5...4...3...2...1...

SPACE LAUNCH SYSTEM

Development and Flight Readiness of the SLS Adaptive Augmenting Control System

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SLS
SPACE LAUNCH SYSTEM

Introduction

◆ **The Space Launch System (SLS) Ascent Flight Control System (FCS) is a primary focus of the Control System Design & Analysis Branch at the Marshall Space Flight Center (MSFC)**
  - Vehicle Critical Design Review (CDR) completed in 2015
  - First Vehicle Verification Analysis Cycle (VAC-1) completed in 2016
  - First unmanned flight, Exploration Mission One (EM-1) with Interim Cryogenic Propulsion Stage (ICPS) in 2018

◆ **The SLS FCS is largely a classically-based algorithm, leveraging from the experience of several manned space flight programs**
  - Saturn V , Shuttle, Ares I-X , Ares I

◆ **An innovative Adaptive Augmenting Control (AAC) algorithm has been developed for NASA's Space Launch System (SLS) family of launch vehicles and implemented as a baseline part of its flight control system (FCS)**

◆ **AAC has three summary-level design objectives:**
  1. "Do no harm"; return to classic control design when adaptation is not needed
  2. Increase responsiveness to recover pointing error within ability of vehicle control
  3. Reduce responsiveness to mitigate effects of undesirable dynamics (i.e., control-structure interaction)
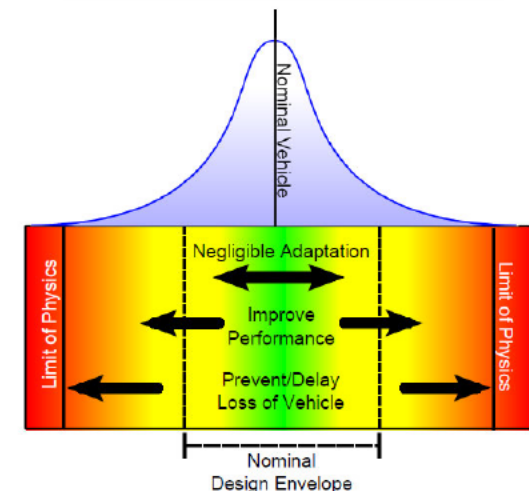
Motivation for Advanced Control: GN&C Opportunities

GN&C issues are rarely the cause for launch vehicle failures. However, a review of historical launch vehicle data from 1990 to 2002 by J. Hanson (NASA MSFC) revealed that 41% of RLV failures might have been mitigated by advanced GN&C technologies.

Conestoga-1620 Wallops Launch

- **1995: Conestoga launch vehicle was lost due to a mis-estimated flex mode frequency**
  - Full integrated vehicle ground vibration test not performed
  - Limited robustness of control filters to flex mode knowledge
  - Lost control due to using up the limited supply of blow-down hydraulic fluid from excessively controlling the mode
- **1994: First Pegasus XL was lost due to flight control being tuned for poor aerodynamic modeling**

- **SLS Adaptive Augmenting Control addresses key launch vehicle uncertainties using a forward-gain multiplicative approach**
  - Increasing the gain can improve the tracking error
    - Useful for extreme discrete-event disturbances, or slow tracking insufficiencies
  - Reducing the gain can mitigate high frequency control structure interaction
    - Large flexible structure with limited pre-flight testing
  - Adaptation only when outside the anticipated design envelope
    - Augmentation is paramount: build upon the well established classical launch vehicle control design and analysis approach

Pegasus XL Air Launch

Components of SLS Adaptive Augmenting Control

Update Law

Adaptation | Error term | "Spectral damper" | Leakage

$$k_T = H_{AAC}(s)\, \mathrm{sat}_{k_{\min}}^{k_{\max}} \{K_e y_e - K_s y_s + 1\}$$
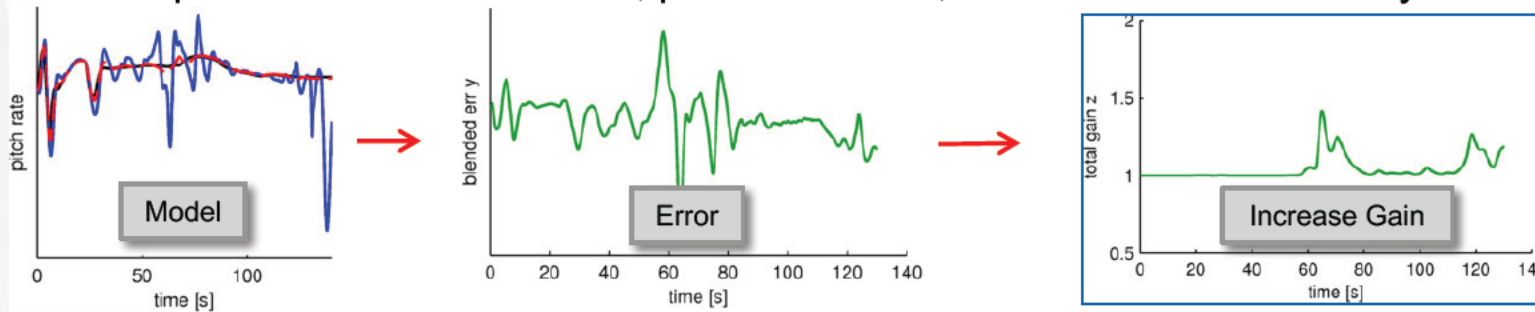
2. Increased Response | 3. Decreased Response | 1. Attract to Nominal

