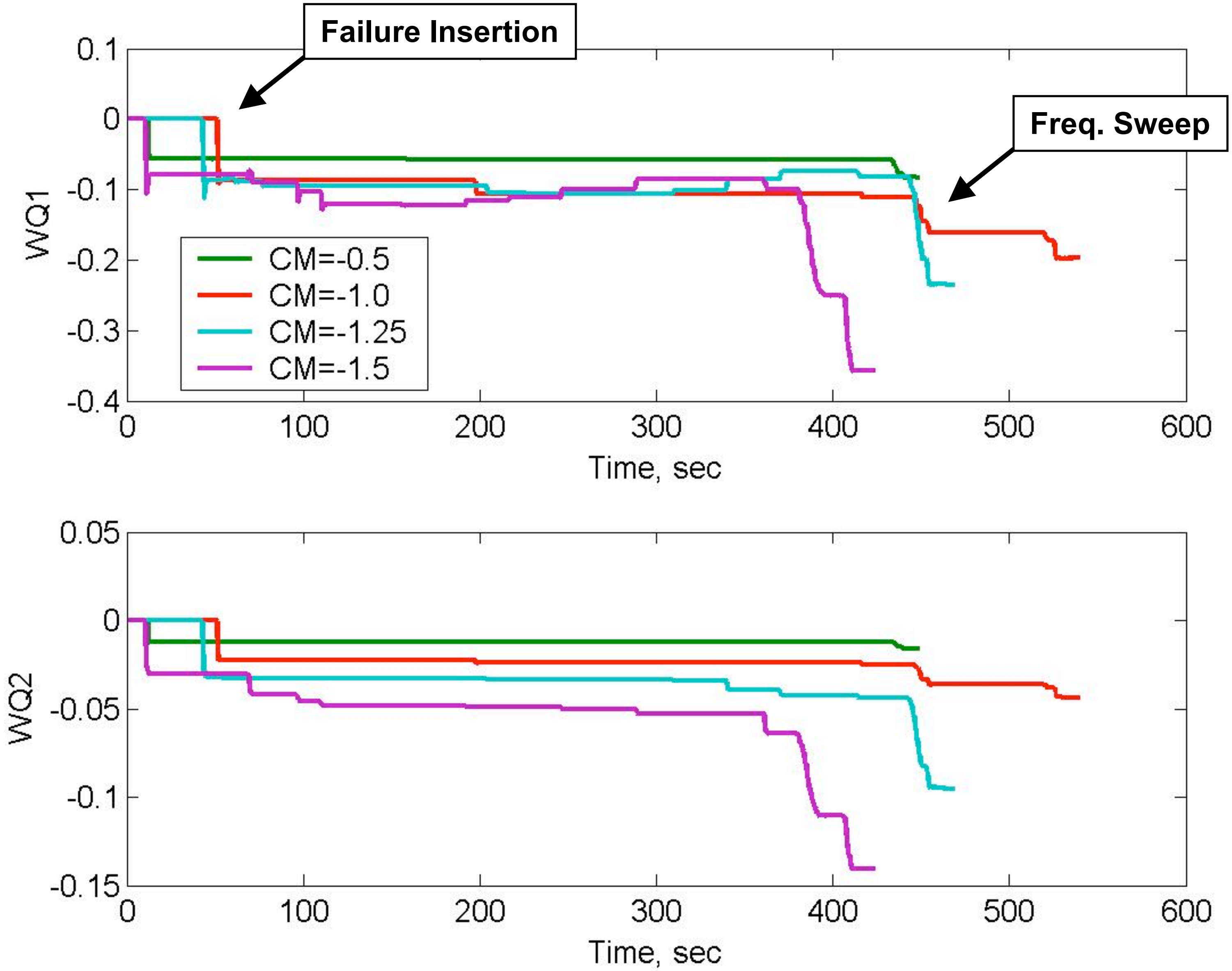
Training Sequence
- Raps
- Doublets
- Pitch & Bank Captures
- Rolls
- WUTs
- Freq. Sweeps



