Space Launch System Implementation of Adaptive Augmenting Control

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♦ **Adaptive Augmenting Control (AAC) has been developed for exploration class manned launch vehicles during the Constellation program [2]**

♦ **The AAC concept has been developed for NASA's Space Launch System family of launch vehicles and implemented as a baseline part of its full-scale flight control software**

♦ **SLS implementation of AAC has been dispersion tested in multiple simulation environments, flight tested using Dryden's specially outfitted F/A-18 test bed [3], and is fast approaching a CDR level of maturity**

♦ **Presentation will describe**
  - Basics of adaptive formulation
  - Changes to Original AAC for SLS
  - Application to SLS Control system
  - Simulation Results
    – Stressing Cases
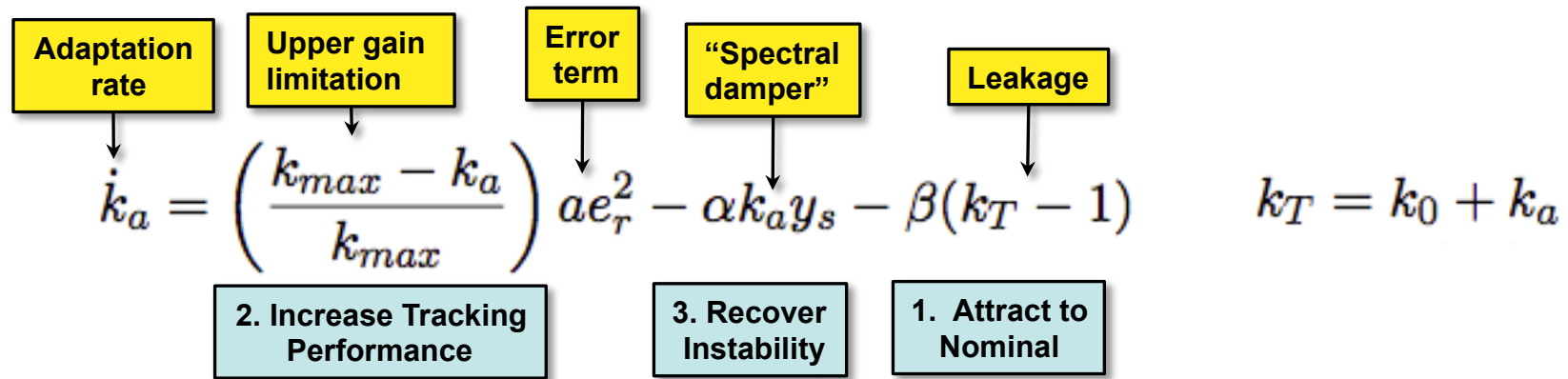   – Monte Carlo Analysis

- **Extends performance and robustness of baseline gain-scheduled ("fixed gain") control system for the conditionally stable launch vehicle**

- **Augmentation uses sensed data to adjust the total loop gain on-line**

- **AAC summary-level design objectives:**

  1. **"Do no harm"; return to baseline control design when not needed**

  2. **Respond to error within ability of vehicle to track commands to increase performance**

  3. **Respond to undesirable parasitic dynamics (i.e., control-structure interaction) to regain stability**
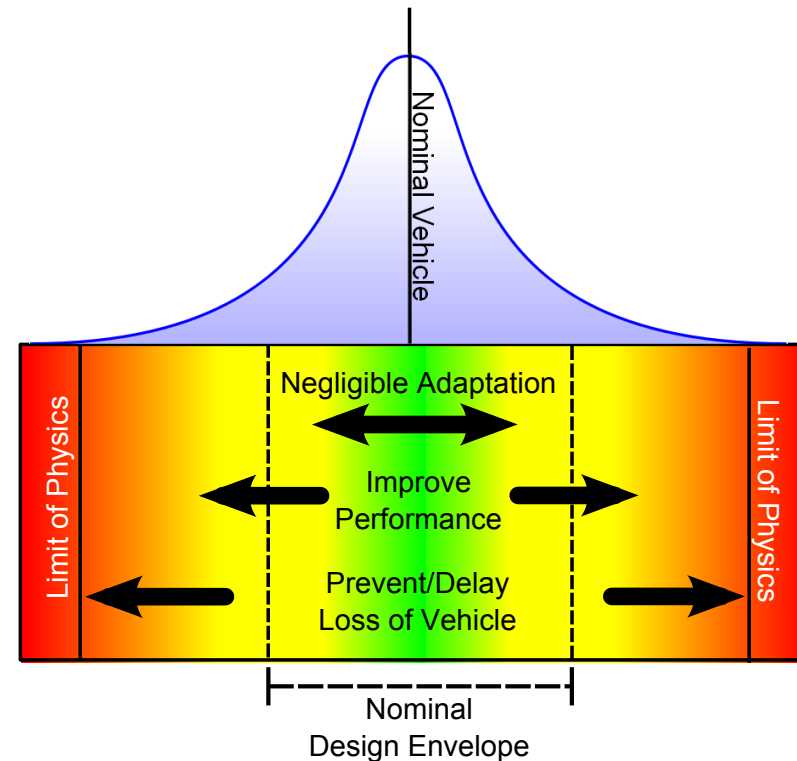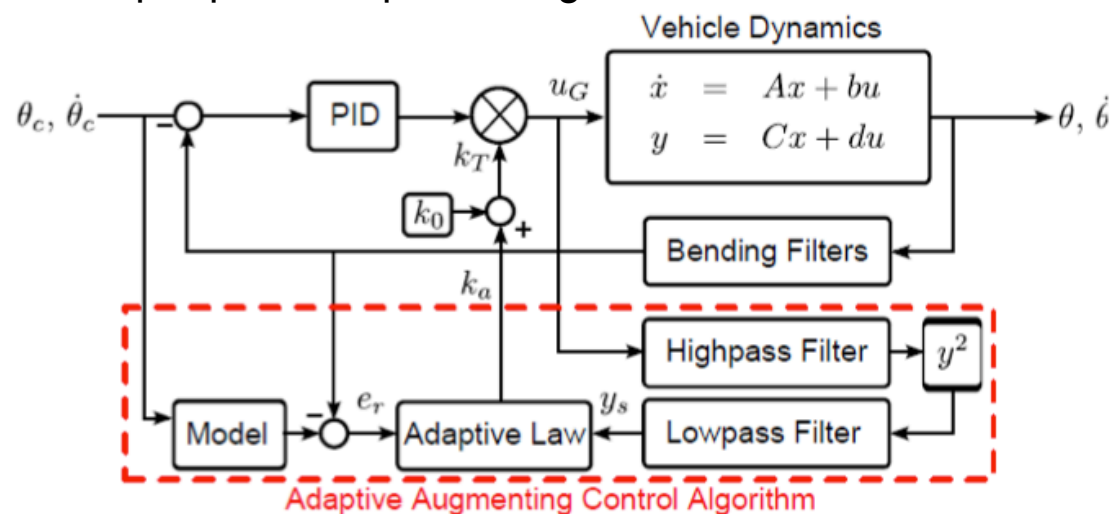
◆ **Original adaptive gain law [2] features three components corresponding to the three objectives**

