National Aeronautics and Space Administration

Airborne Simulation of Launch Vehicle Dynamics

2015 American Astronautical Society (AAS) Guidance, Navigation , and Control Conference

Breckenridge, CO Jan 30-Feb 4, 2015

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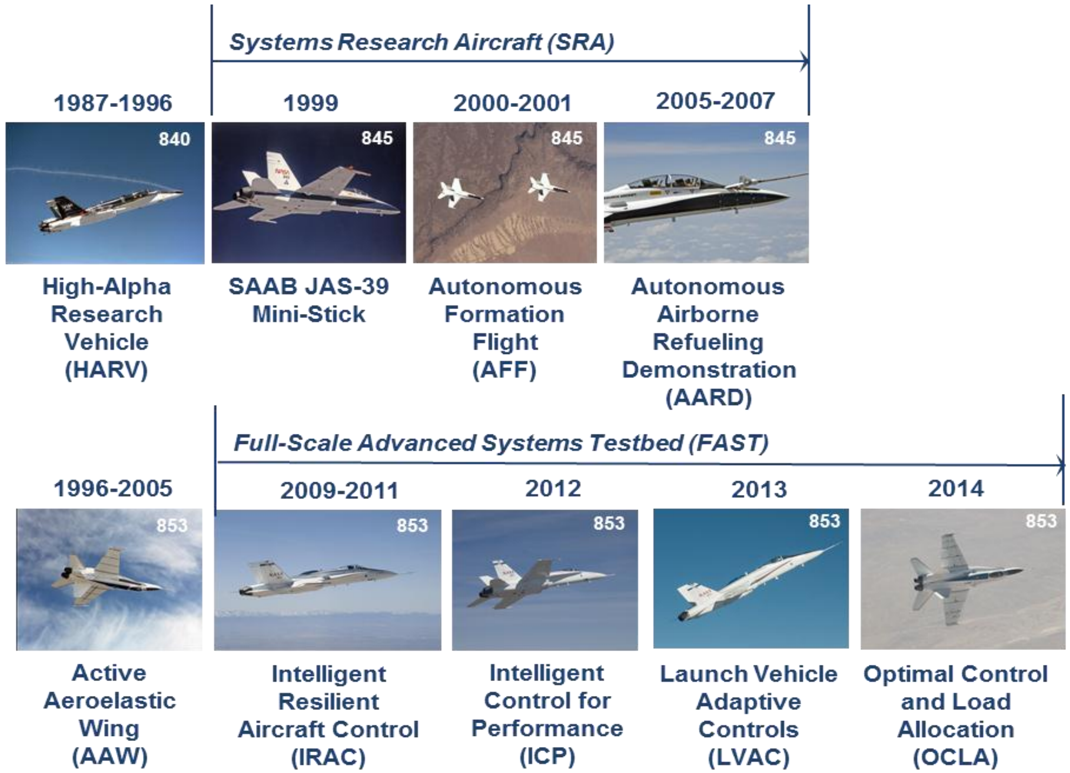
Motivation for Algorithm Flight Testing

- **Testing in a relevant environment critical for the maturation of any new technology prior to fielding in an operational environment**
  - Extensive simulation testing including Monte Carlo analysis
  - Subsystem and hardware in the loop testing
  - **Flight testing on surrogate platforms for risk reduction**
- **Advance the Technology Readiness Level (TRL) of the SLS Adaptive Augmenting Control (AAC) algorithm**
  - **The Adaptive Augmenting Controller (AAC) was the only part of SLS autopilot that had not been flight tested**
  - Flight testing increased internal and external confidence in AAC
  - Software V&V and flight certification of the full-scale algorithm
  - Characterize the algorithm on a flight test platform that is dynamically similar to the launch vehicle
  - Piloted flight test program
  - Flight Test objectives mirrored the design objectives in order to fully vet the algorithm
- **Aggressive Flight Schedule**
  - 24-Jan-2013: Project Start (AFRC-MSFC agreement signed)
  - 22-Aug-2013: Approval for First Flight
  - 12-Dec-2013: Flight Tests (6) Complete

Flight Control Research at AFRC Using the F/A-18 as a Testbed

- **Recent flight control research**
  - **Integrated Resilient Aircraft Control (IRAC)**
    - Evaluated simple adaptive control technologies (performance, VV&C, and pilot interactions)
  - **Intelligent Control for Performance (ICP)**
    - Explored intelligent control technologies for reducing fuel burn for aircraft in cruise
  - **Optimal Control and Load Allocation (OCLA)**
    - Utilized measured strain within an optimal control allocator
    - Actively limited sensed load while maintaining aircraft handling qualities and performance