Adaptation Weights

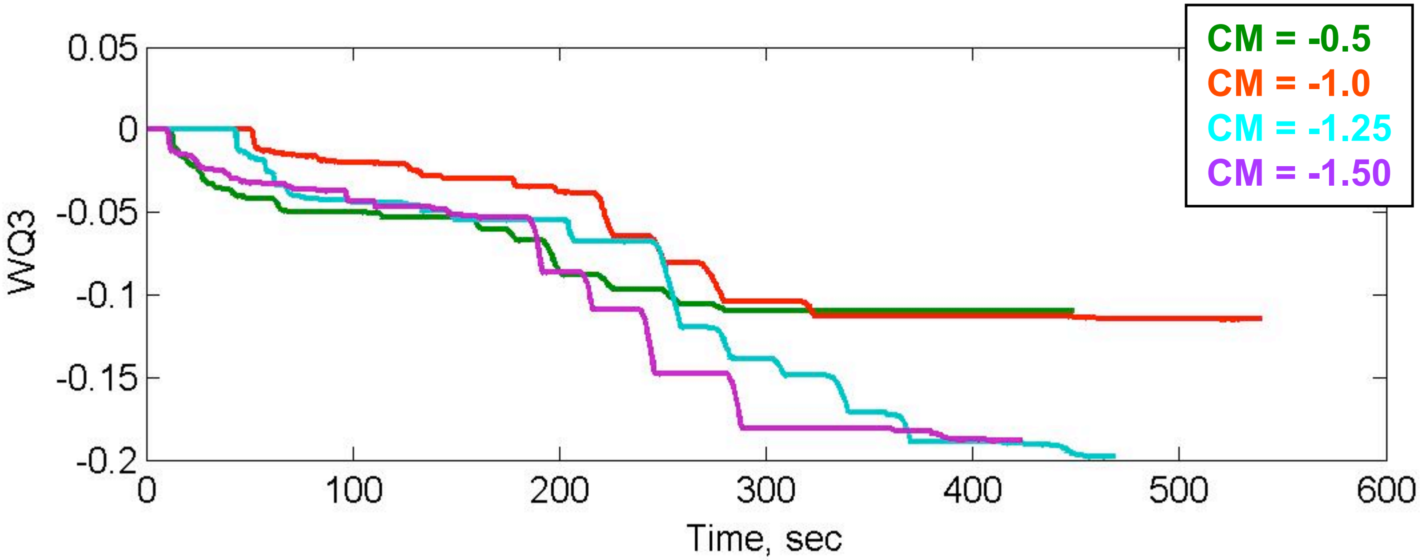
Forward Path

Prop. Error

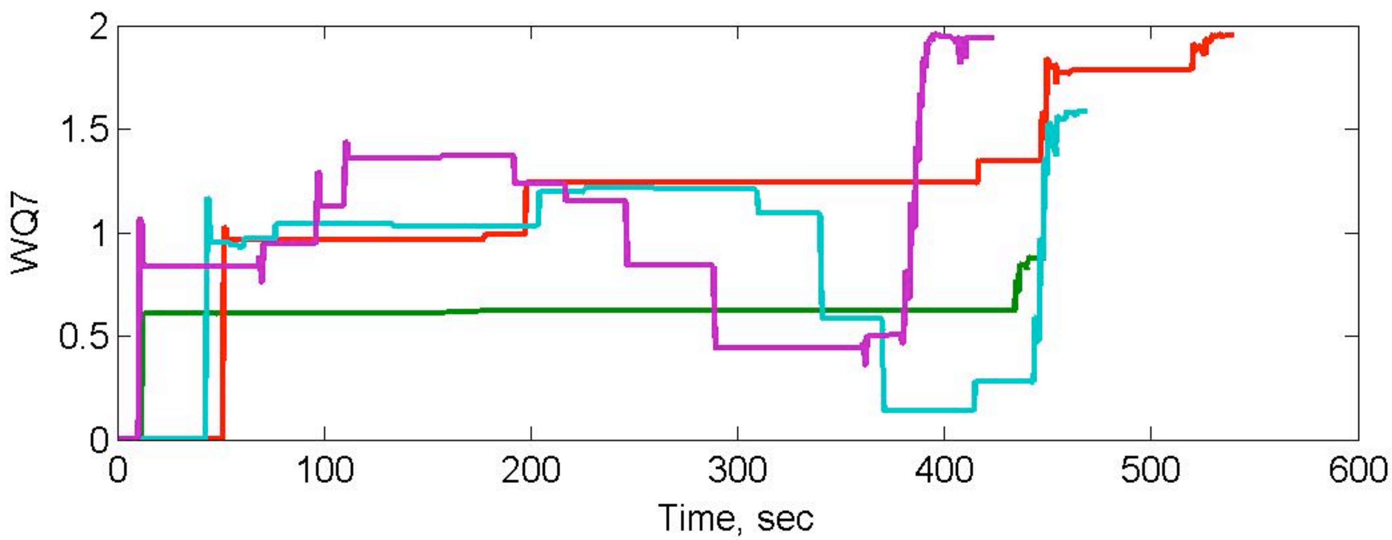


Adaptation Weights

Int. Error



Angle of Attack Error

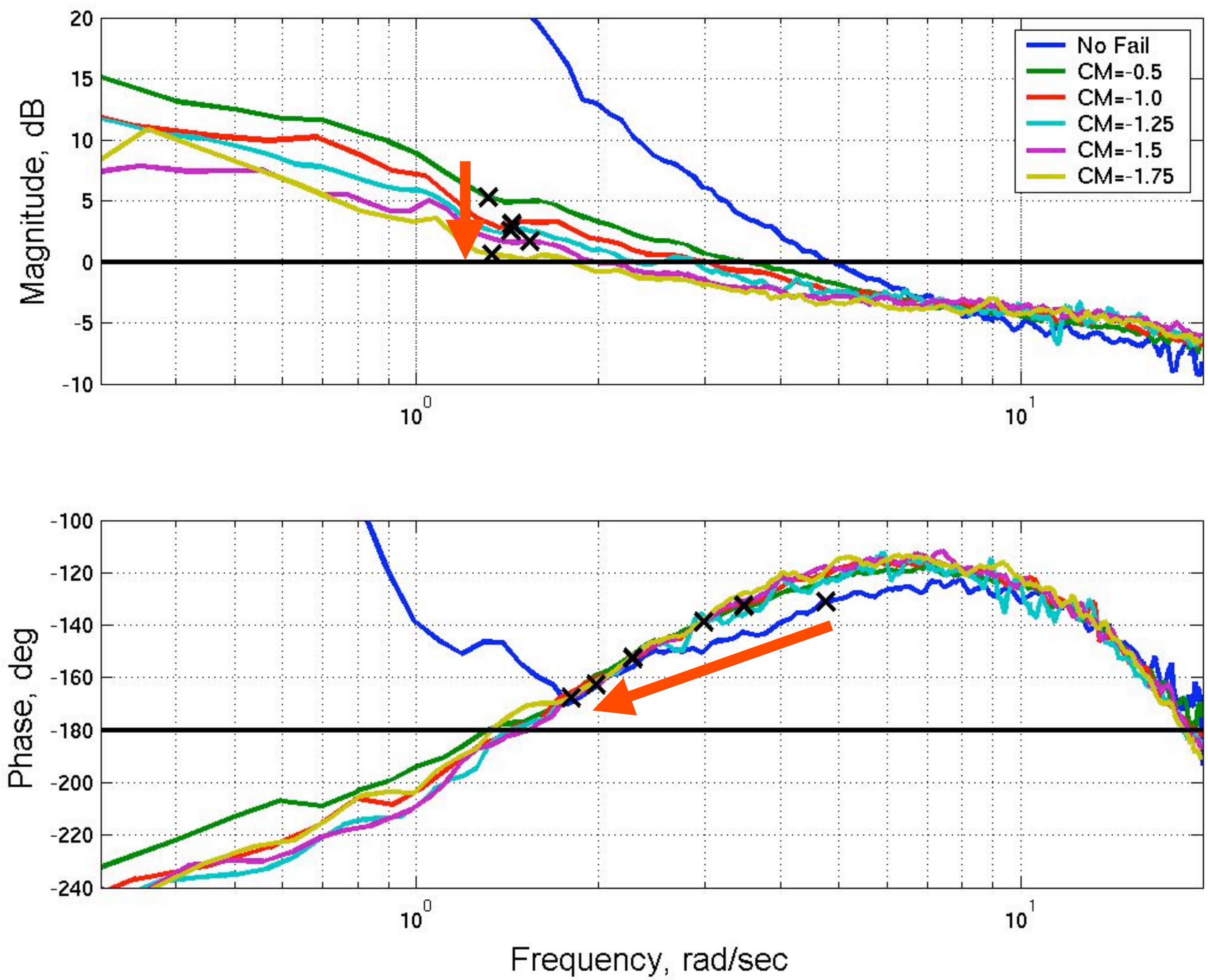


Linearity Assumption

- **System is really nonlinear and time varying**
- **If adaptive system weights settle to constant value:**
  - **System is no longer time varying**
  - **System is linearizable**
  - **Frequency response analysis can then be applied**
    - **Use weight values at end of training sequence**