Adaptation rate
Upper gain limitation
Error term
"Spectral damper"
Leakage

$$\dot{k}_a = \left(\frac{k_{max} - k_a}{k_{max}}\right) ae_r^2 - \alpha k_a y_s - \beta(k_T - 1) \qquad k_T = k_0 + k_a$$

2. Increase Tracking Performance
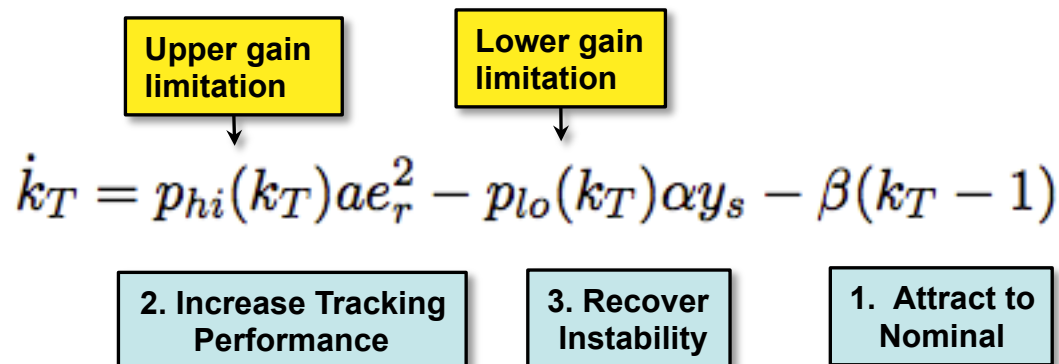
3. Recover Instability

1. Attract to Nominal

◆ **Total Gain resulting from adaptation applied to PID control signal**
- AAC reference model provides error signal to gain up control
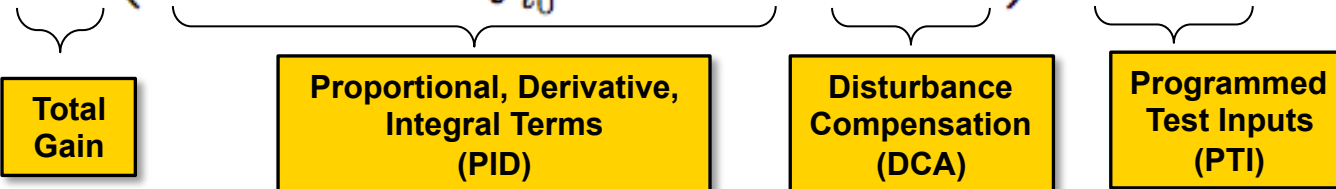- AAC spectral damper provides power to gain down control

Vehicle Dynamics

$$\dot{x} = Ax + bu$$
$$y = Cx + du$$

PID

u_G

k_T

k_0

k_a

Bending Filters

Highpass Filter → y^2

Lowpass Filter

Model → e_r → Adaptive Law ← y_s

$\theta_c, \dot{\theta}_c$ → → $\theta, \dot{\theta}$

Adaptive Augmenting Control Algorithm

$$\dot{k}_a = \left(\frac{k_{max} - k_a}{k_{max}}\right) ae_r^2 - \alpha k_a y_s - \beta(k_T - 1) \quad k_T = k_0 + k_a$$

♦ **SLS implementation carries three terms matching the original three objectives but with updates to the formulation**

