Engine Yaw Augmentation for Hybrid-Wing-Body Aircraft via Optimal Control Allocation Techniques

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Motivation

- Environmentally Responsible Aviation project goal:
  - Improve noise and efficiency of future aircraft
- Hybrid-Wing-Body (HWB) aircraft have potential to reduce fuel burn and noise compared with current aircraft

- Due to lack of a large vertical tail with a large moment arm aft of the center of gravity, HWB aircraft tend to have reduced bare airframe yaw stability and control
  - Some aircraft augment with a closed-loop flight control system which uses split ailerons to create yaw moment with asymmetric drag

➢ Use asymmetric engine thrust to reduce control surface deflection

Prior Research

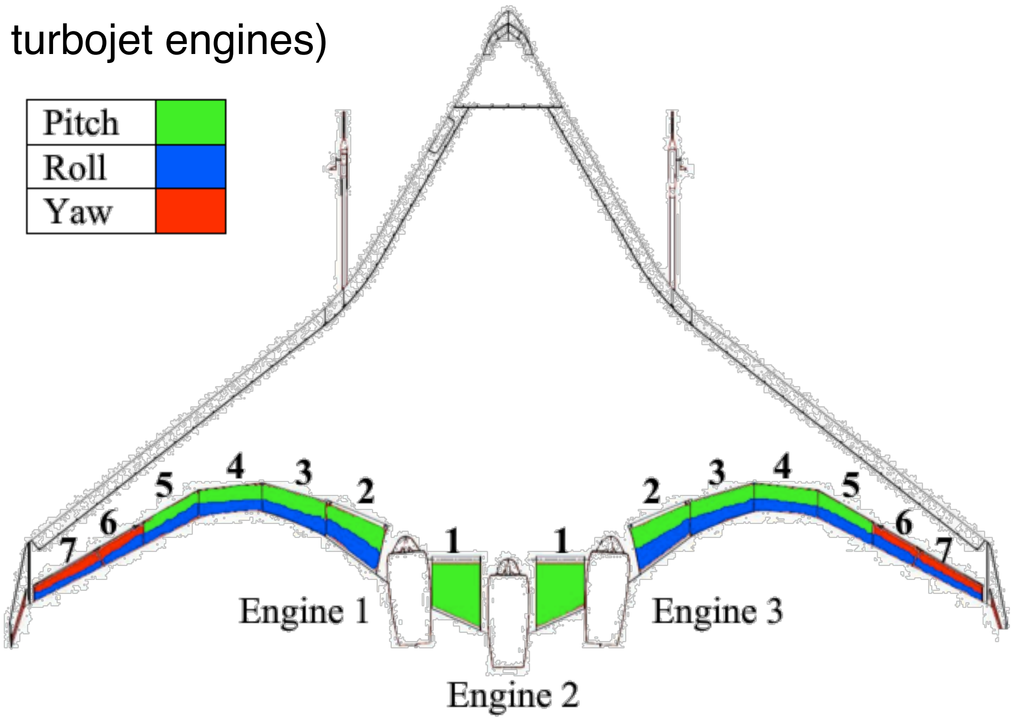
- Propulsion controlled aircraft research began following the complete loss of hydraulic power on United Airlines Flight 232
  - Pilots manually operated engines in order to control the aircraft and attempt a landing in Sioux City, Iowa
- Led to extensive research in the use of propulsion control to replace or augment the control authority of the baseline aircraft in the event of failures
- Research on thrust vectoring to reduce trim drag reductions on a NASA F-15 aircraft
  - 3.5% drag reduction for pitch thrust vectoring
  - 1.5% drag reduction for yaw thrust vectoring

➢ Controller to reduce surface activity during trim and low frequency inputs on HWB aircraft

➢ Implemented as an add-on to the baseline control laws

X-48B Background

- Research partnership of Boeing, NASA, and AFRL
  - Design and fabrication contracted to Cranfield Aerospace
- Airframe
  - Remotely piloted from ground control station
  - 8.5% dynamically scaled (rigid body)
    - Wingspan: 20.4 ft
    - Weight: 525 lbf
    - Thrust: 54 lbf each (3 JetCat turbojet engines)
  - Closed-loop flight control system
  - 20 control surfaces
    - 4 split ailerons
    - 2 winglet rudders