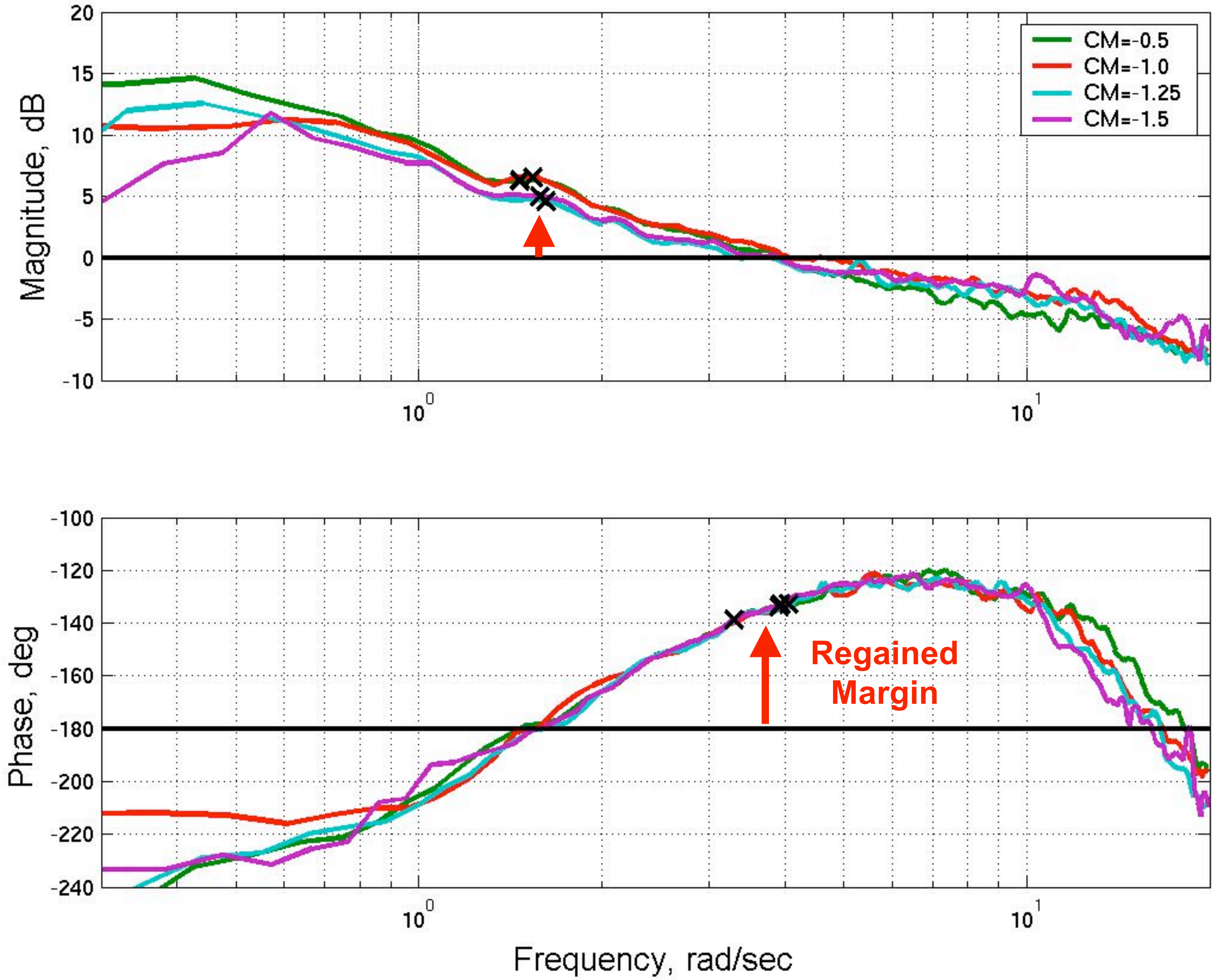
Open Loop Frequency Response

No Adaptation

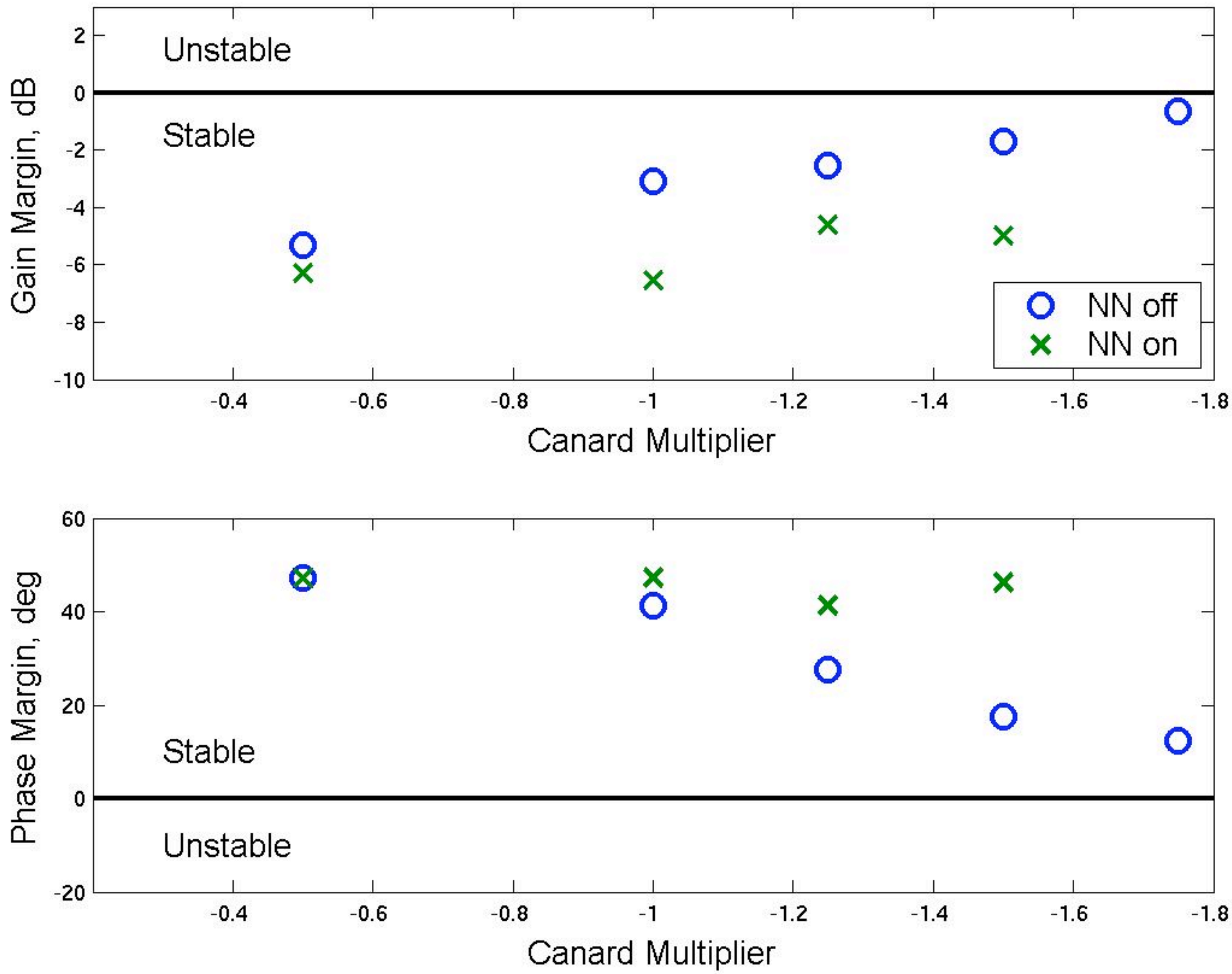