Upper gain limitation

Lower gain limitation

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

2. Increase Tracking Performance

3. Recover Instability

1. Attract to Nominal

♦ **Right hand nonlinear dependencies on adaptation gain have been removed**
  • Provides for a more linear response of gain adaptation to inputs
♦ **Employed parameterized saturation functions to allow tunability of adaptation response to inputs**
  • Can yield a more rapid adaptation response than in the original formulation
  • SLS parameterized to effect a rapid, linear, response within 90% of allowable gain range
♦ **Adaptive law has been recast directly in terms of total gain**
  • Simplification of expression and flight code

♦ **Baseline controller issues single angular acceleration command to the control allocator (OCA) per axis (pitch axis "q" shown)**

$$\dot{q}_c = k_T \left(k_p \theta_e + k_d q_e + \int_{t_0}^{t_0+t} k_i \theta_e d\tau + \dot{q}_{DCA} \right) + \dot{q}_{PTI}$$

| Total Gain | Proportional, Derivative, Integral Terms (PID) | Disturbance Compensation (DCA) | Programmed Test Inputs (PTI) |

♦ **Total gain is adjusted by adaptive law and applied to PID & DCA terms**

♦ **Application to DCA aids in two ways**
  • Objective 2: increases disturbance rejection performance, maintains PID/DCA gain ratios
  • Objective 3: allows adaptation decrease for parasitic dynamics in DCA loop

♦ **PTI is excluded from total gain**
  • Open loop table-lookup input for the purpose of flight test system identification

♦ **Angular acceleration command is the point at which SISO open loop (OL) response is constructed**
  • Total gain adjustments shifts the forward gain of the entire OL transfer function

♦ **Baseline Control System**
  - PID – (proportional, derivative, integral)
    – Quaternion and rate commands
  - Bending Filters – attenuates, phases parasitic dynamics (flex, slosh, actuator lag)
  - DCA (Disturbance Compensation Algorithm)
    – Rate and acceleration inputs
  - OCA (Optimal Control Allocator) – linear allocator based on weighted least-squares
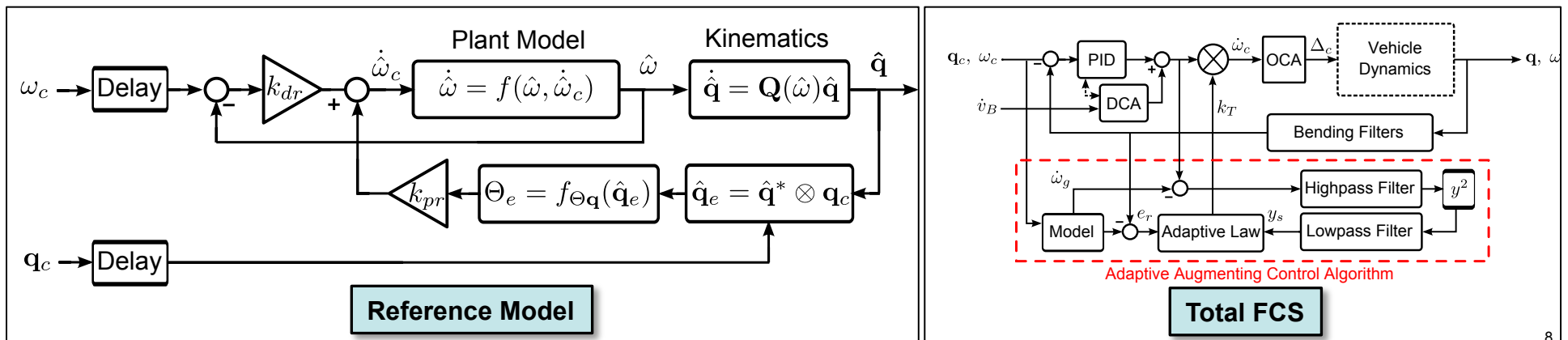
♦ **Adaptive Augmenting Control**
  - Reference model
  - Spectral damper process (filters, rectification)
  - Adaptive Law