◆ **(1) No adaptation when not needed**
- Unforced solution returns to equilibrium state (unity gain)

Stay the course

◆ **(2) Increased response driven by reference model error**
- Simple onboard math model indicates expected launch vehicle motion
- Model compared with actual motion, produces error, and increases control system response

Model → Error → Increase Gain

Increase Gain

◆ **(3) Decreased response driven by spectral damper power estimator**
- Measures thrust vector activity in specific frequency band
- Produces an estimate of the squared power to effect decreased system response

Control Command → High Pass → Est. Power Signal → Decrease Gain

Decrease Gain

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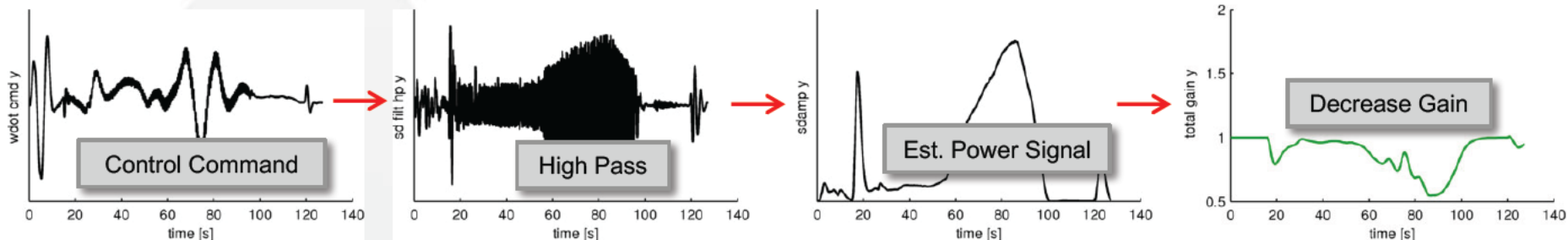
◆ **The algorithm has evolved over time**
- Maintain performance
- Increase simplicity
- Mitigate failure modes
- Enhance analytical tractability

◆ **The current version of the algorithm is essentially an input-limited low-pass filter with a bias of 1**
- Critical innovations in design and implementation for flight software
- Easier to analyze and predict performance using frequency-domain techniques
- Up-gain portion links to Lyapunov stability theory
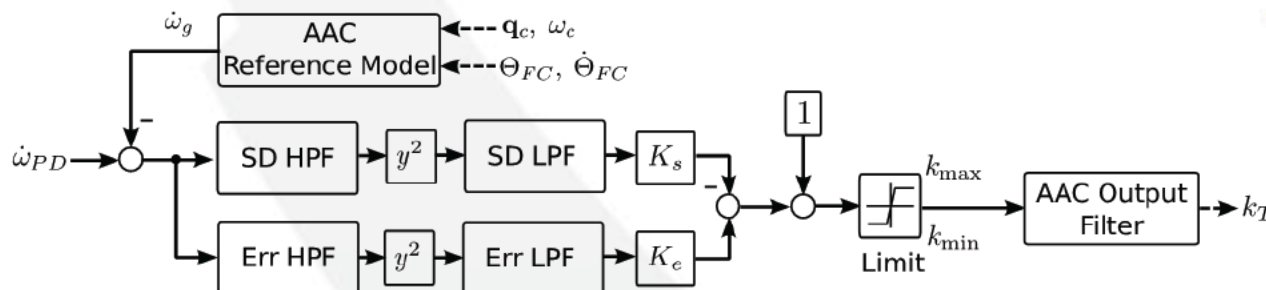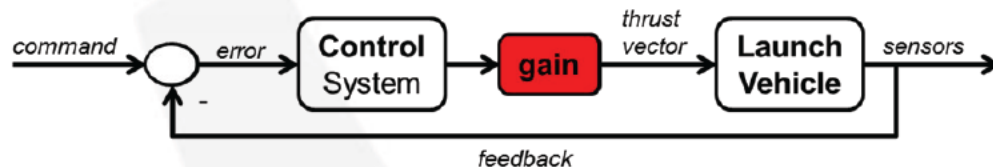
Ares I - Early SLS
Nonlinear limiting of adaptive portion of gain

$$\dot{k}_a = \left(\frac{k_{max} - k_a}{k_{max}}\right) ae_r^2 - \alpha k_a y_s - \beta(k_T - 1)$$

F/A-18 Test – SLS PDR
Total gain with input limiting and output saturation

$$\dot{k}_T = p_{hi}(k_T)ae_r^2 - p_{lo}(k_T)\alpha y_s - \beta(k_T - 1)$$

SLS CDR
Output-biased filter with input saturation

$$k_T = H_{AAC}(s)\,\mathrm{sat}_{k_0}^{k_{max}}\left\{a\left(H_{EF}(s)e_r^2\right)^{\frac{1}{2}} - \alpha y_s + 1\right\}$$