Open Loop Frequency Response

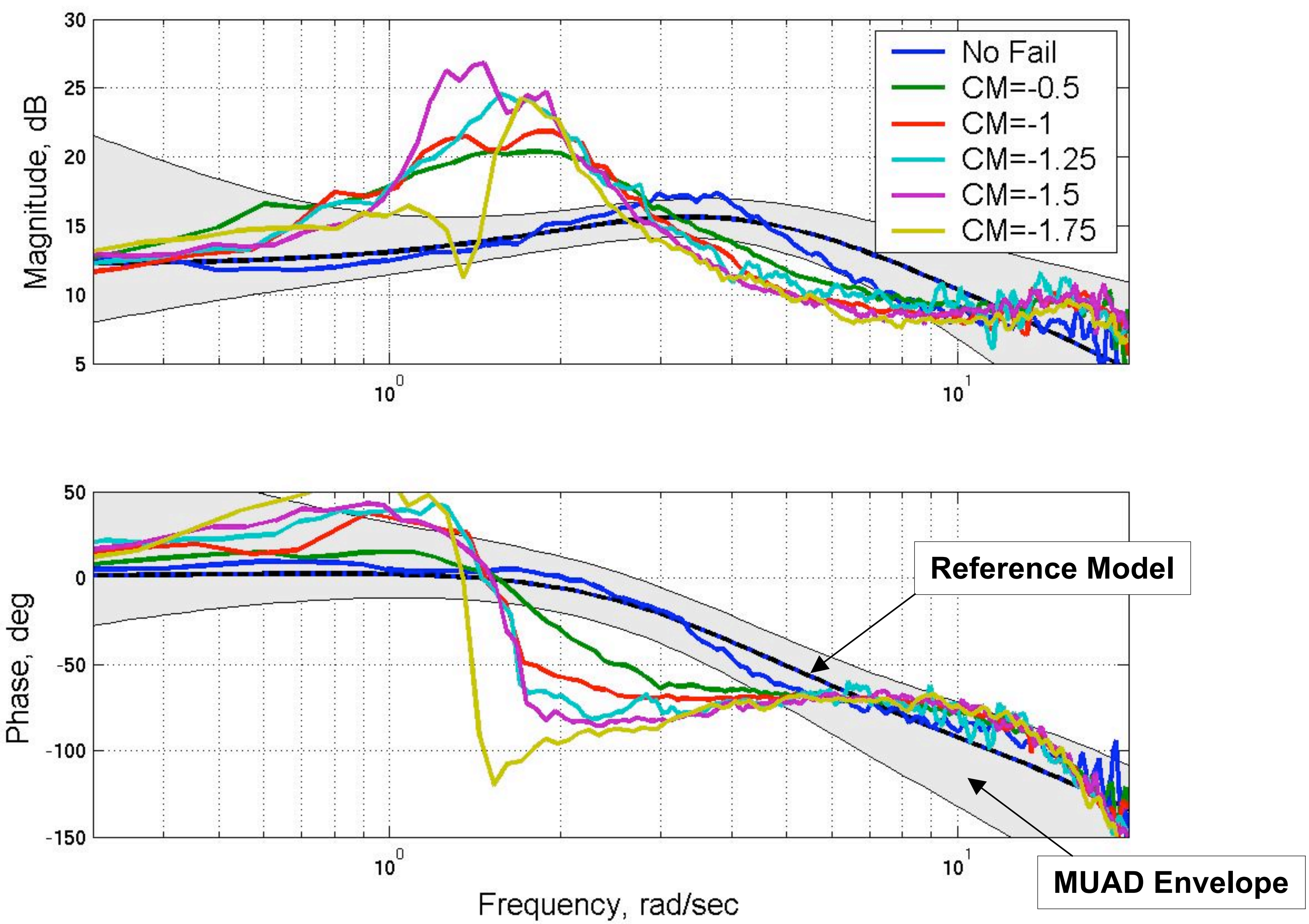
With Adaptation