Keys to Relevance and Value of Surrogate Testing

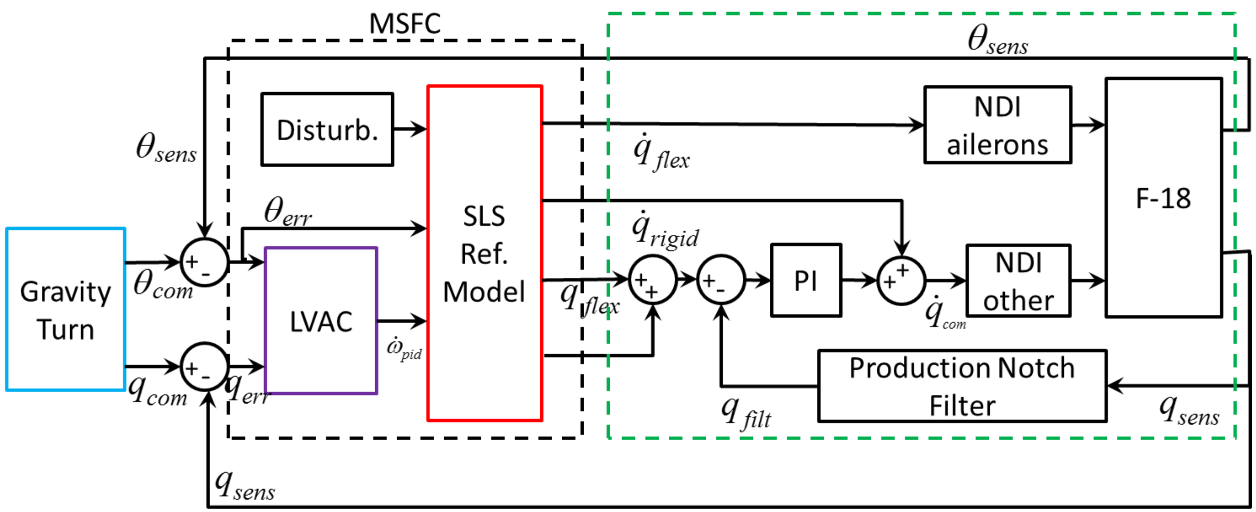
- Testbed is able to facilitate rapid prototyping on aggressive schedule
- Vehicle performance permits launch vehicle-like maneuver profile maximizing dynamic similarity
- Nonlinear dynamic inversion controller used to simulate SLS vehicle dynamic response with the aircraft rigid body dynamics
- Actual SLS autopilot flight software prototype hosted on the testbed flight control hardware
- Multiple test cases are mapped to each flight test objective allowing back to back performance comparisons
- Real structural mode at a relevant frequency that was able to be destabilized safely

Key Research Capabilities and Rapid Prototyping Features of FAST

- **Research Capabilities**
  - High performance tightly coupled research flight control computers
    - Quad redundant 68040 processors inside the production FCC's
      - Ada programmable
    - Dual redundant Power PCs linked via 1553 to the production FCC's
      - C Code, and Autocoded Simulink
  - The research systems have full authority over the vehicle control surfaces and throttle positions
  - Extensive research instrumentation system that an be easily expanded and utilized as feedback sensors for control laws
  - Experiments have the ability to provide basic pilot queuing via the ILS needles
- **Design Features that Enable Rapid prototyping**
  - Protected envelope
    - Allows for minimal testing prior to flight
    - Full envelope capability available with additional testing and verification for closed loop control experiments (Open loop experiments require no additional testing)
  - Robust production control laws, systems, and vehicle structure
  - Autocoding capability
  - High fidelity hardware-in-the-loop simulation with control room link for real-time mission rehearsals