SLS VAC-1
Symmetric Formulation, Up-gain portion is Lyapunov supported

$$k_T = H_{AAC}(s)\,\mathrm{sat}_{k_{min}}^{k_{max}}\{K_e y_e - K_s y_s + 1\}$$

$$\dot{\omega}_{AAC} = \dot{\omega}_{PD} - \dot{\omega}_g$$

$$y_e = H_{EF}(s)\left(H_{EW}(s)\dot{\omega}_{AAC}\right)^2$$

$$y_s = H_{LP}(s)\left(H_{HP}(s)\dot{\omega}_{AAC}\right)^2$$

final form similar to 1960s-era forward gain adaptive approaches

Major Developments in SLS Adaptive Control: Timeline

◆ **SLS DAC-1 (Design & Analysis Cycle)**
- AAC implemented in flight software based on original Ares I Whitepaper

◆ **SLS DAC-2**
- _Began running AAC_ in Monte Carlo analysis, algorithm in baseline simulations

◆ **SLS DAC-2R (PDR)**
- Flight test stressing cases developed to demonstrate algorithm
  - Subsequent algorithm modifications added for improved performance & robustness
- _F/A-18 flight test, support across agency, AAC baselined_

◆ **SLS DAC-3**
- _Applied Describing Function (DF) techniques to analyze fundamental behavior_
  - DF analysis provides quantification of robustness to limit cycle phenomena, means to optimally select parameters, and yields significant insight into dynamic behavior
- Began Joint SLS/NESC Flight Readiness & Stability Review with external support partners

◆ **SLS DAC-3R (CDR)**
- Performed large set of analyses with matured AAC algorithm and flight models

◆ **SLS/NESC "Stability of the SLS FCS with Adaptive Augmentation" Report**
- _Consolidation of comprehensive set of analyses of AAC_
- Recommended minor algorithm modifications to improve traceability to Lyapunov theory

◆ **SLS VAC-1**
- _Incorporated SLS/NESC recommended modifications_, re-performed and finalized program documentation of pertinent analyses to demonstrate flight readiness
- Performed code & algorithm peer reviews and finalized SLS Flight Control System Flight Software

◆ **Current to FRC (Flight Readiness Cycle)**
- Final flight vehicle parameter development, repeat key analyses as models update

◆ **PDR AAC Algorithm (in C-code Standalone FSW prototype form) was flown on the NASA Dryden F/A-18 FAST testbed which, with different control surfaces, emulated the SLS pitch attitude dynamics under ~20 stressing scenarios**
- Employed NDI approach to emulate the slower launch vehicle attitude dynamics & control

◆ **~100 flight trajectories across a five flight campaign**

◆ **The three objectives of AAC were demonstrated in all cases**
- Special test case with actual F/A-18 structural mode demonstrated suppression of airframe-control limit cycle oscillation
- Some exploration of manual steering interactions with adaptive controller

◆ **No significant findings or adjustments to algorithm from/during actual test**
- Pre-flight test development of stressing case scenarios provided a lot of insight (with external exposure) into the response characteristics of AAC, implementation, and scope of needed analysis activities
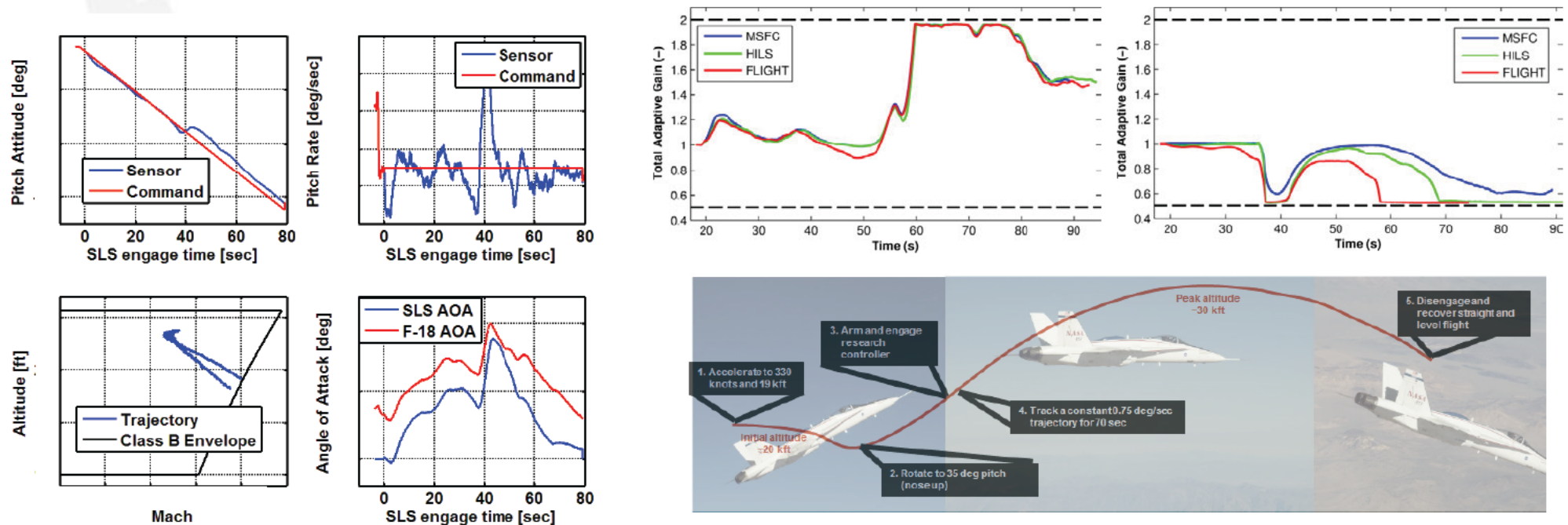
**Objective:** **Mitigate Unstable Mis-Modeled Internal Dynamics via AAC spectral damper action**