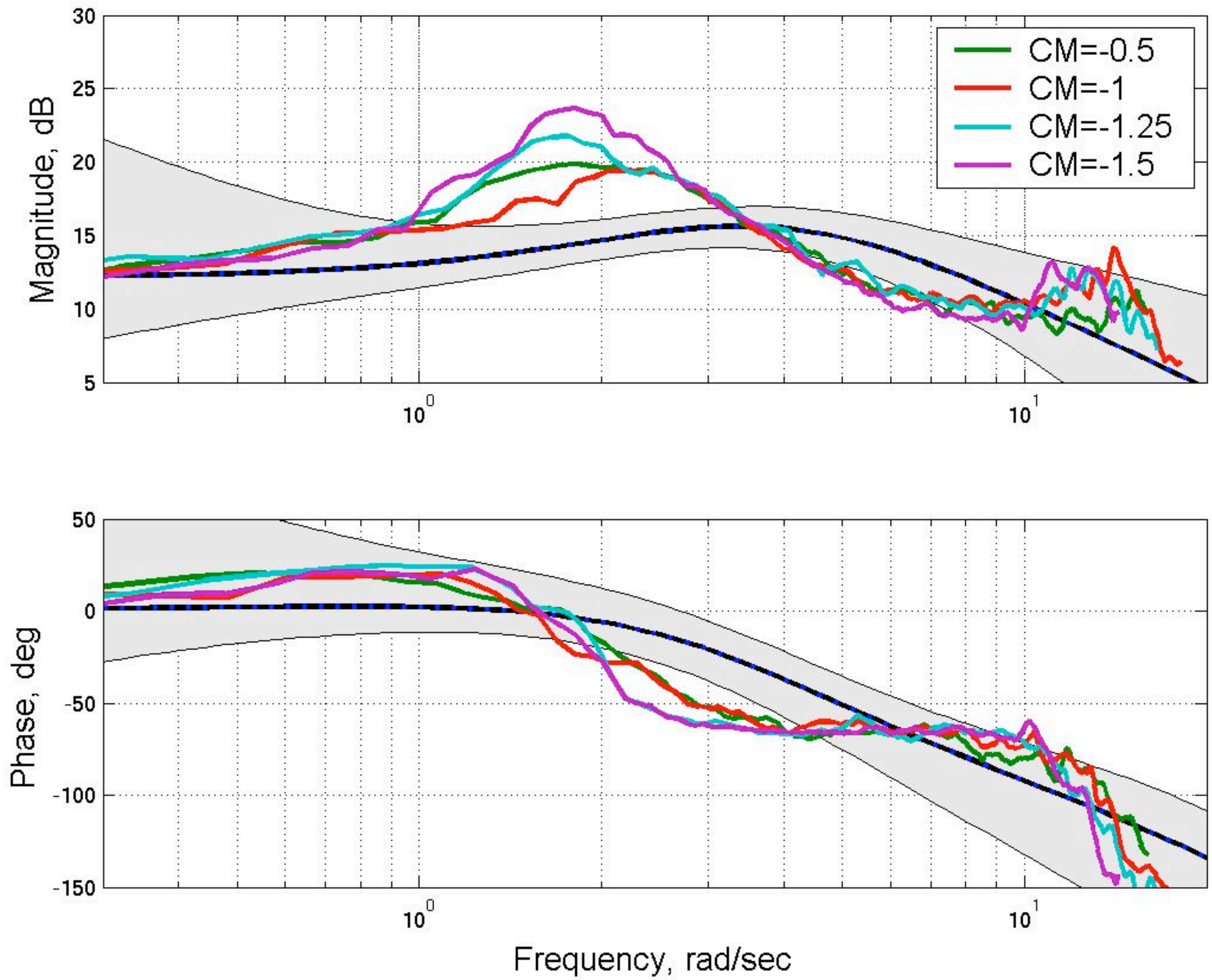
Stability Margins
With Adaptation



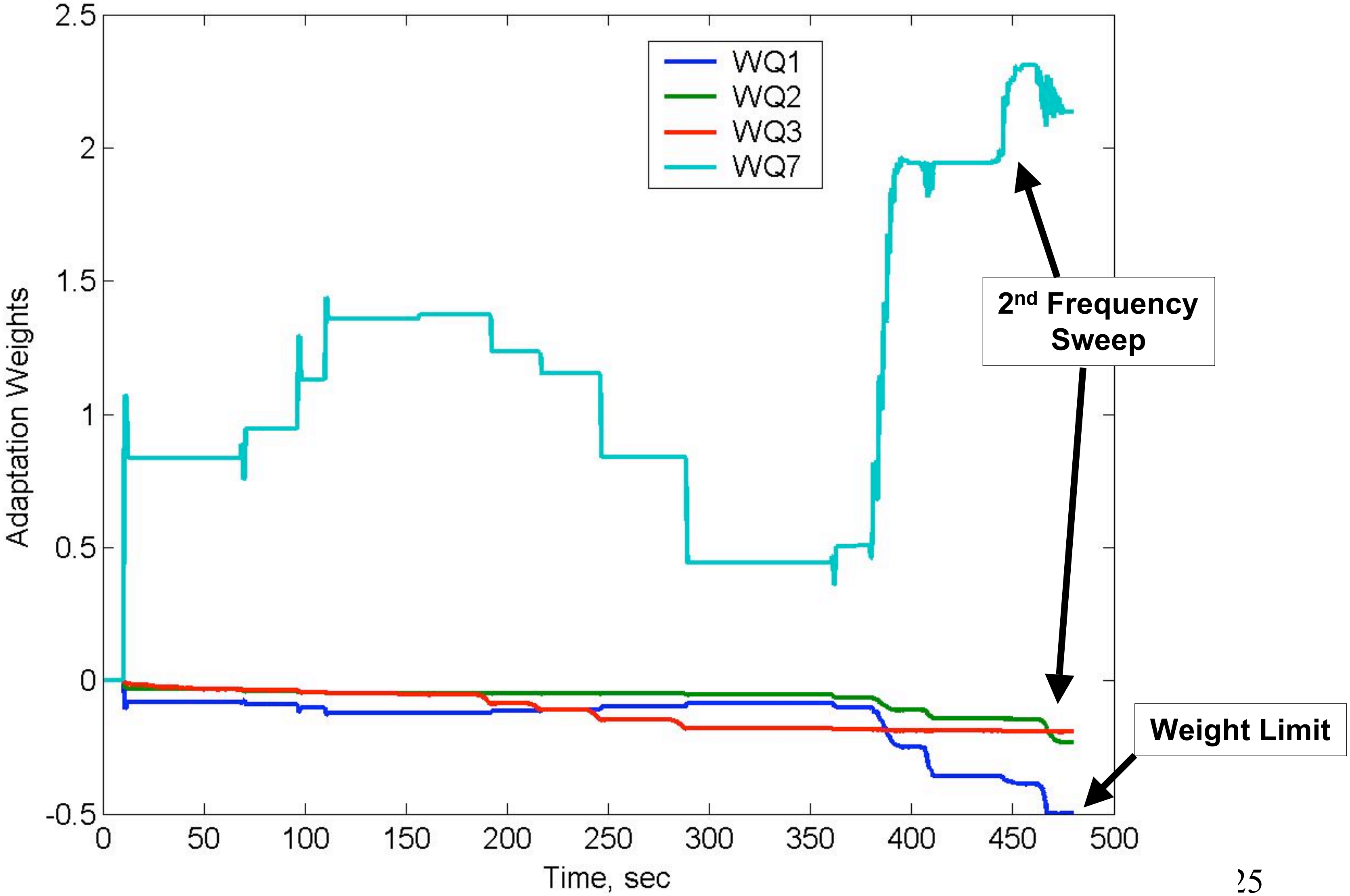
Closed Loop Frequency Response