Adaptive Augmenting Control Algorithm

Multi-Axis Reference Model Mechanization
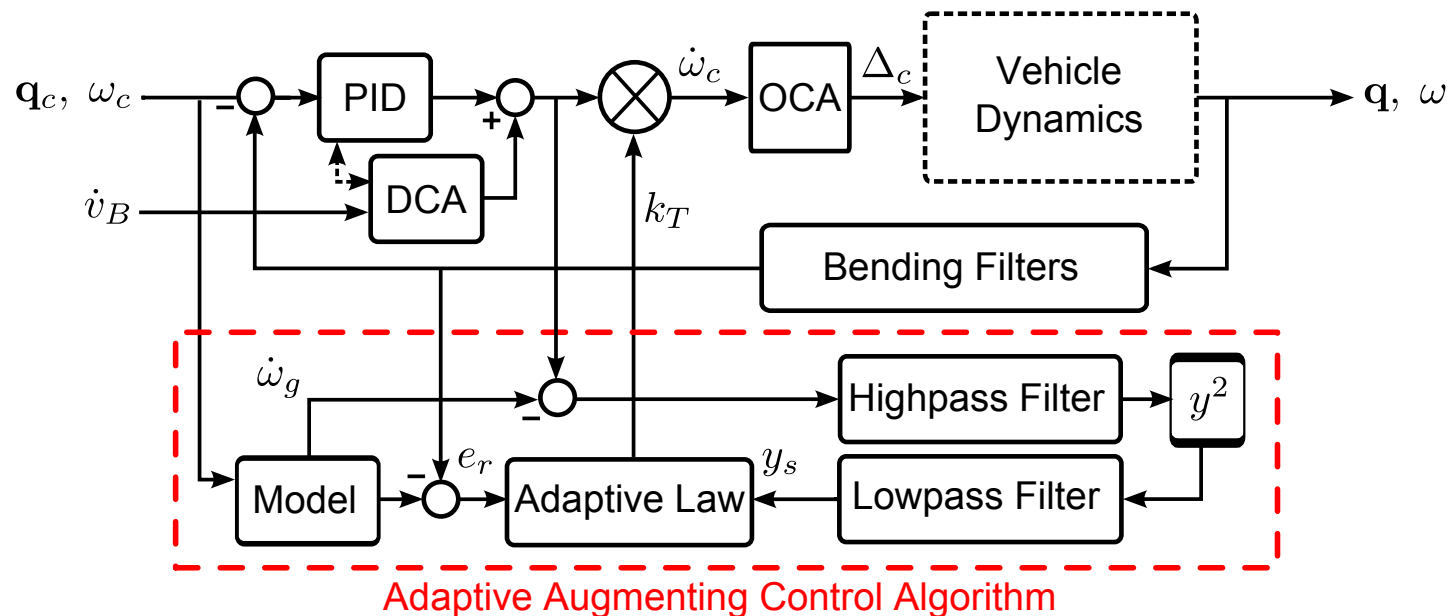
- ♦ **2nd order transfer function with input delay models nominal/baseline control response to guidance inputs**
  - Performs acceptably well compared to higher order systems
- ♦ **Each of the roll, pitch, and yaw control axes are sufficiently decoupled and parameterized independently**
  - Natural frequency, damping, and delay per axis
  - Parameters scheduled as a function of flight condition
- ♦ **Parallel roll, pitch, yaw rate transfer functions integrated in series with an outer loop quaternion mechanization**
  - Guidance inputs
    - Inertial to Body Quaternion Command, $\mathbf{q}_c$
    - Roll, Pitch, Yaw Rate Commands, ω_c
  - Output
    - Inertial to Body Quaternion Response, $\hat{\mathbf{q}}$
   - Roll, Pitch, Yaw Body Rate Response, $\hat{\omega}$

$$\hat{\dot{q}} = k_{pr}\left(\theta_c - \hat{\theta}\right) + k_{dr}\left(q_c - \hat{q}\right)$$

$$H_r(s) = e^{-s\tau}\frac{\omega_r^2 + 2\zeta_r\omega_r s}{s^2 + 2\zeta_r\omega_r s + \omega_r^2}$$

Reference Model

Total FCS

♦ **Reference model response compares well to actual system system**
  - Rate response for each axis shown on different scale
  - Roll shows largest commands during first half of boost phase trajectory
  - Pitch shows initial tower avoidance maneuver and day-of-launch wind adjustments
  - Yaw axis shows smallest command (cross-axis coupling during maneuvers)
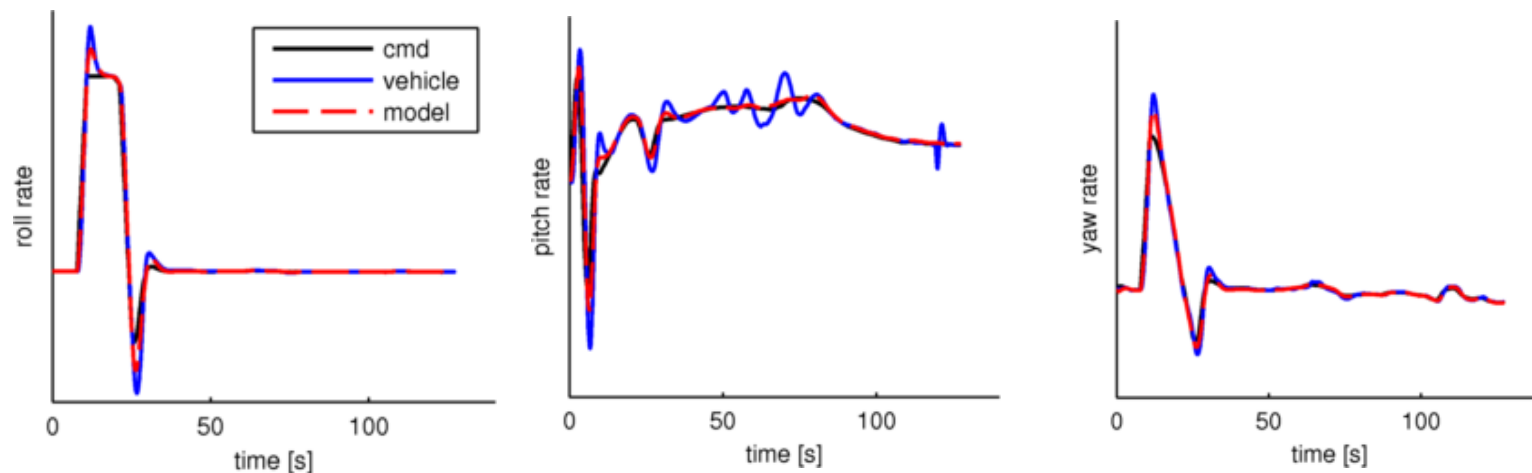
♦ **Reference model response is compared to actual vehicle response to generate error signals indicating the extent to which rigid body control response has deviated from nominal/desired**

$$\dot{\gamma}_r = \hat{\omega} - \omega \qquad \gamma_r = \hat{\Theta} - \Theta$$