F/A-18 Mode Sys ID Test: Reconstruction based on a 60 sec multi-sine input with frequencies centered at anticipated first fuselage mode
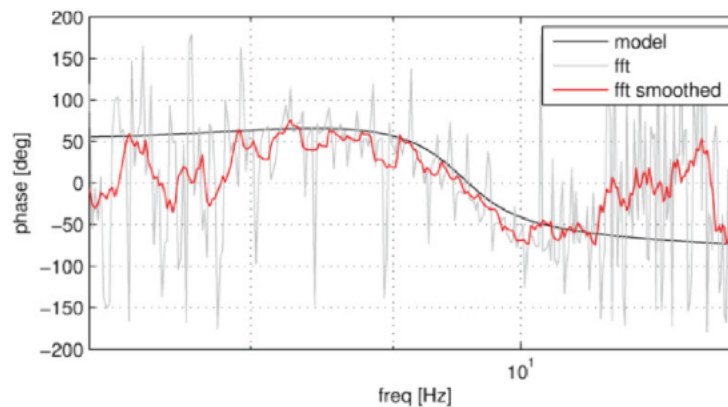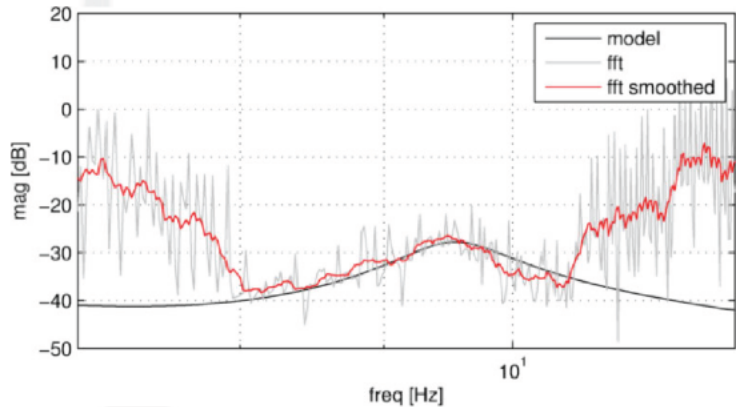
Excellent match to first fuselage bending mode

**F/A-18 Unstable Mode Recovery Test :** AAC Mitigates Unstable Airframe Mode

- Baseline F/A-18 notch filters removed & SLS control filters adjusted to create a closed loop instability of the ID-ed flex mode

- Instability reached until rate limit cycle, AAC reduces gain, yielding a smaller limit cycle amplitude

- First known suppression of unstable mode on manned spacecraft
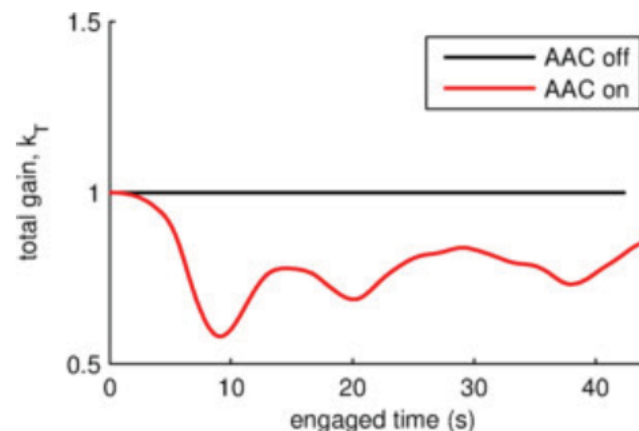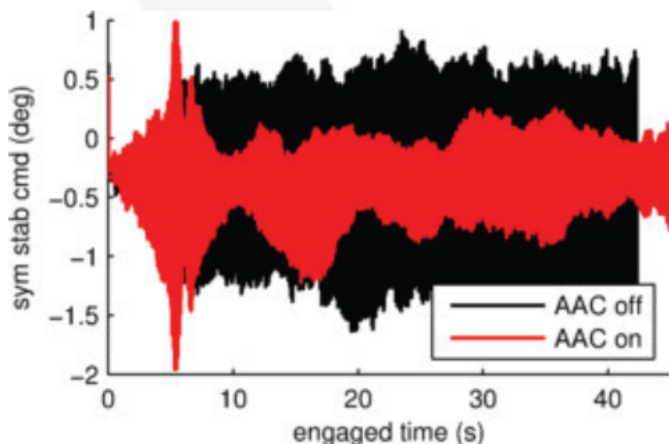
AAC drops gain to reduce the limit cycle amplitude