No Adaptation



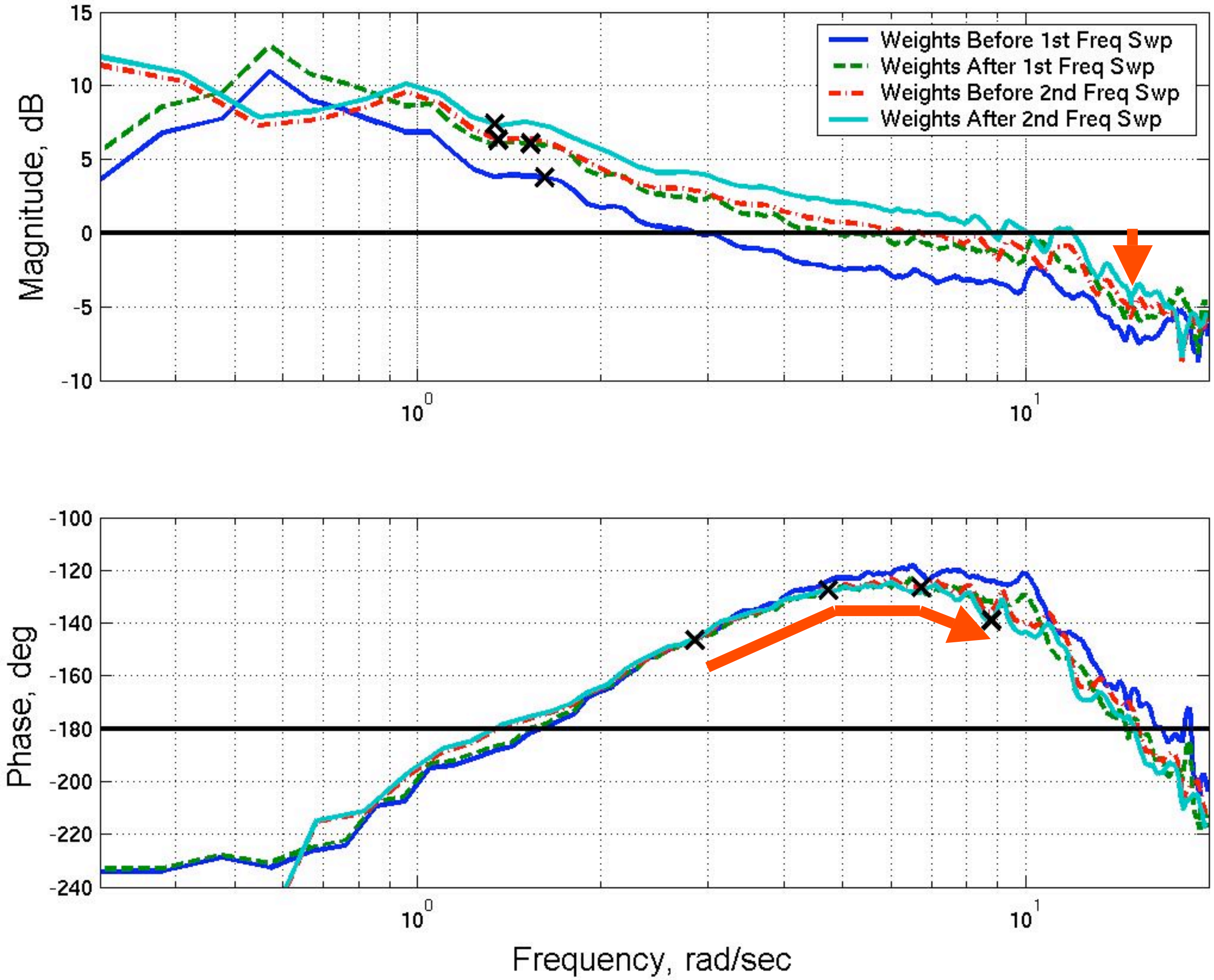
Closed Loop Frequency Response
With Adaptation