Experiment Software Implementation

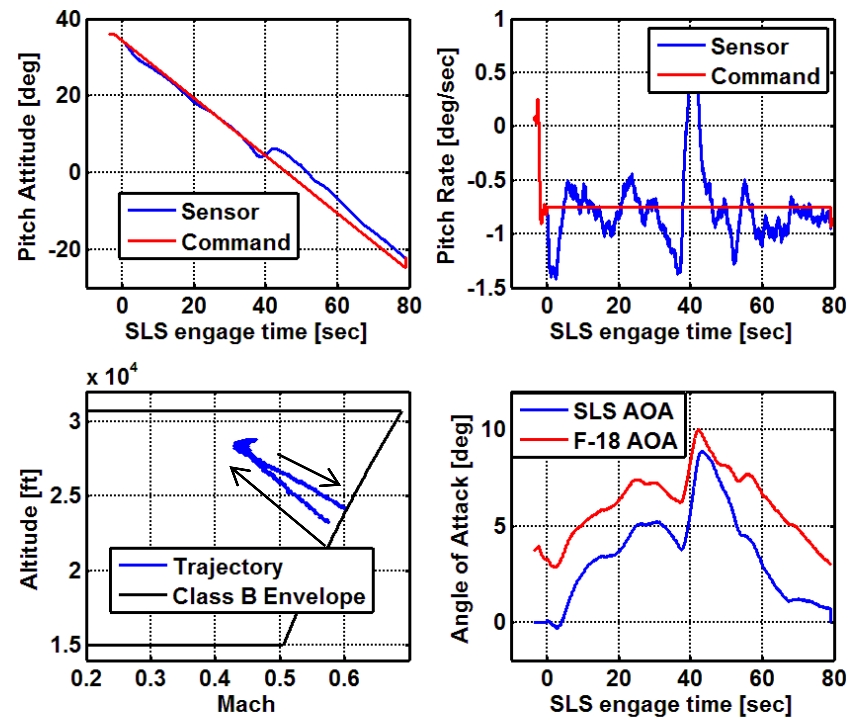
- **Guidance commands generated to perform a gravity-turn-like zoom-climb trajectory**
- **SLS autopilot generates actuator commands which are fed to the reference dynamics**
- **The outputs from the SLS reference dynamics are sent to the NDI as the desired F/A-18 rigid body dynamics**
  - Flex and rigid body dynamics tracked by separate sets of F/A-18 control surfaces
- **F/A-18 sensed dynamics fed back into the SLS production flight software prototype which tracks the gravity turn**



Dynamically Similar Trajectory

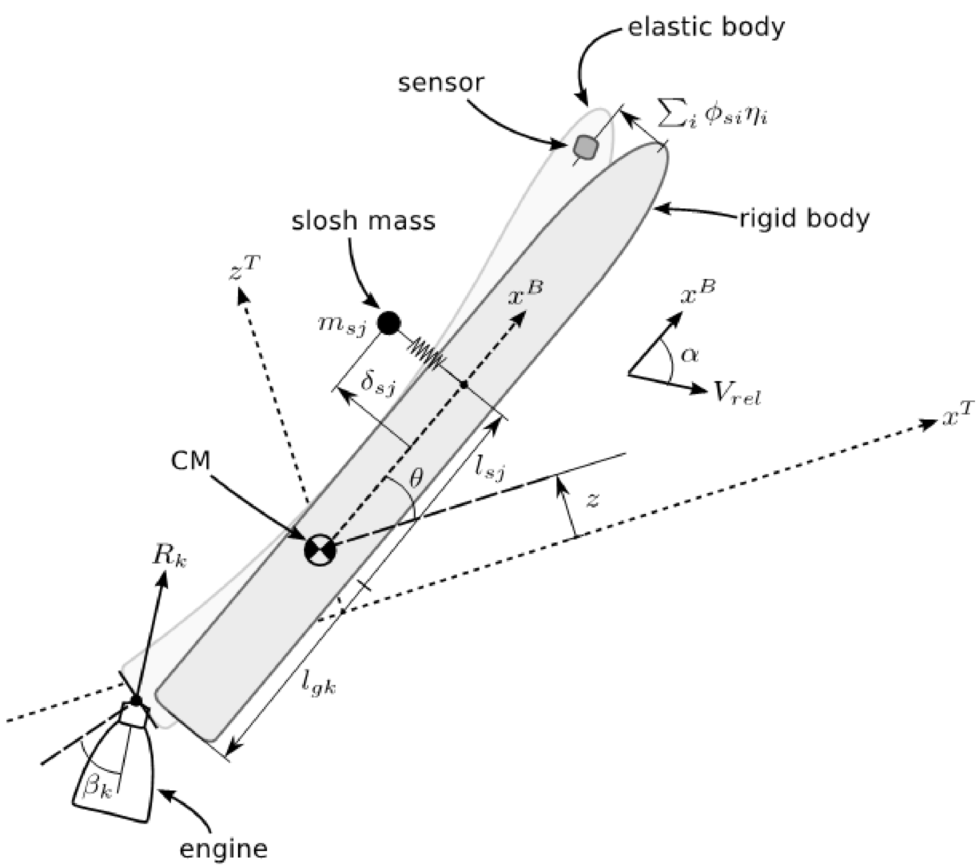
- **Trajectory Description**
  - Zoom climb followed by pitch over maneuver lasting ~75 seconds at a constant pitch rate of -0.75 deg/sec
- **Similarities to SLS boost trajectory**
  - Pitch axis dynamic response (Provided by NDI) including static instability
  - Attitude rate and pitch attitude command shape
  - Time scaling
- **Differences from SLS boost trajectory**
  - Actual vehicle Mach, altitude, and dynamic pressure profile
    - Simulated within the SLS reference model
  - Lift curve slope
    - angle of attack similarity achieved by NDI rigid body matching
  - Actual vehicle normal acceleration
    - Must disable load relief loop
- **Other Benefits of the platform**
  - Number of test points and total test time
  - Wide variety of failure/off nominal scenarios including the real F-18 fuselage mode
  - Pilot in the loop testing