♦ **Rate errors and attitude errors are blended together for each axis to produce a single signal in each axis to effect an adaptation gain increase in the corresponding axis**

$$e_r = c\gamma_r + \dot{\gamma}_r$$

♦ **Spectral damper, consistent with the original formulation, provides an estimate of the power of undesirable frequency content in the feedback path**

♦ **Input signal is constructed from the angular acceleration control command**
  - Taken prior to application of total loop gain (avoids direct gain-induced transients)

$$\dot{q}_c = \cancel{k_T}^{1}\left(k_p\theta_e + k_d q_e + \int_{t_0}^{t_0+t} k_i\theta_e d\tau + \dot{q}_{DCA}\right) + \cancel{\dot{q}_{PTI}}^{0}$$

  - Includes DCA to capture undesirable dynamics in its feedback paths
  - Subtracts a angular acceleration compensation term based upon the reference model dynamics to account for guidance-induced control commands

$$\dot{q}_g = \omega_r^2\left(\theta_c - \hat{\theta}\right) + 2\zeta_r\omega_r\left(q_c - \hat{q}\right)$$

♦ **Resultant signal is then band-passed, squared, and low-passed to provide a smooth positive signal used to effect an adaptation gain decrease**

♦ **Filter parameters selected to highlight frequency spectrum associated with dynamics which can be suppressed by a gain decrease**
  - propellant slosh
  - structural flexibility
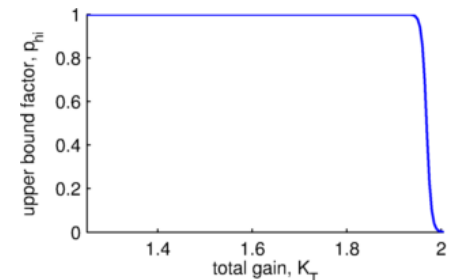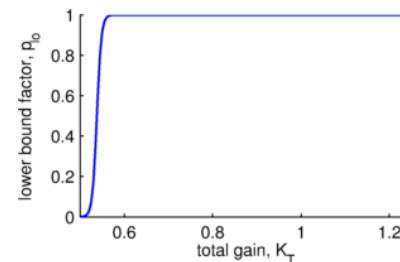 - actuator dynamics

Adaptive Augmenting Control Algorithm
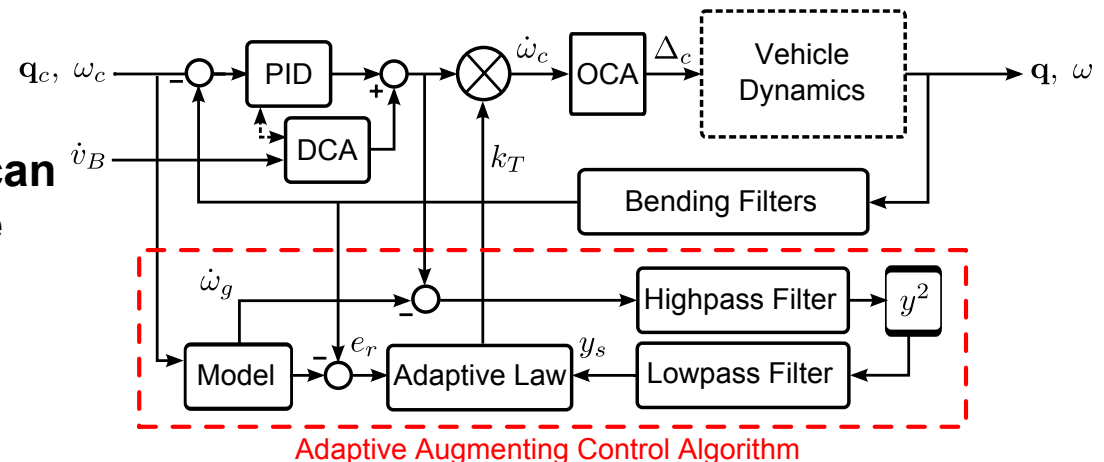
♦ **Saturation Functions Applied to Squared Error and Spectral Inputs**
   • Smooth saturation at ends of total gain range with tunable shape

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

$$p_{hi}(k_T) = 1 - \left(1 + \exp\left[A\left(\frac{1}{A}\log\left(\frac{\epsilon k_{Tmax}}{1 - \epsilon k_{Tmax}}\right) + k_{Tmax} - k_T\right)\right]\right)^{-1}$$

$$p_{lo}(k_T) = \left(1 + \exp\left[A\left(\frac{1}{A}\log\left(\frac{1 - \epsilon k_{Tmax}}{\epsilon k_{Tmax}}\right) + k_{Tmin} - k_T\right)\right]\right)^{-1}$$

♦ **Explicit hard limits are additionally imposed on total gain**
   • 0.5 and 2.0 are current SLS total gain limits
   • correspond to -/+ 6 dB nominal gain margin design criteria