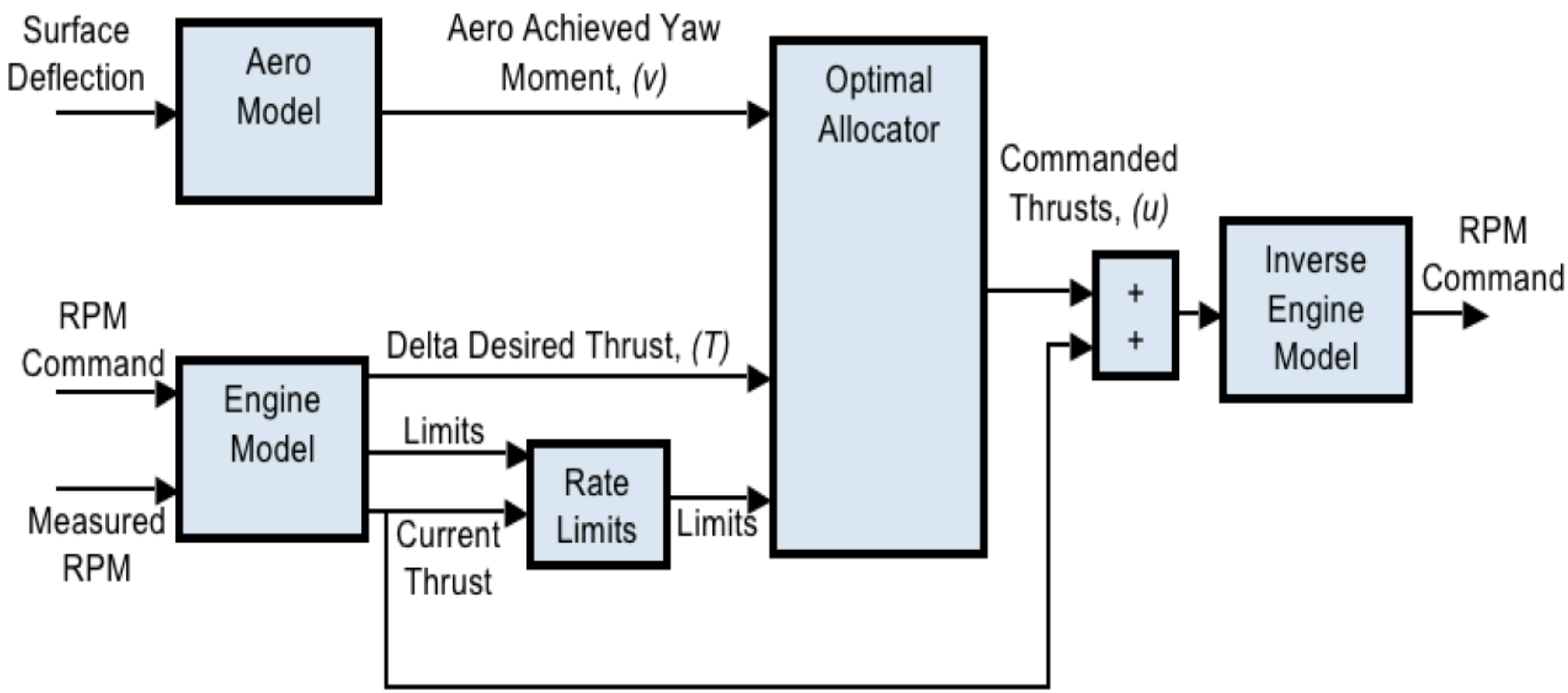


Approach

- Engine yaw control implemented as an add-on to the baseline control laws
  – Objective: to reduce the amount of control surface deflection while not degrading performance of baseline control laws
  – Baseline control laws have no “knowledge” of the add-on