Test Case 7 AAC on (Hardover, Wind Shear)



Reference Dynamics Simulated

- **Quasi-linear time varying perturbation dynamics**
  - Linearized with respect to an accelerating reference frame
- **Angle of attack approximated using measured attitude error and simulated normal velocity due to aircraft limitation**
- **Rigid body dynamics (pitch plane only), along with 6-10 bending modes, and two slosh degrees of freedom are modeled**
- **Nonlinear dynamics modeled for all 6 vectored engines**



Tracking Reference Dynamics

- **Conservation of angular momentum formulation**
- **Control surface aerodynamic effectiveness computed from flight verified look up tables**
  - Flex mode dynamics generated by symmetric aileron deflections
  - Rigid body dynamics generated by all other pitch surfaces
- **Proportional plus integral compensator in the loop to improve tracking and provide robustness**
- **Production notch filters preserved to prevent ASE**

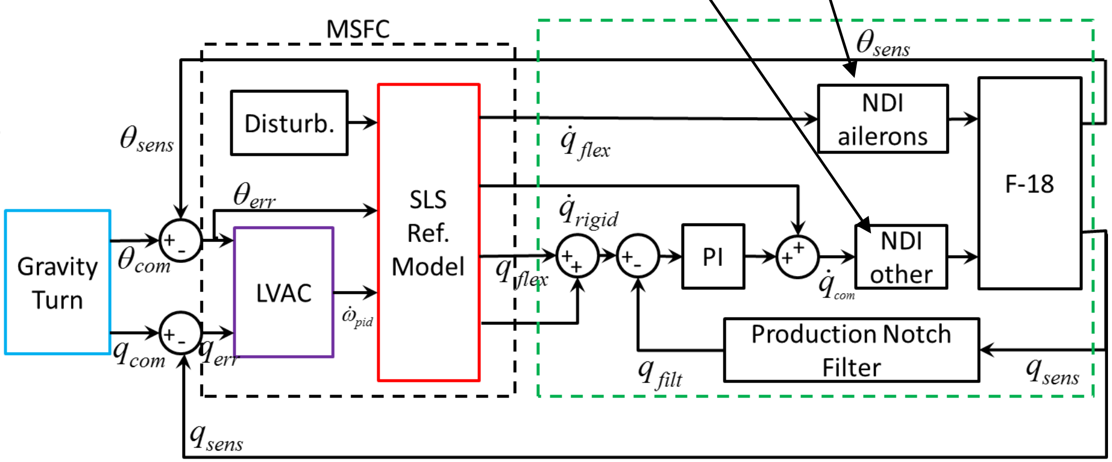
$$\mathbf{J}_a\dot{\omega}_c + \omega^{\times}\mathbf{J}_a\omega = q_i S\mathbf{A}\mathbf{x} + q_i S\mathbf{B}\mathbf{u}$$

$$\mathbf{J}_a\left(\begin{bmatrix}\dot{p}_c\\ \dot{q}_{cr}\\ \dot{r}_c\end{bmatrix} + \begin{bmatrix}0\\ \dot{q}_{cf}\\ 0\end{bmatrix}\right) + \omega^{\times}\mathbf{J}_a\omega = q_i S\mathbf{A}\mathbf{x} + q_i S\mathbf{B}_r\mathbf{u}_r + q_i S\mathbf{B}_f\mathbf{u}_f$$

$$\mathbf{u}_r = \mathbf{B}_r^{\dagger}\left\{\frac{1}{q_i S}\left(\mathbf{J}_a\begin{bmatrix}\dot{p}_c\\ \dot{q}_{cr}\\ \dot{r}_c\end{bmatrix} + \hat{\omega}^{\times}\mathbf{J}_a\hat{\omega}\right) - \mathbf{A}\hat{\mathbf{x}}\right\}$$