8

AAC Impact to Non-Failure Design Envelope is Negligible

◆ **Gain activity is present during non-failure Monte Carlo analysis**
  • Result of aero dispersions during max-q and booster dispersions during tailoff
◆ **AAC results in minor impact to response across design envelope, slight improvement if any**
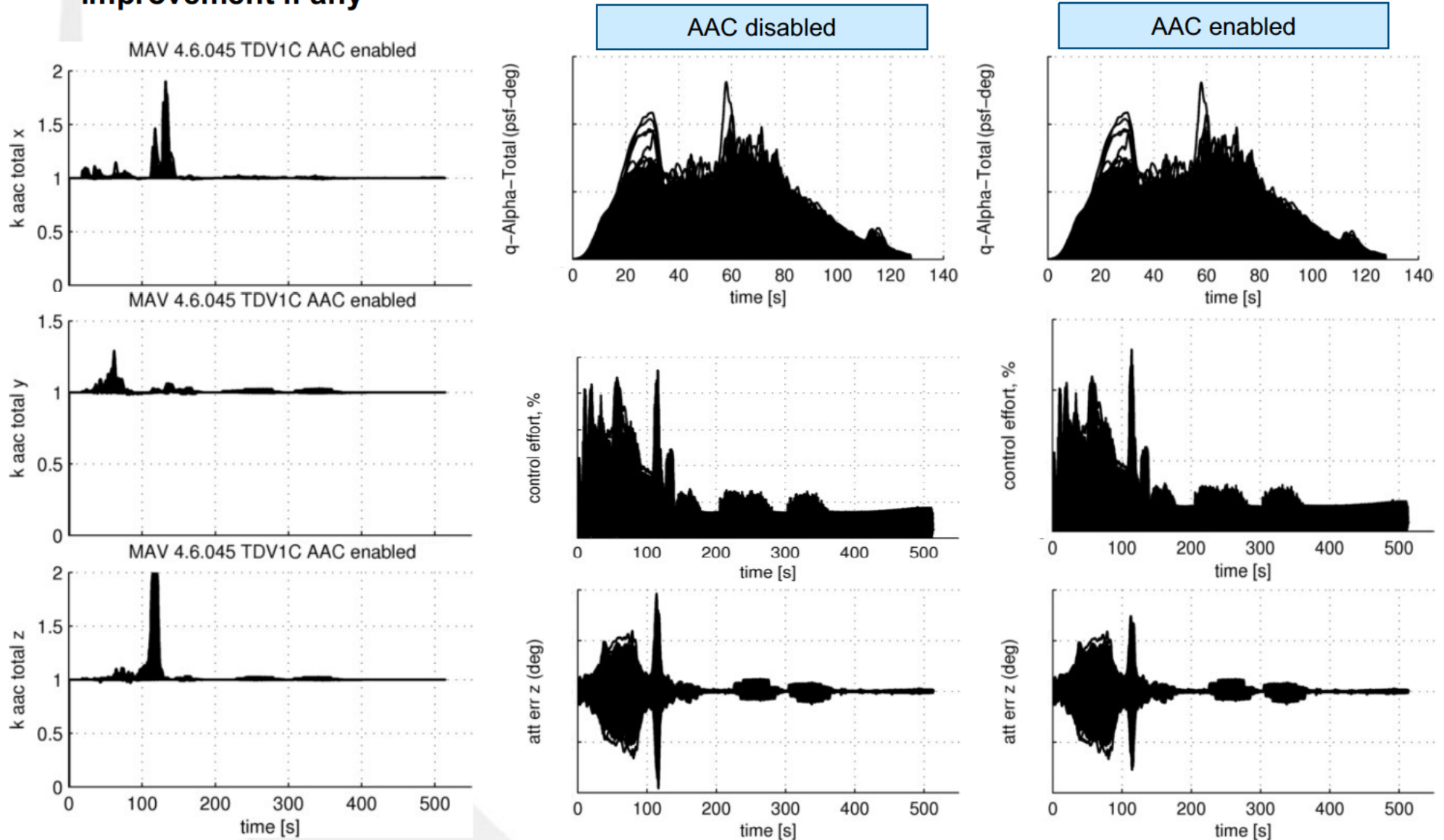
◆ **40+ stressing cases are maintained in hi-fi 6-DOF to demonstrate algorithm objectives and explore conditions that might break the algorithm**

◆ **Scenarios largely represent mis-modeling of dynamics or scenarios in which significant degradation to stability margins and controllability are present**

   • Assigning probabilities to such unknown-unknowns is difficult and qualitative at best (hence single runs)

◆ **Stressing cases readily demonstrates the ability of and builds confidence in the robustness/performance of the AAC algorithm in such scenarios**
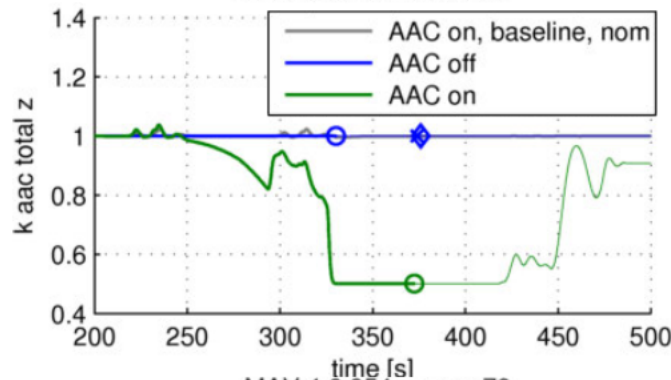