- Optimal control allocation techniques used to determine the optimal thrust for each engine
  – Track the total thrust command from the power lever angles (PLA)
  – Generate yaw moment to drive the split ailerons to zero
  – Keep the individual engines as close to their individual PLA commands as possible

System Diagram



- Rate limiting:
  - +/- 3% of the total engine thrust
  - Step size 1% of the total engine thrust
  - 343 computations per frame

Optimal Allocator Objectives

- Optimal control allocation techniques used to determine the optimal thrust for each engine
  - Track the total thrust command from the power lever angles (PLA)
  - Generate yaw moment to drive the split ailerons to zero
  - Keep the individual engines as close to their individual PLA commands as possible

$$J = \underbrace{\left| \sum_{i=1}^{3} \left(T_i - u_i \right) \right|}_{\textbf{Total Thrust}} + \underbrace{\varepsilon \left| v - Bu \right|}_{\textbf{Yaw Moment}} + \underbrace{\gamma \sqrt{\left(T_1 - u_1 \right)^2 + \left(T_2 - u_2 \right)^2 + \left(T_3 - u_3 \right)^2}}_{\textbf{Individual PLA}}$$

Subject to: $u_{i_{\min}} \le u_i \le u_{i_{\max}}$

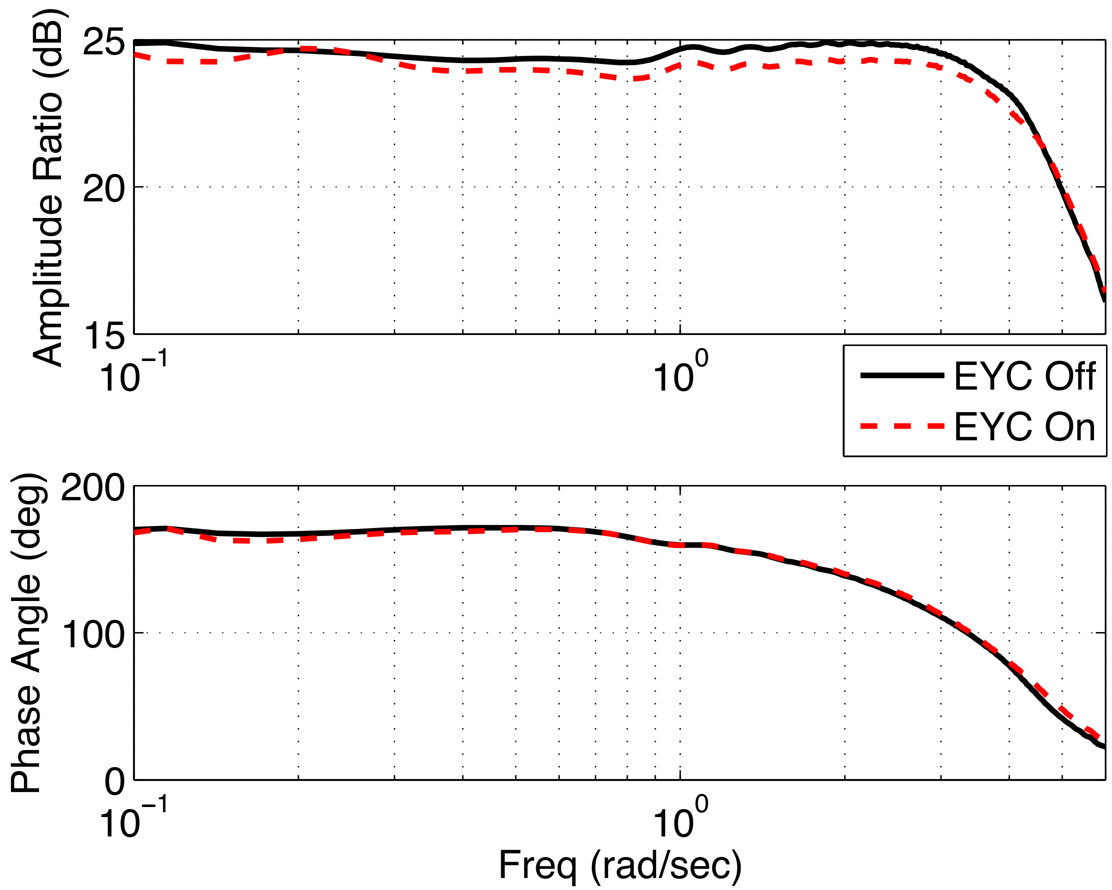
Implementation

- Implemented in X-48B non-linear simulation
  - Ensure engine yaw add-on did not degrade performance of baseline control laws
  - Measure the benefits of the engine yaw controller
  - Ensure engine yaw controller is robust to modeling errors and instrumentation noise

- Simulation tests:
  - Lateral-Directional frequency response
  - Benefits and performance around the attainable moment set boundary
  - Aerodynamic modeling errors
  - Instrumentation noise

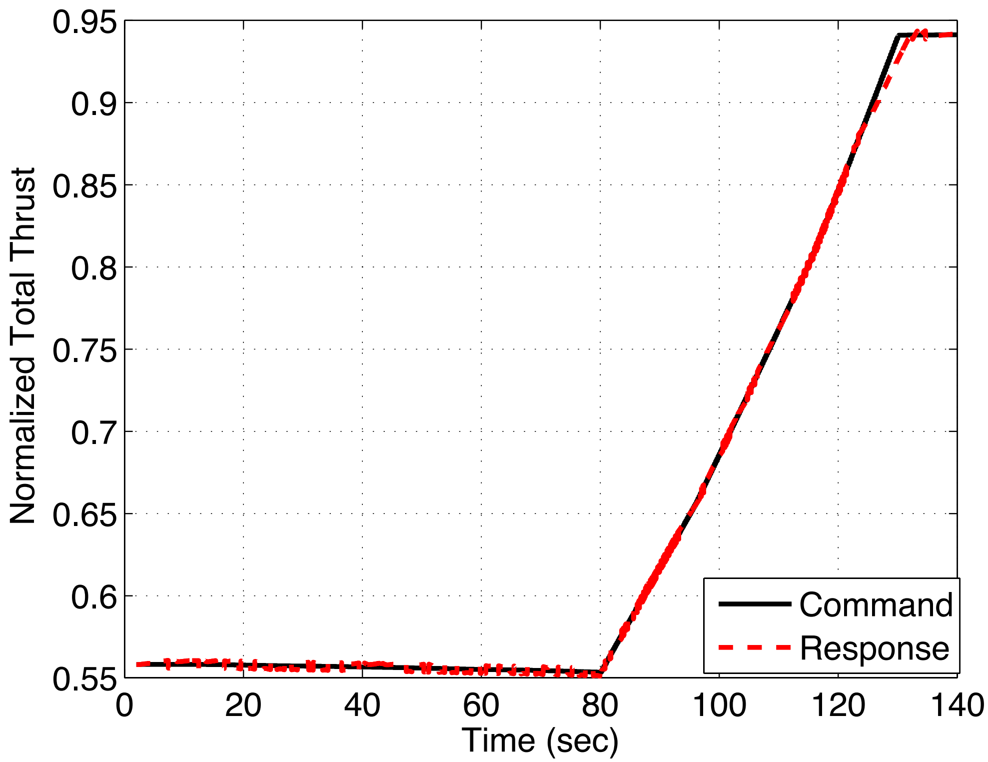
Frequency Response

- Frequency sweep of rudder to sideslip angle with engine add-on turned on and off
- Matches well below 6 rad/s
  - Engine response has 6 dB attenuation at 6 rad/s