♦ **Adaptive rate limits imposed on squared error and spectral inputs**
   • Parameterized by the time for the term to effect a full scale gain change
   • Safeguards to preclude numerical problems due to large or spurious inputs

$$e_{lim}^2 = \left(\frac{k_{Tmax} - k_{Tmin}}{a\Delta t_{elim}}\right) \qquad y_{slim} = \left(\frac{k_{Tmax} - k_{Tmin}}{\alpha\Delta t_{sdlim}}\right)$$

♦ **Squared error and spectral signal are forced to be positive**
   • Spectral signal can be negative for low pass filters with complex poles

♦ **SLS AAC has been enabled for the boost phase of flight although plans exist to explore its extension through core stage flight**

♦ **The SLS FCS including AAC has been implemented in four main simulation tools:**

♦ **MAVERIC (Marshall Aerospace VEhicle Representation In C)**
  • MSFC developed 6-DOF time-domain simulation
  • Main ascent performance, guidance, navigation and control analysis tool

♦ **CLVTOPS (Crew Launch Vehicle Tree tOPology)**
  • Multi-body simulation built upon legacy TREETOPS tool
  • Employed for dispersed vehicle liftoff and staging separation clearance analysis

♦ **SAVANT (Stability Aerospace Vehicle ANalysis Tool)**
  • Simulink-based Verification and Validation Tool for SLS

♦ **STARS (Space Transportation Analysis and Research Simulation)**
  • NASA Langley developed, main simulation for Ares I-X
  • Simulink-based Verification and Validation Tool for SLS

♦ **Results using MAVERIC tool are shown in the following slides**
  • Stressing case demonstrating objectives 1 and 2
  • Stressing case demonstrating objectives 1 and 3
 • PDR Monte Carlo Analysis results

♦ **Example case: increased aerodynamic instability, severe winds, and a single-engine dual actuator hardover occurring during maximum dynamic pressure**

♦ **Extreme scenario with AAC off results in a violation of the rigid body load indicator (dynamic-pressure * total angle of attack) limit**
  • Plot terminates

♦ **AAC gains up the system at the onset of the disturbances**
  • Greatly improves attitude tracking
  • Load indicator stays well below limit
  • Control effort only temporarily saturates

♦ **AAC gain returns to nominal unity value after disturbances subside (objective 1)**
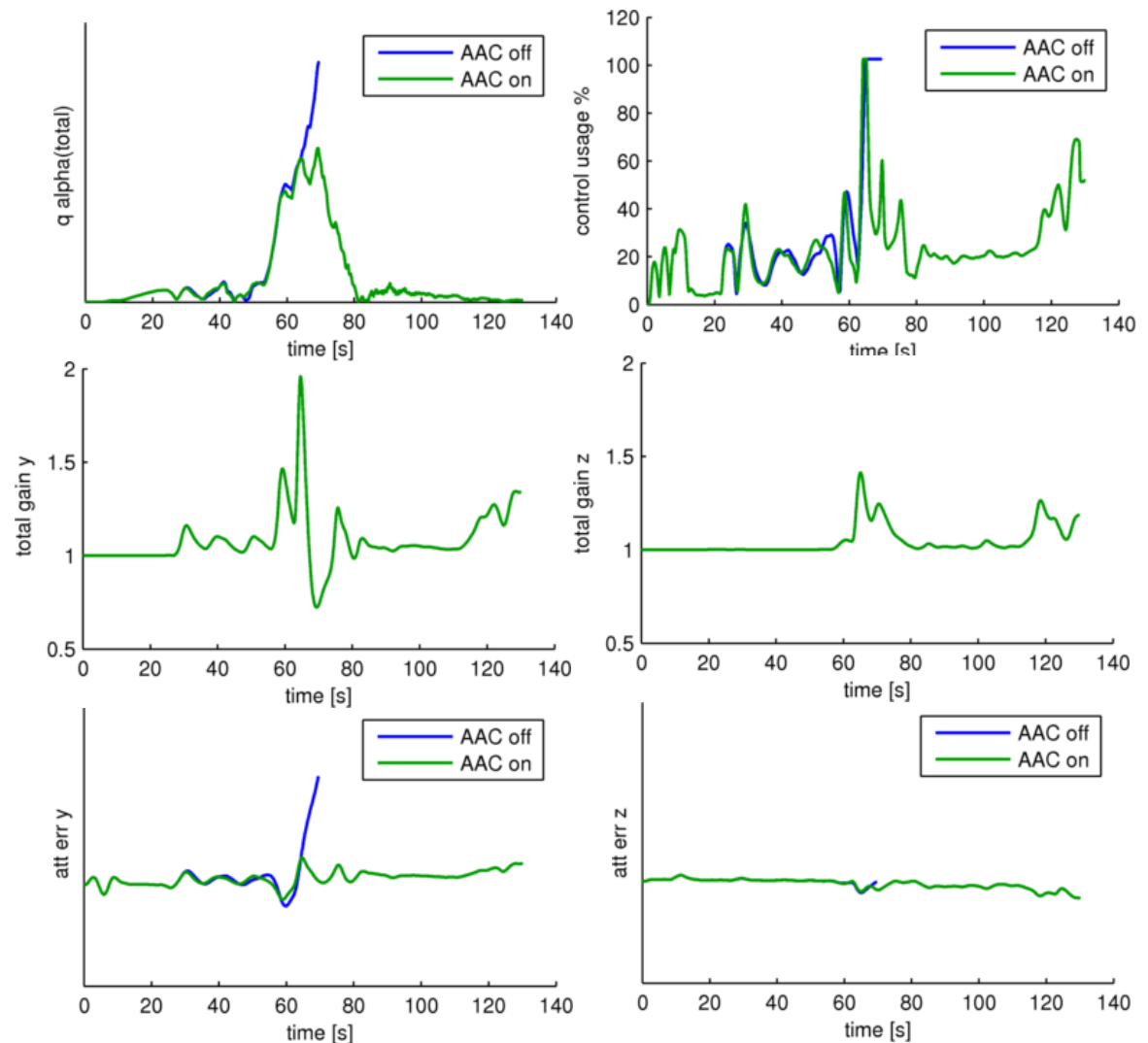
♦ **Example case: primary structural mode undergoes simulated instability during region of flight where gain of mode is higher than necessary attenuation provided by control filters**