Stiff Aero, Stressing Wind, Dual CSE Hardovers
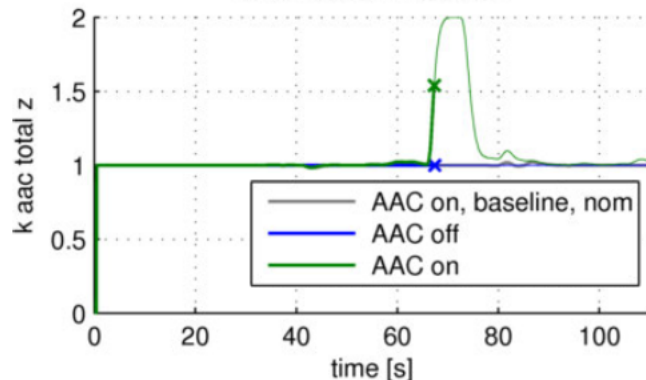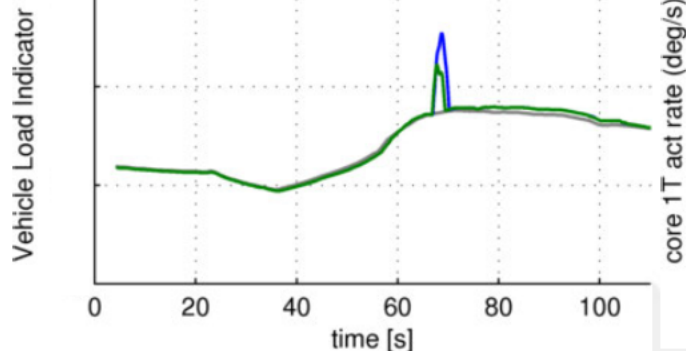
Unstable Flex Mode
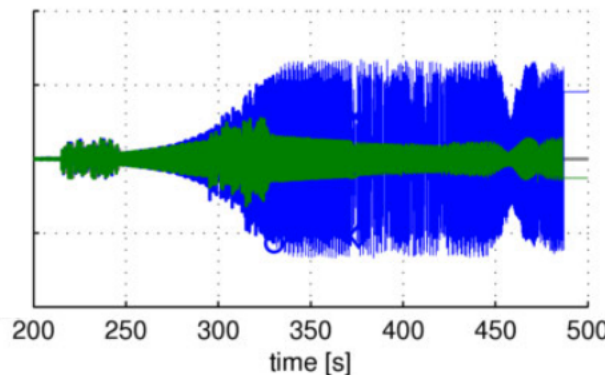
SRB Hardover
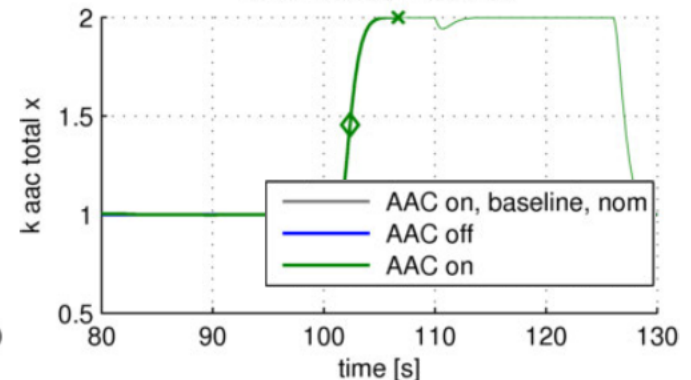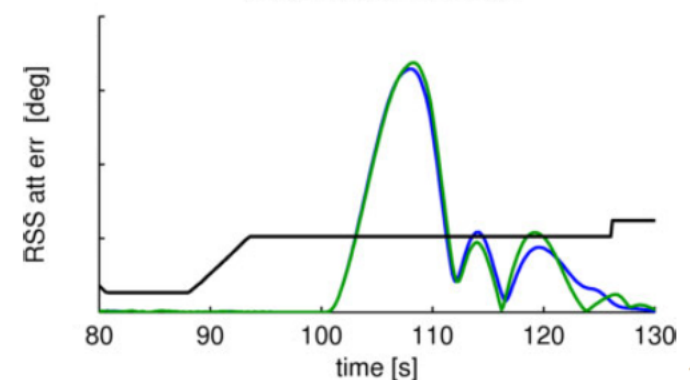
◆ **Time domain stability margins were extracted from 6-DOF by applying fixed gain & time delays incrementally about the expected point of instability to nonlinear 6-DOF simulations**