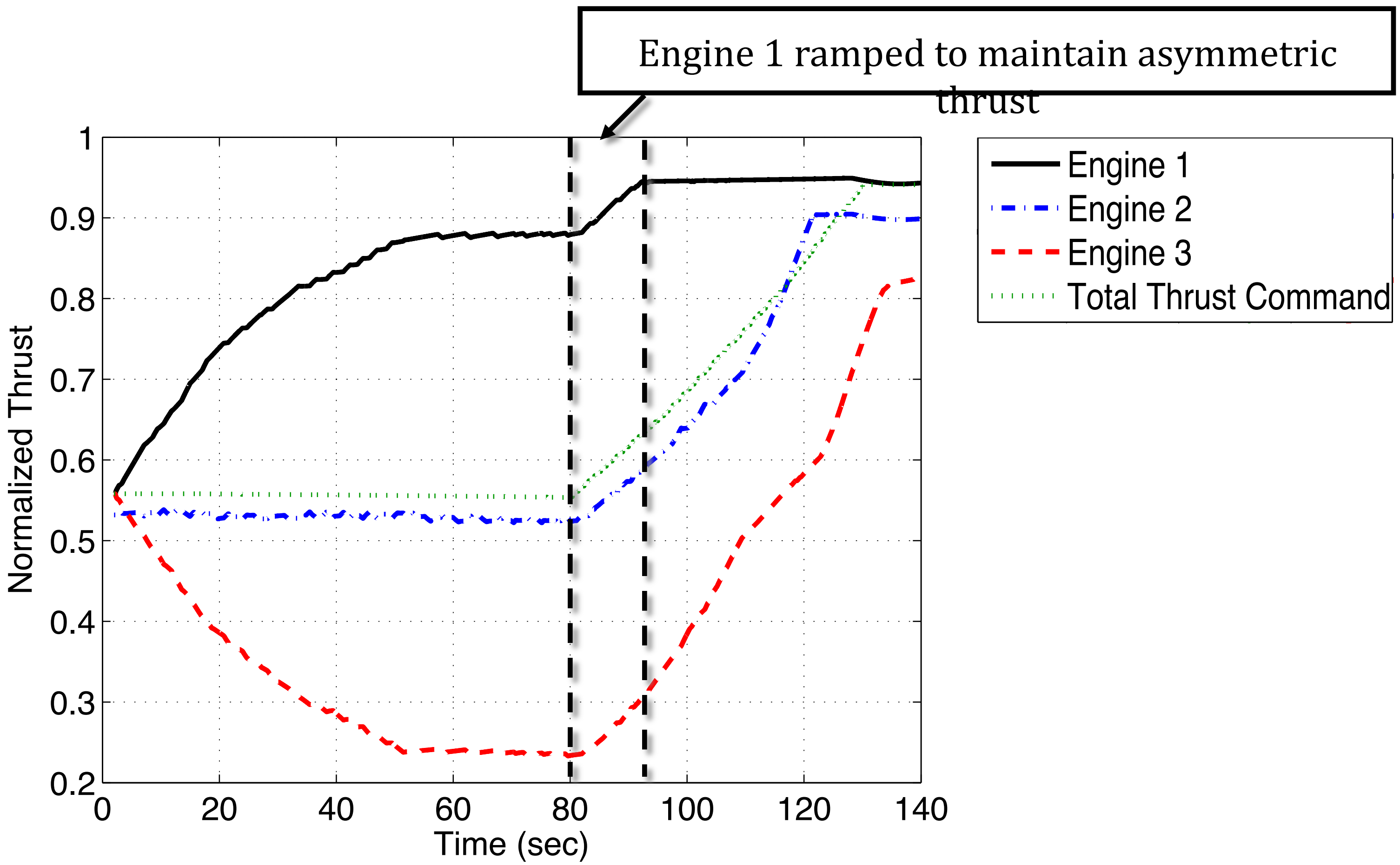
Attainable Moment Set Testing

- 2% rudder step
- PLA ramp at 80 seconds
- Total thrust tracked before and after the PLA ramp