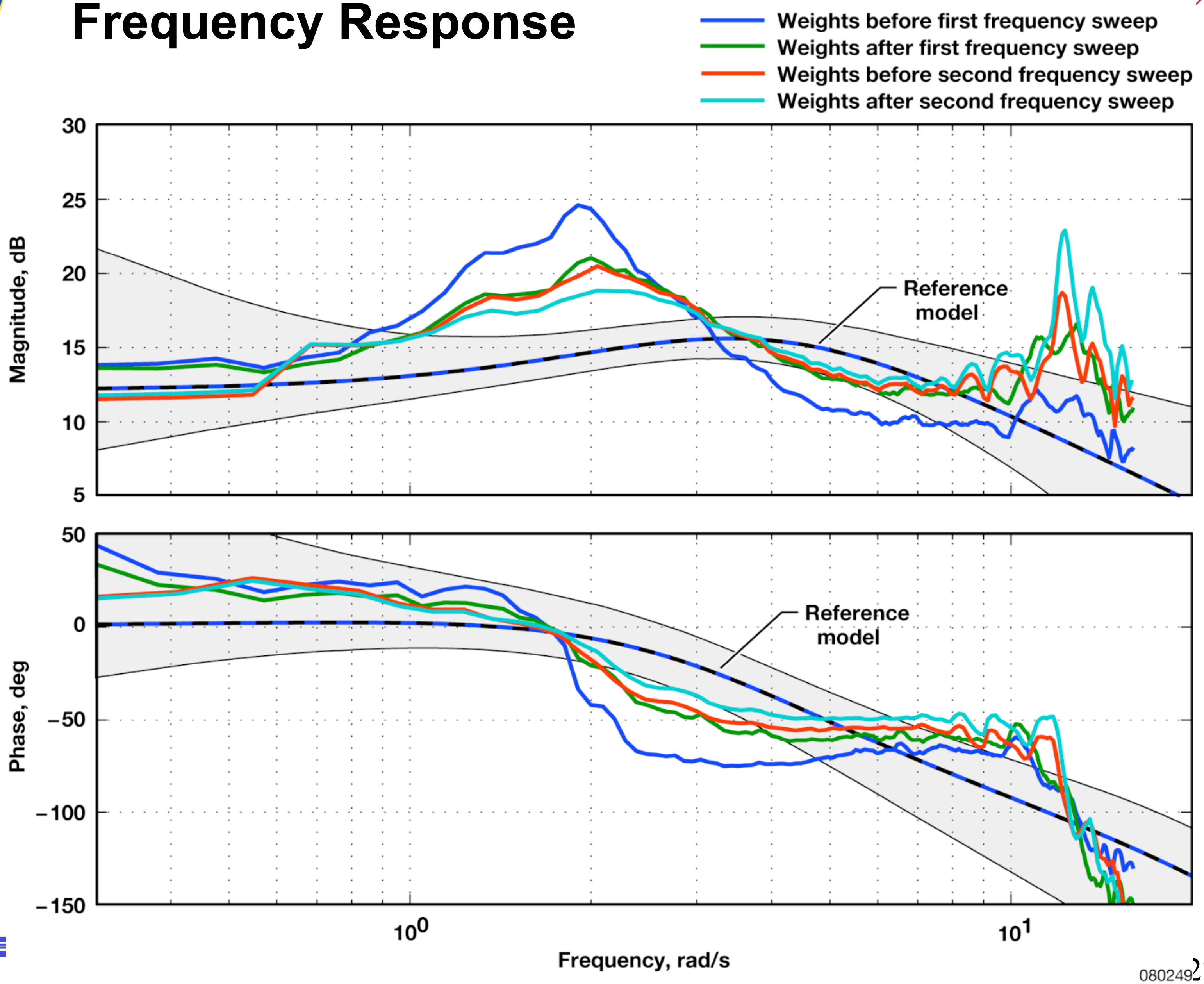
Continued Training



Open Loop Frequency Response



Closed Loop Frequency Response



Improved Adaptive Controller

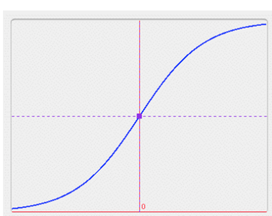
- **ARTS II software delivered 2/19/2008**
  - **Working implementation bugs**
    - **New inputs from simulation side**
    - **How to handle sideslip input**