TDSM study, pitch, RB gain margin, AAC off

Rigid Gain Margins
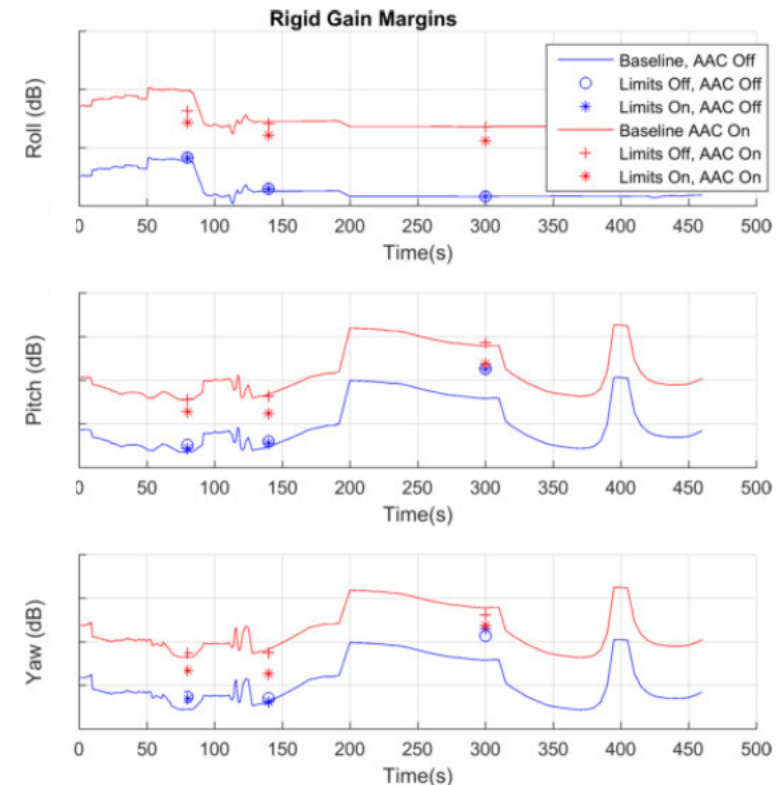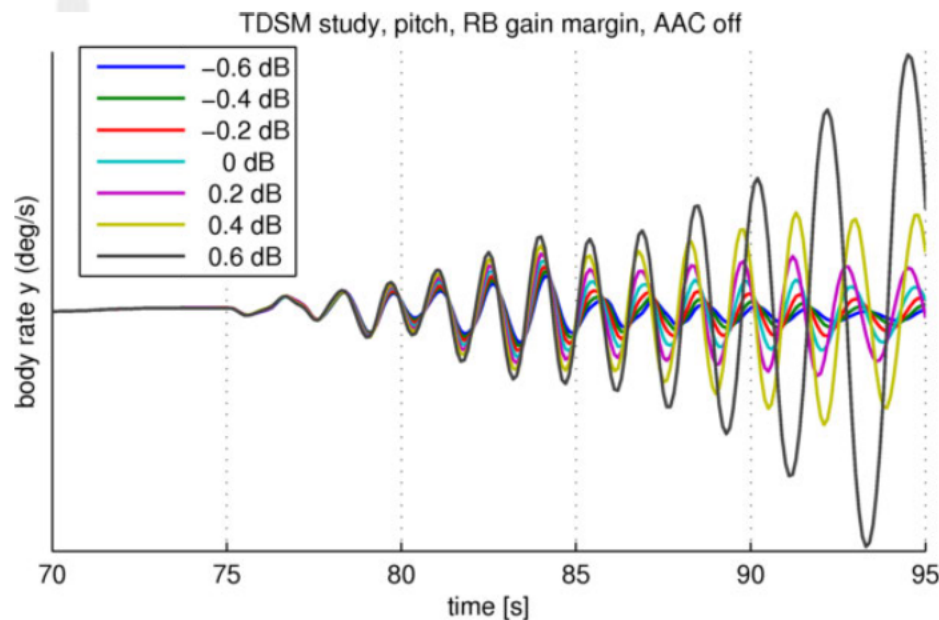
◆ **The system with AAC off demonstrated margins agree in time & freq domain**
• Verifies the applicability of the LTI frequency domain approach to the nonlinear simulation

◆ **The system with AAC demonstrates its objectives**
• Demonstrates that gain margins were always increased up to 6 dB limit
• Amount of gain increase constrained by nonlinearities (TVC limits, nonlinear slosh damping) and time varying nature of the system (eg. low damping slosh near crossovers)