♦ **Extreme scenario with AAC off results in divergent behavior in the actuator rates**

♦ **AAC gains down the system at the onset of the instability**

  • Suppresses modal response to a limit cycle of non-destructive magnitude

♦ **AAC gain returns to nominal unity value after instability ceases to persist (objective 1)**
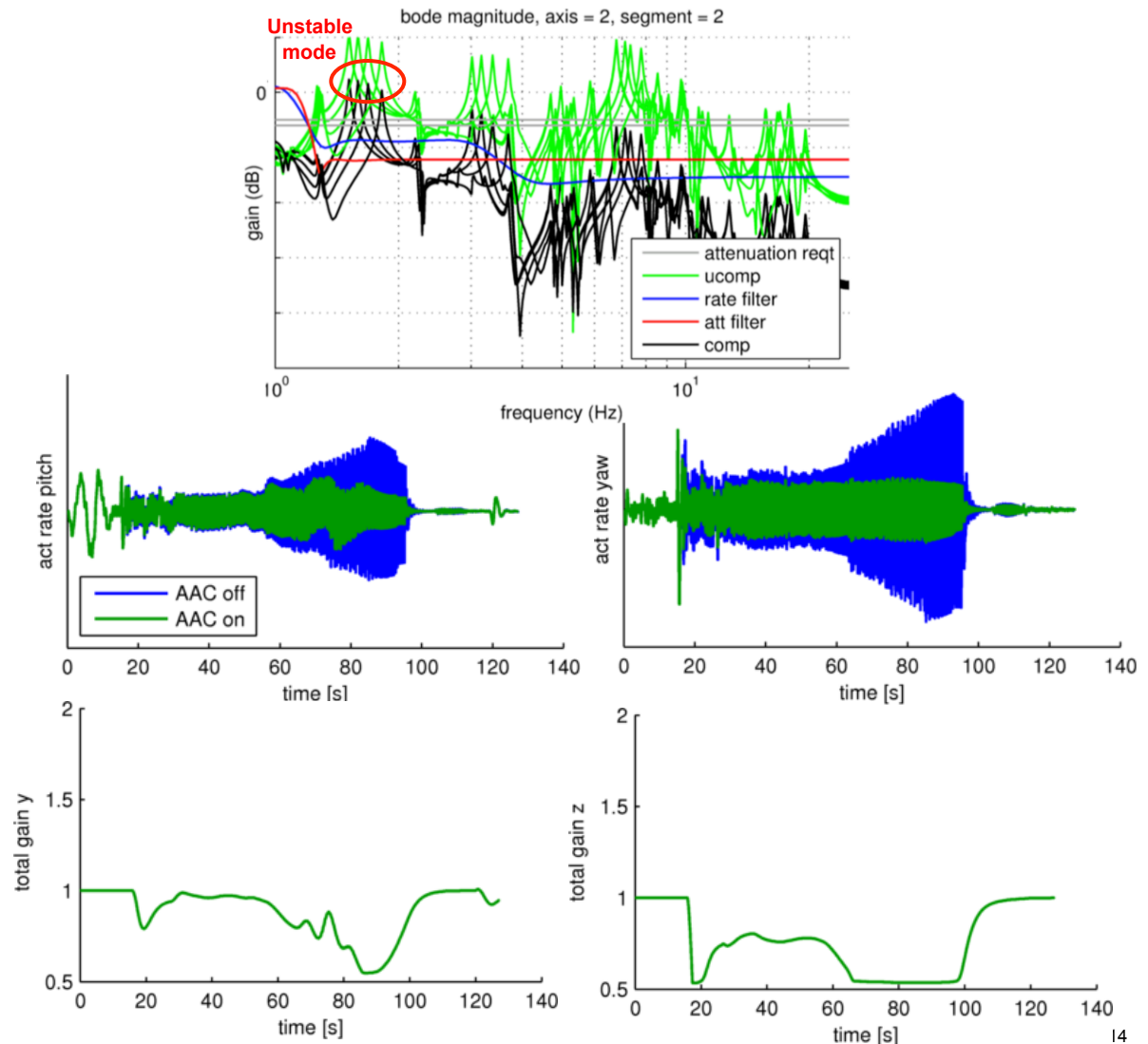
- ♦ **Example Monte Carlo simulation from liftoff to booster separation (2000 runs)**
- ♦ **Dispersions include but not limited to mass properties, structural dynamics, sensor noise, aerodynamics, winds, thrust misalignment**