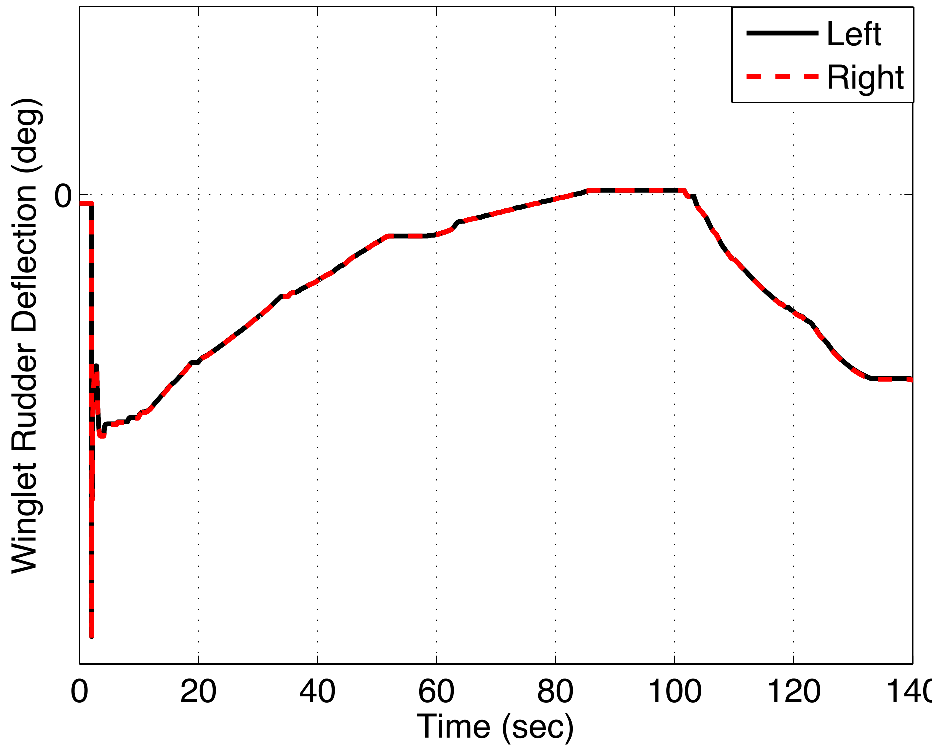
Attainable Moment Set Testing

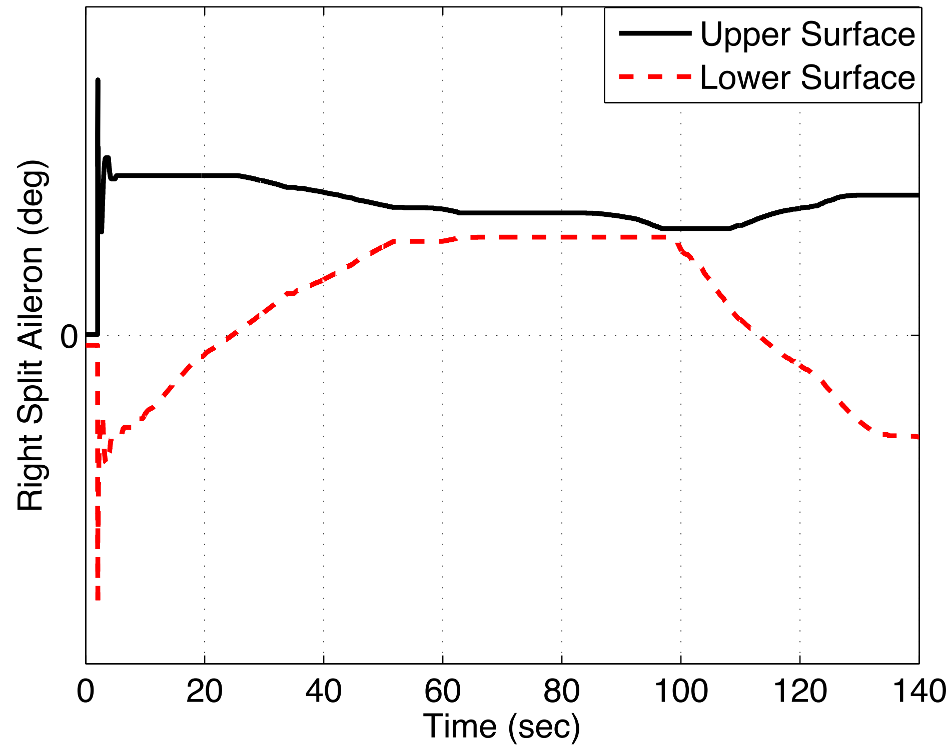
- Asymmetric thrust within attainable moment set
- Convergence time approximately 50 seconds