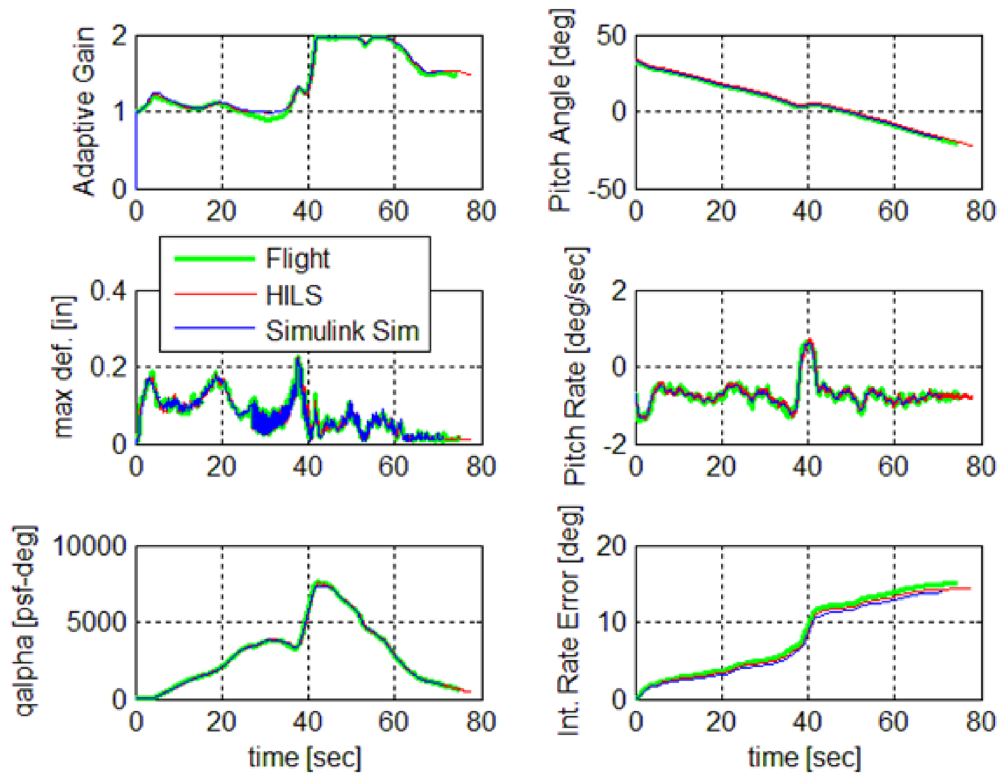
$$\mathbf{u}_f = \frac{1}{q_i S}\mathbf{B}_f^{\dagger}\mathbf{J}_a\begin{bmatrix}0\\ \dot{q}_{cf}\\ 0\end{bmatrix}$$

Reduces to 2nd order transfer function
Pitch rate from Ref. model -> Pitch rate sensed



"Low" Frequency Test Case Results

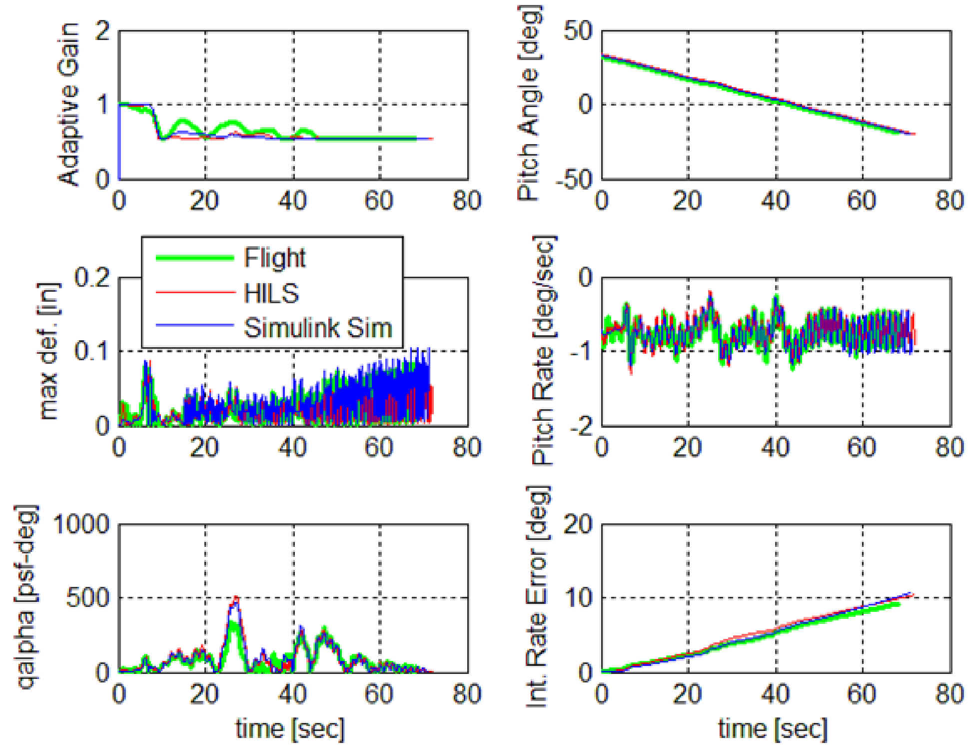
- Very good agreement in all three environments for nominal test cases and failure scenarios with low frequency or bias type properties such as:
    - Aerodynamic instabilities
    - Inertia property discrepancies
    - Actuator failure and wind shear scenarios
- NDI able to track the relevant reference dynamics such that even the integrated error over the entire trajectory is well predicted