- ♦ **Total gain in pitch shows minimal adaptation**
  - • Small deviation towards end of flight due to booster tailoff timing variations
- ♦ **Yaw shows adaptation in booster tail-off region**
  - • Corresponding to highly dispersed booster thrust imbalance
- ♦ **Roll shows the most adaptation**
  - • Large guidance commands, excursions due to high winds, booster tailoff, and conservative booster slag model
- ♦ **Overall, minimal effect on load indicators and control usage despite vehicle and environment design dispersions (objective 1)**
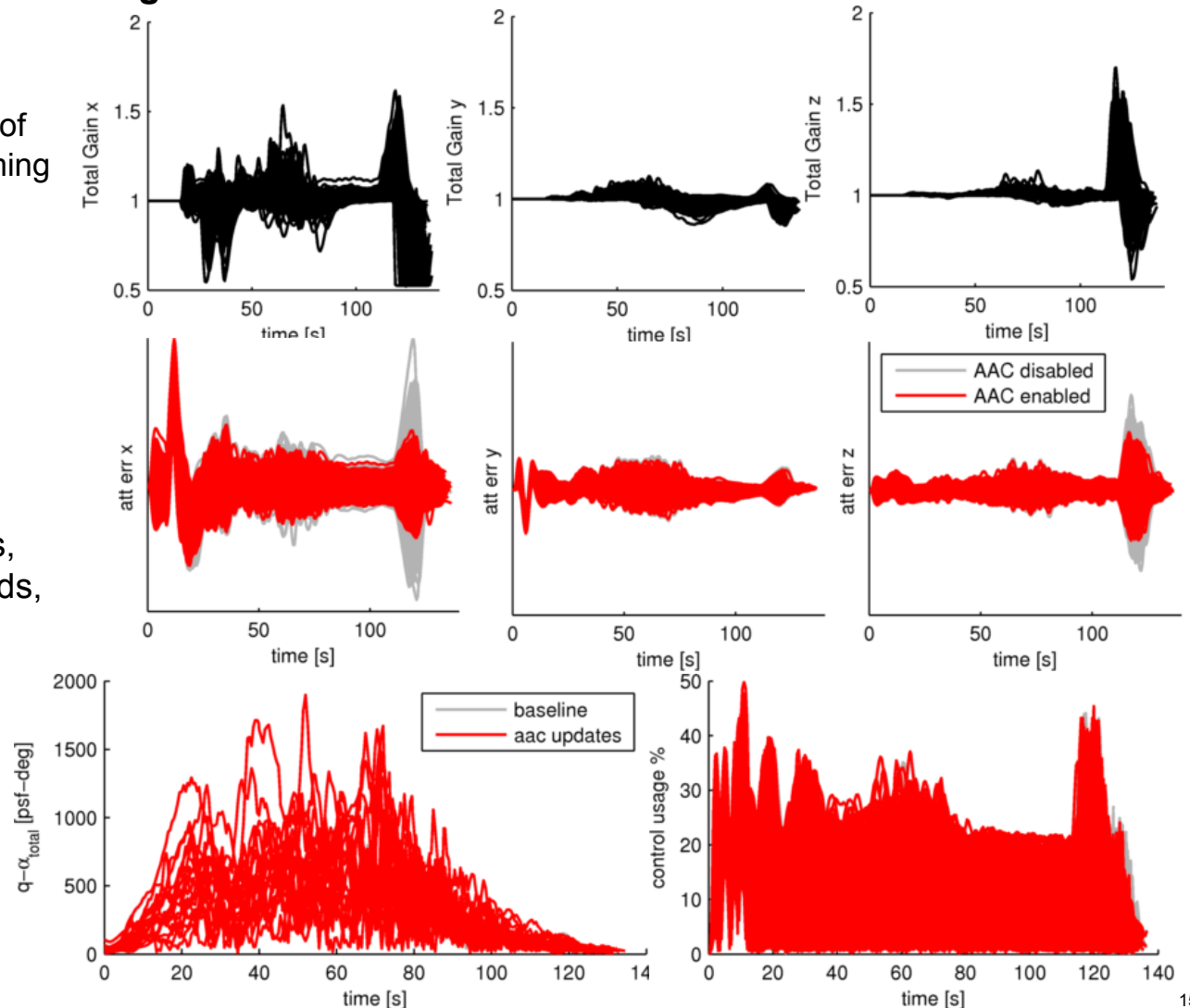
- [1] J. Orr, J. Wall, T. VanZwieten, and C. Hall, "Space Launch System Ascent Flight Control Design," in *AAS Guidance, Navigation, and Control Conference, Breckenridge, CO*, 2014.

- [2] J.Orr and T.VanZwieten, "Robust, Practical Adaptive Control for Launch Vehicles," in *AIAA Guidance, Navigation, and Control Conference, Minneapolis, MN, AIAA-2012-4549*, August 2012.

- [3] T. VanZwieten, E. Gilligan, J. Wall, and J. Orr, "Adaptive Augmenting Control Flight Characterization Experiment on an F/A-18," in *AAS Guidance, Navigation, and Control Conference, Breckenridge, CO*, 2014.

- [4] J. Orr, "Optimal Recursive Digital Filters for Active Bending Stabilization," in *AAS Guidance, Naviga- tion, and Control Conference, Breckenridge, CO*, 2013.

- [5] J. Hanson and C. Hall, "Learning About Ares I from Monte Carlo Simulation," in *AIAA Guidance, Navigation, and Control Conference, Honolulu, HI, AIAA-2008-6622*, 2008.