Attainable Moment Set Testing

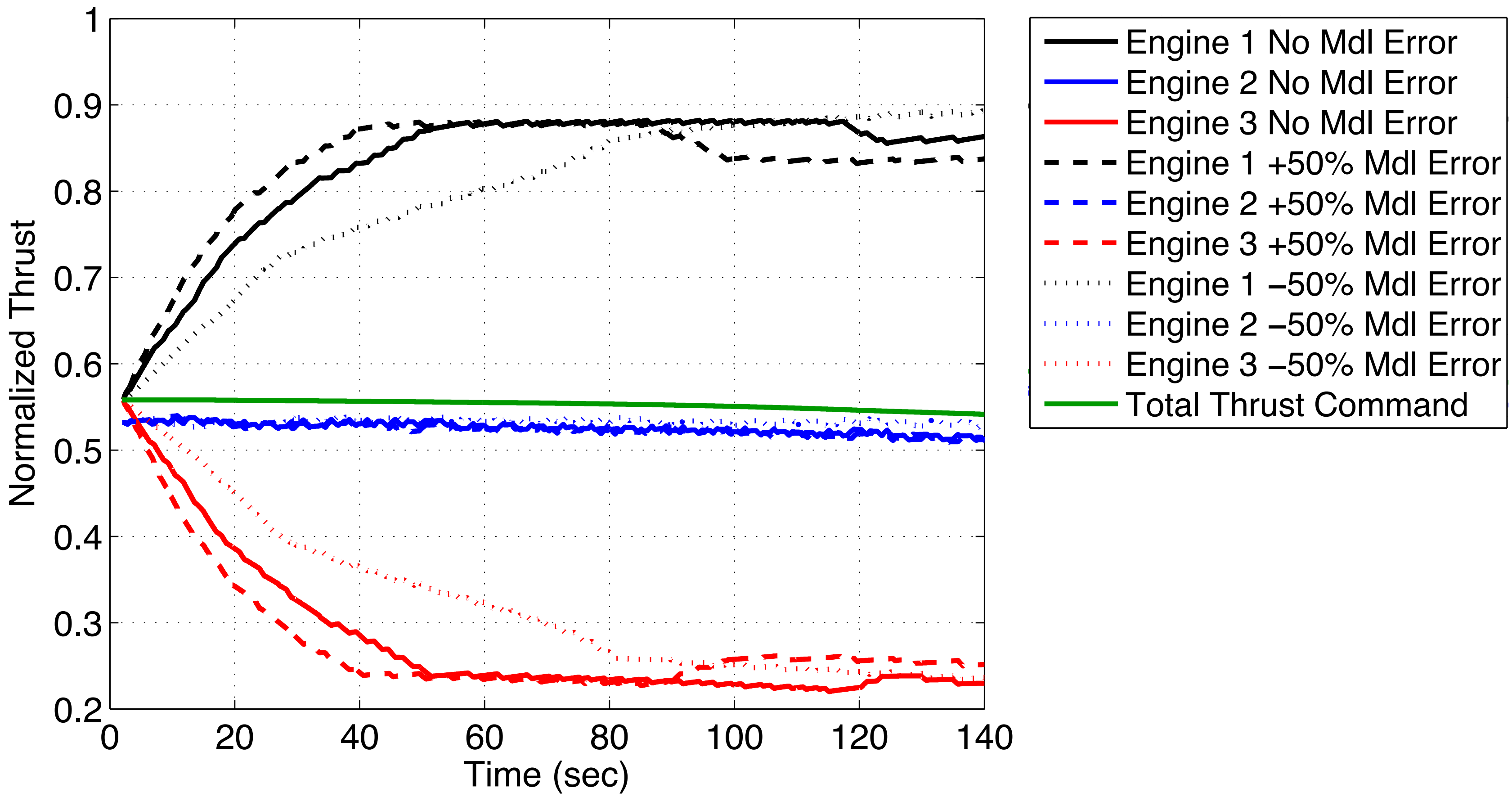
- Split aileron deflection is driven to zero
  - Due to baseline control laws, winglet rudder deflection is also driven to zero
- As the asymmetric thrust is reduced to track total thrust, surface deflection is increased to meet the yaw command