Simulation-to-Flight Comparison with an Actuator Hardover

"High" Frequency Test Case Results

- **Test cases with slosh and structural dynamics uncertainties more complex**
- **NDI tracks the magnitude and shape of the dynamics very well**
  - Some small phase response differences uncovered upon close inspection
- **Resulted in oscillatory behavior on adaptive gain**
  - Revealed a adaptive controller phasing sensitivity
  - Further analysis and additional simulator testing of similar test cases at MSFC resulted in a small design change for AAC on SLS



Comparison with a Simulated Slosh Instability

LVAC Key Outcomes

- **AAC as applied to the SLS provides significant benefit and all of the design objectives were demonstrated in flight:**
  - Minimal Adaptation in the Nominal Case, Improved Tracking Performance, Restrict Parasitic Dynamics
- **Benefits of the rigor of software development for flight**
  - A number of software bugs in the SLS code were uncovered because the team refused to ignore seemingly insignificant anomalies
- **Benefits of testing on a platform with the right balance of similarities and differences**
  - The response of the controller to non-zero initial body rates was improved as a result of a small initialization shortcoming discovered due to the nature of the test points on the F-18
  - Bugs in filter initialization were discovered due to the back to back repeat of test points
  - Limitations in the performance of the algorithm for well damped poorly attenuated modes was uncovered (not something that requires addressing for SLS)
- **Findings related to interactions between the pilot and the adaptive controller**
  - AAC and the piloted mode as implemented for this test complement one another for failures that require a gain reduction
  - For failures where pilot effectively wants to increase tracking performance (increase gain) the AAC algorithm erroneously interprets the pilot’s aggressiveness as a parasitic mode and in effect fights the pilot by reducing the gain (PIO)
- **Preliminary generic finding for other applications of the adaptive architecture**
  - Delay in the rectifier drives a gain oscillation due to a delay in the spectral damper term for modes with relatively good damping but poor attenuation, which can be compounded by the design of the shape of adaptation rates at the edges and the trade between the leakage term and the other objectives