- **Improvements with new adaptive software**
  - **Neural Network Input Selection**
    - **Control inputs that are highly correlated with tracking error can result in over-learning, and lead to high gain situations *(by having a tendency of addressing all error with additional gain).***
  - **Better yaw axis control – added sideslip reference model**
  - **Reduced reliance on deadbands and weight limits**
  - **Adaptive conditioning for large commands**
  - **Gen 2B option uses modeling error to trigger adaptation (Nelish Kulkarni) instead of tracking error**

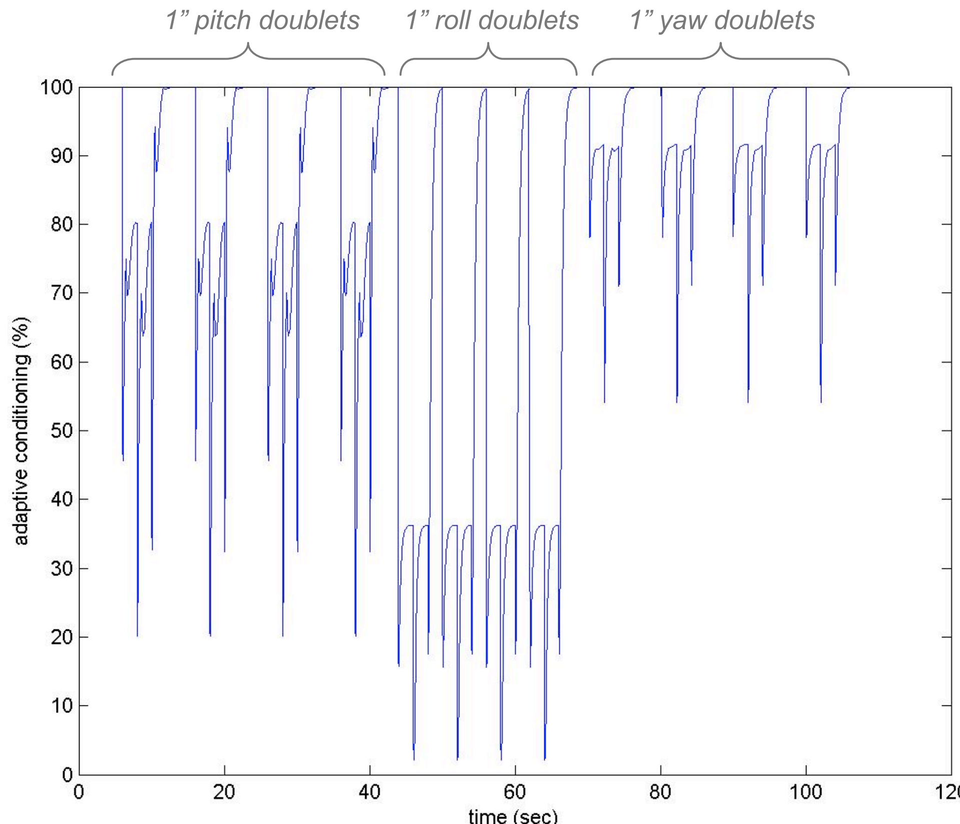
Adaptive Conditioning

Adaptive conditioning reduces adaptation gains during large acceleration and rate commands, since they often result in persistent error, and during periods of low neural network confidence factor (i.e. large augmentation and error).

$$\hat{G} = G * \left(1 - \left|squash\left(K_{\dot{x}_{ref}} * \dot{x}_{ref}\right)\right|\right) * \left(1 - \left|squash\left(K_{x_{ref}} * x_{ref}\right)\right|\right) * \left(1 - \left|squash\left(K_{U_{ad}Z} * U_{ad} * Z\right)\right|\right)$$

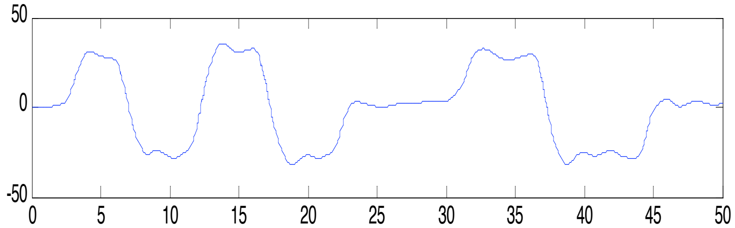


$$squash(x) = \frac{1 - e^{-x}}{1 + e^{-x}}$$

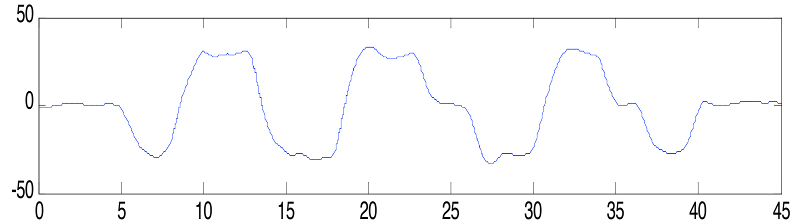


Gen2 & Gen2a Sigma Pi Flight Results

Gen2 Results: Bank-to-Bank



Gen2a Results: Bank-to-Bank



Note: Reduced Tracking errors for similar Pilot Inputs

Gen 2B

- **Without modeling error, the stable second order dynamics of the PI controller will successfully drive the tracking error to zero**
- **Modeling error (**not tracking error) **should trigger adaptation (eg. large transients should not trigger adaptation if airplane behavior is *normal*)**
- **Placing error dead-bands for adaptation is arbitrary**
- **Present design tries to achieve stability but not performance.**

Conclusions

- **Full scale flight test forces designers to address real-world issues**
- **Provides high-visibility demonstration**
- **Adds credibility that adaptation technology can be a viable design option**

- **Helps to "separate the real from the imagined"**

Questions?