◆ **Under NESC Assessment TI-14_00964, Dr. Mark Balas (ERAU) evaluated the current AAC architecture and tailored existing adaptive control theory to provide improved traceability to Lyapunov-based stability proofs**
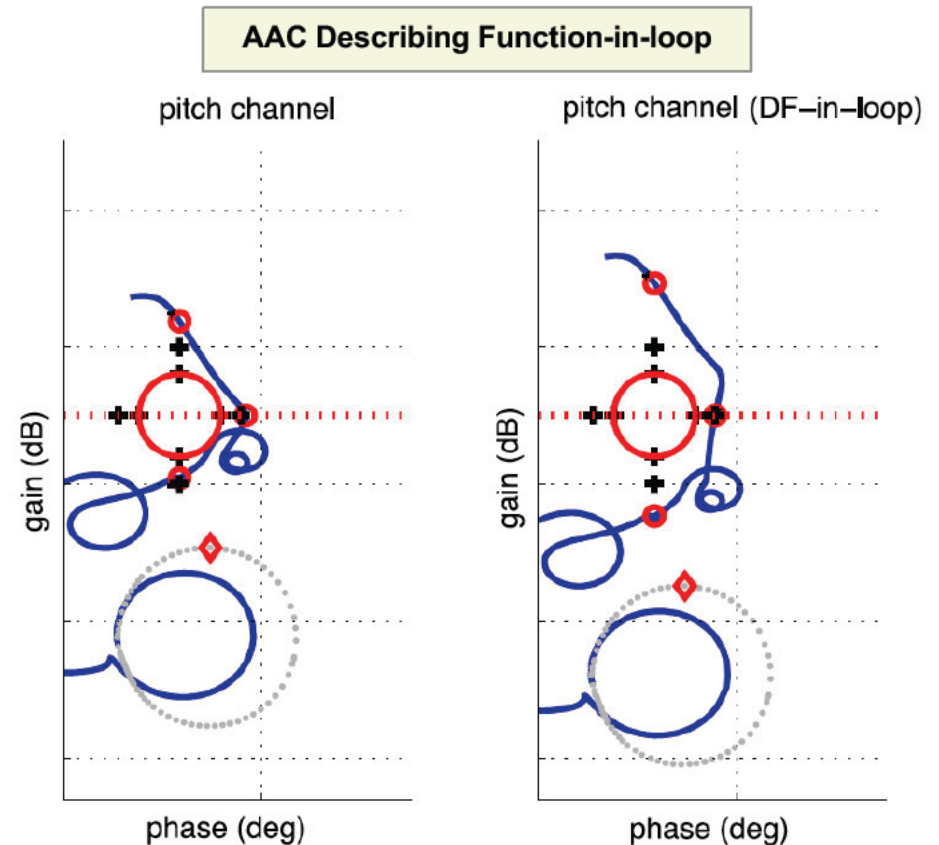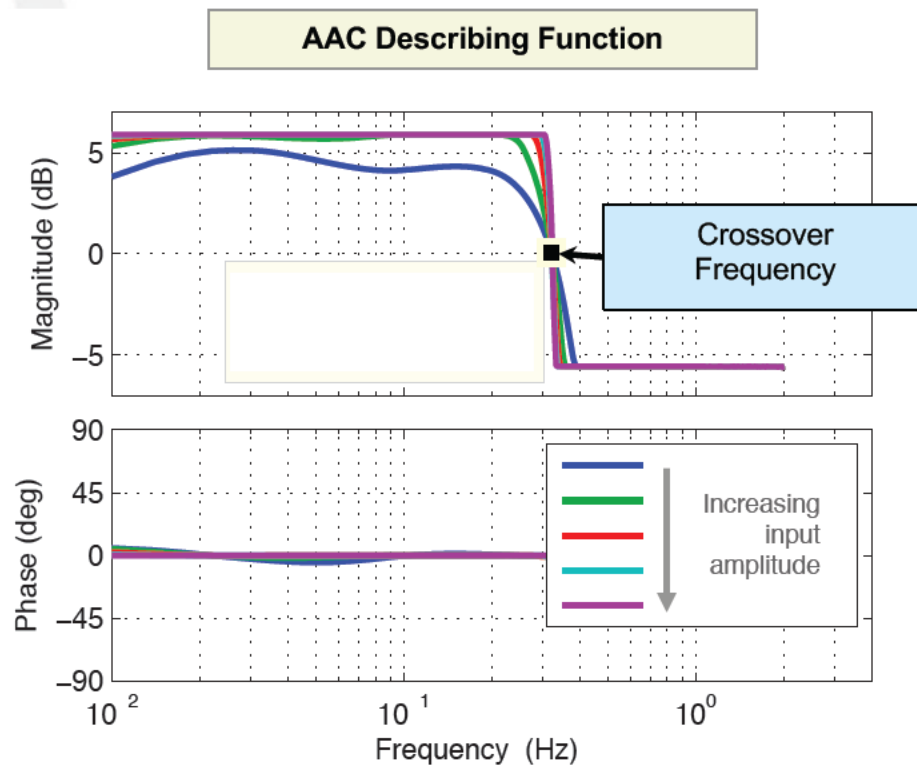
◆ **Result applies existing Lyapunov adaptive control theory to the existing "up-gain" portion of the AAC algorithm, from which came a few recommended changes**
- Adaptive gain must be computed from the same signal to which it will be applied
- Use PD terms to drive AAC gain, apply AAC gain to PD terms only
- Apply PID integrator to PD terms instead of the traditional P term, add to gained signal
  - (adaptive disturbance mitigation control form)
- Error signal must be squared (F/A-18 Tested PDR design)

◆ **Algorithm modifications were incorporated following NESC Assessment, and relevant analysis re-conducted to verify and accept changes**
- DF analysis & parameter re-tuning
- Stressing cases demonstration
- Time Domain Stability Margins
- Circle Criterion: Gain Limits

Fig 2: Alternate AAC Architecture – 2 ("up-gain" only)

Control command:
$$u = k_T(e_{PD}) e_{PD} + u_I + d\omega_{BIAS}$$

Adaptive Update Law
$$\dot{k}_T = a * e_{PD}^2$$
$$k_T(0) = 1$$

◆ **Describing function & other nonlinear freq domain methods developed for AAC**
- Derived from numerical sinusoidal inverse describing function (SIDF) techniques
- AAC is cast as an amplitude and frequency dependent nonlinear filter
- When operating as designed, AAC acts as a near zero-phase low-pass loop shaper
- The DF-in-the-loop approach can be used to show approx. nonlinear gain & phase margin*
- Frequency separation principles used to eliminate limit cycling risk and simplify gain tuning

◆ **Nonlinear frequency response techniques provide criteria for robust selection of parameters**

AAC Describing Function

Crossover Frequency

Increasing input amplitude

AAC Describing Function-in-loop

pitch channel

pitch channel (DF-in-loop)

*Not the same as classical gain and phase margins: must be carefully interpreted as pointwise in frequency

Concluding Remarks

◆ Classical, flight proven, control design approaches have been applied to produce the SLS Flight control system: a generalized, well-characterized, and robust set of algorithms

◆ The innovative Adaptive Augmenting Control (AAC) component of the FCS has been thoroughly simulated and analyzed, flight tested, independently (NESC) reviewed, and ready for the first test flight of SLS

◆ AAC will extend the robustness of the basic control system for the first test flight and beyond

BACKUP

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