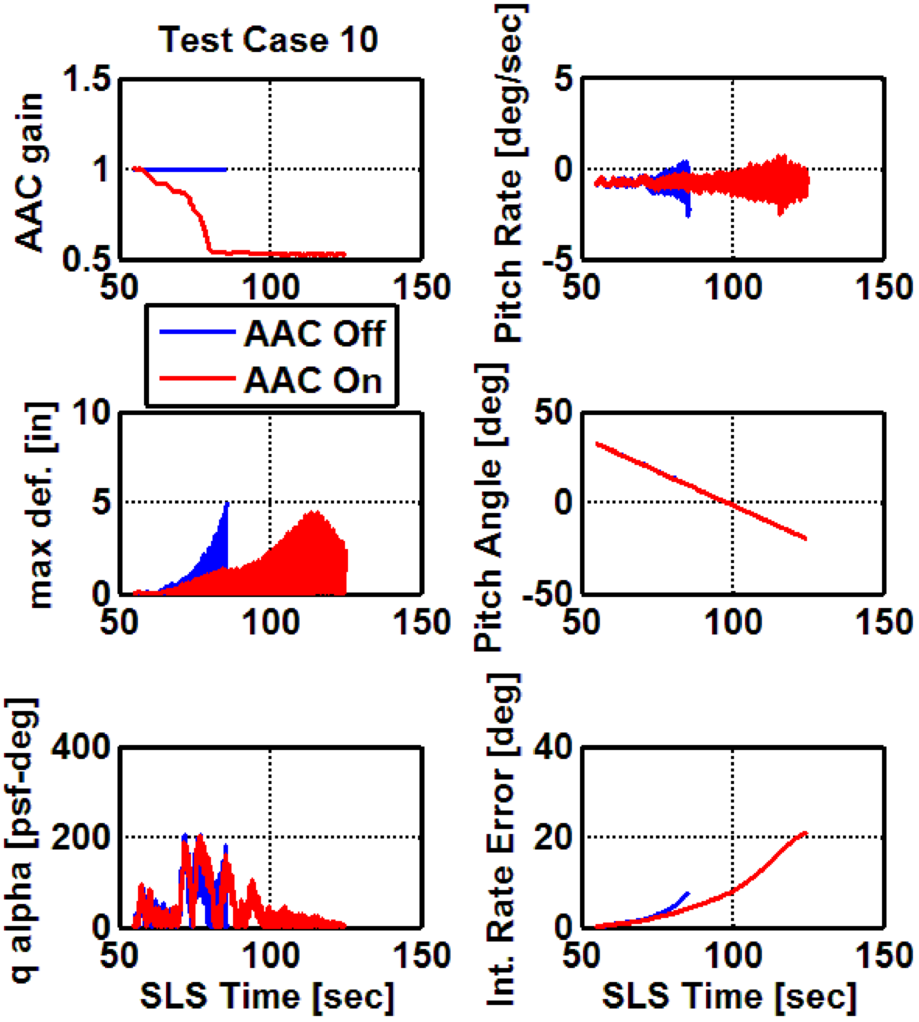
Concluding Remarks and Acknowledgments

- **This flight experiment has shown that a high performance fighter aircraft on an aggressive trajectory can simulate a dynamic environment similar to that of a launch vehicle during a boost trajectory.**
- **This successful flight-test campaign demonstrated the use of a surrogate aircraft to simulate the dynamics of an orbital launch vehicle for the purposes of flight software and algorithm characterization, evaluation, and test.**
  - The test data continue to be used by the SLS flight control design team to tune algorithm parameters and enhance the robustness of the design.
- **The experiment illustrated that with careful evaluation of the goals and objectives of a test, an aircraft can represent a low-cost option for the maturation of launch vehicle software**
  - By pairing mature test assets with innovative technologies, valuable insight can be gained about a technology with minimum risk, on an aggressive schedule.
- **A coordinated investment in these test environments is necessary to accomplish the bold and inspiring goals of NASA's Agency-level mission.**
- **Multi-Center, Multi-Organization Partnership**
  - Armstrong Flight Research Center
  - Marshall Space Flight Center including the SLS program
  - NASA Engineering and Safety Center (NESC)
  - STMD Game Changing Development, Autonomous Systems

Back-up

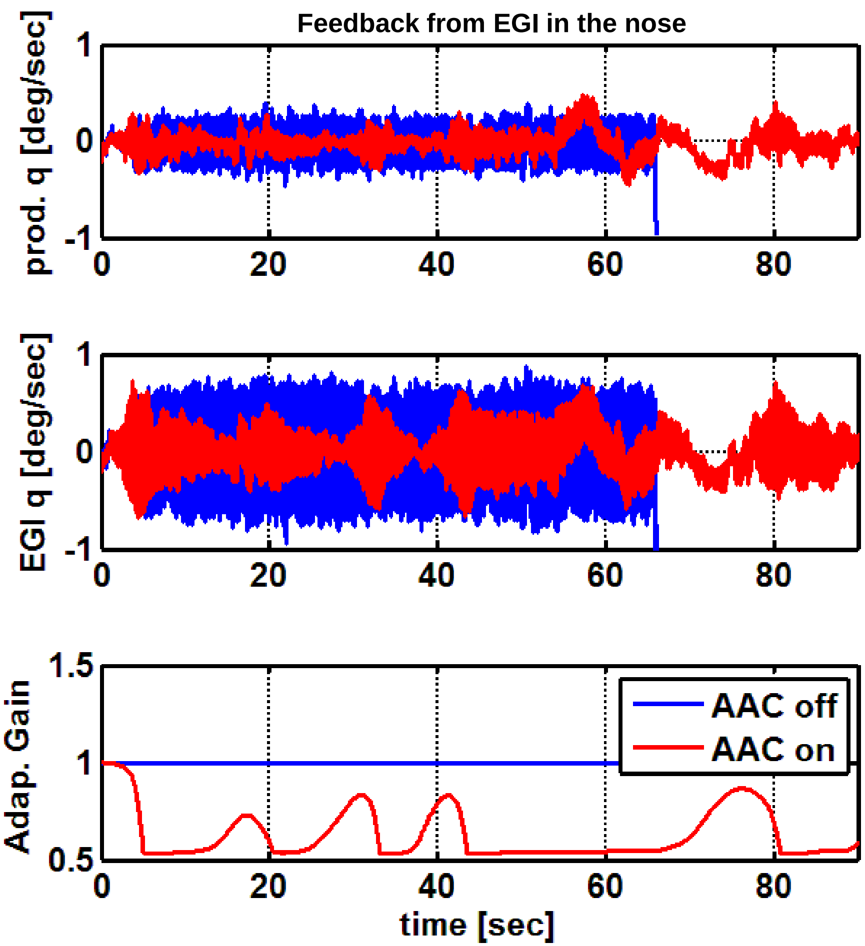
Restrict Parasitic Dynamics to a Bounded Non-Destructive Limit Cycle (Structural Mode)

- **Demonstrate Restriction of Unstable Parasitic Dynamics**
- **TC 10 – Structural Instability**
- **Successfully demonstrated the objective**
- **Anomalies**
  - Ailerons (used to simulate SLS structural mode) were more effective than predicted in the simulation
  - Resulted in a slightly more unstable mode than predicted
  - Did not affect the successful completion of test condition

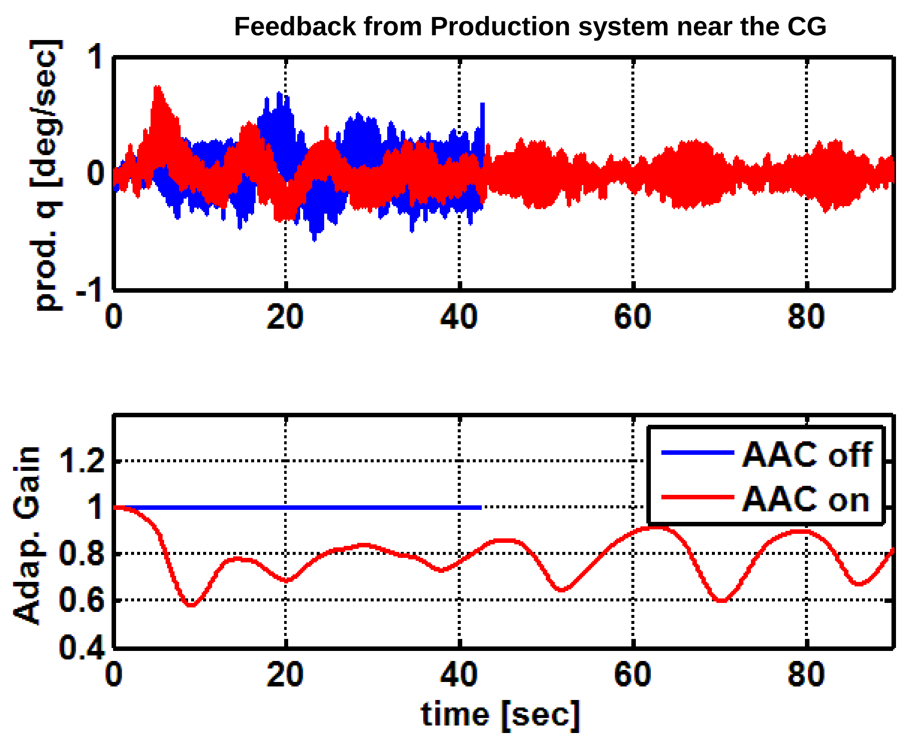


AAC Response to the Real F-18 Structural Mode

- Data from the first flight used to generate a test case that destabilized the SLS controller's response to the real F-18 first fuselage bending mode



- Multiple sensor locations and fuel loadings tested
- AAC was effective at attenuating the mode, but did exhibit an oscillatory behavior that allowed the mode to return
- Caused by overshoots of the ideal gain due to the lag in the spectral damper term exacerbated by an imbalance in the adaptive terms for a parasitic mode of this shape



Manual Steering Mode and AAC Interactions