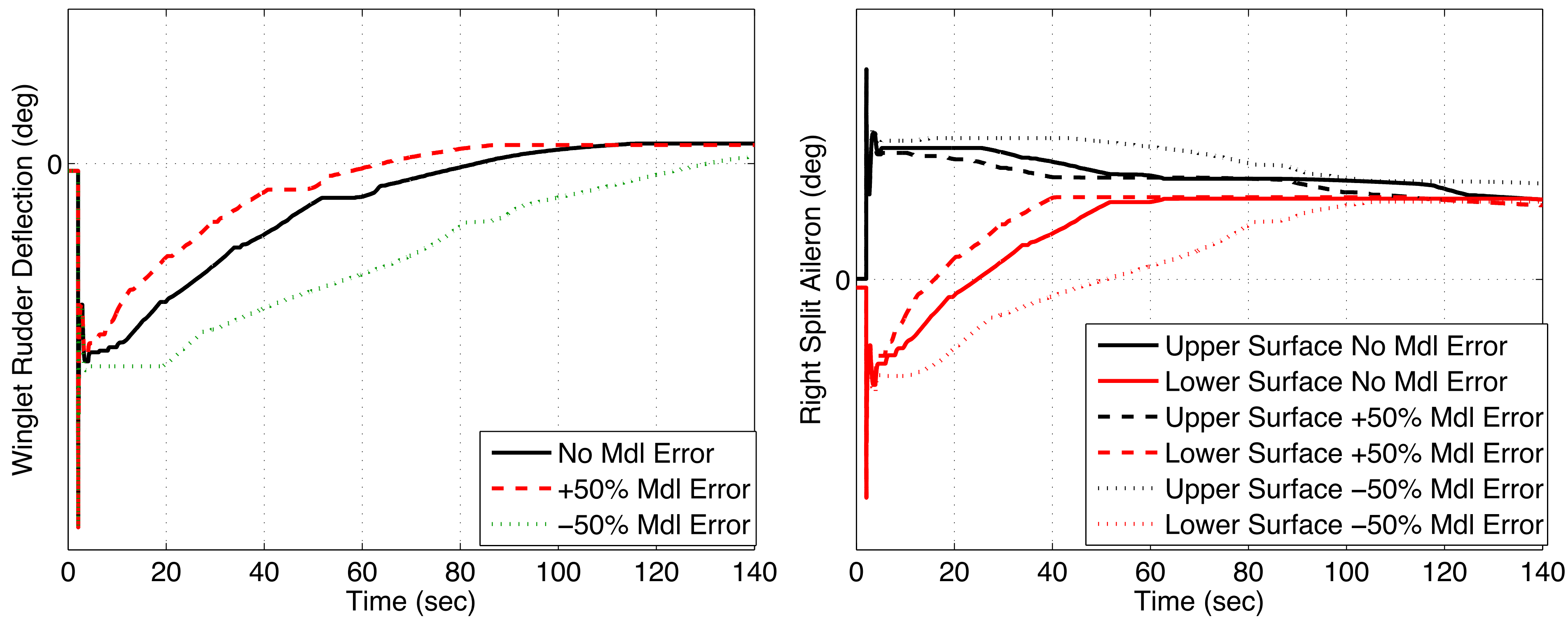
Aerodynamic Modeling Errors

- 2% rudder step and +/-50% error used on the aerodynamic model affecting the aero achieved yawing moment
- Convergence times change with error, but similar steady state is reached



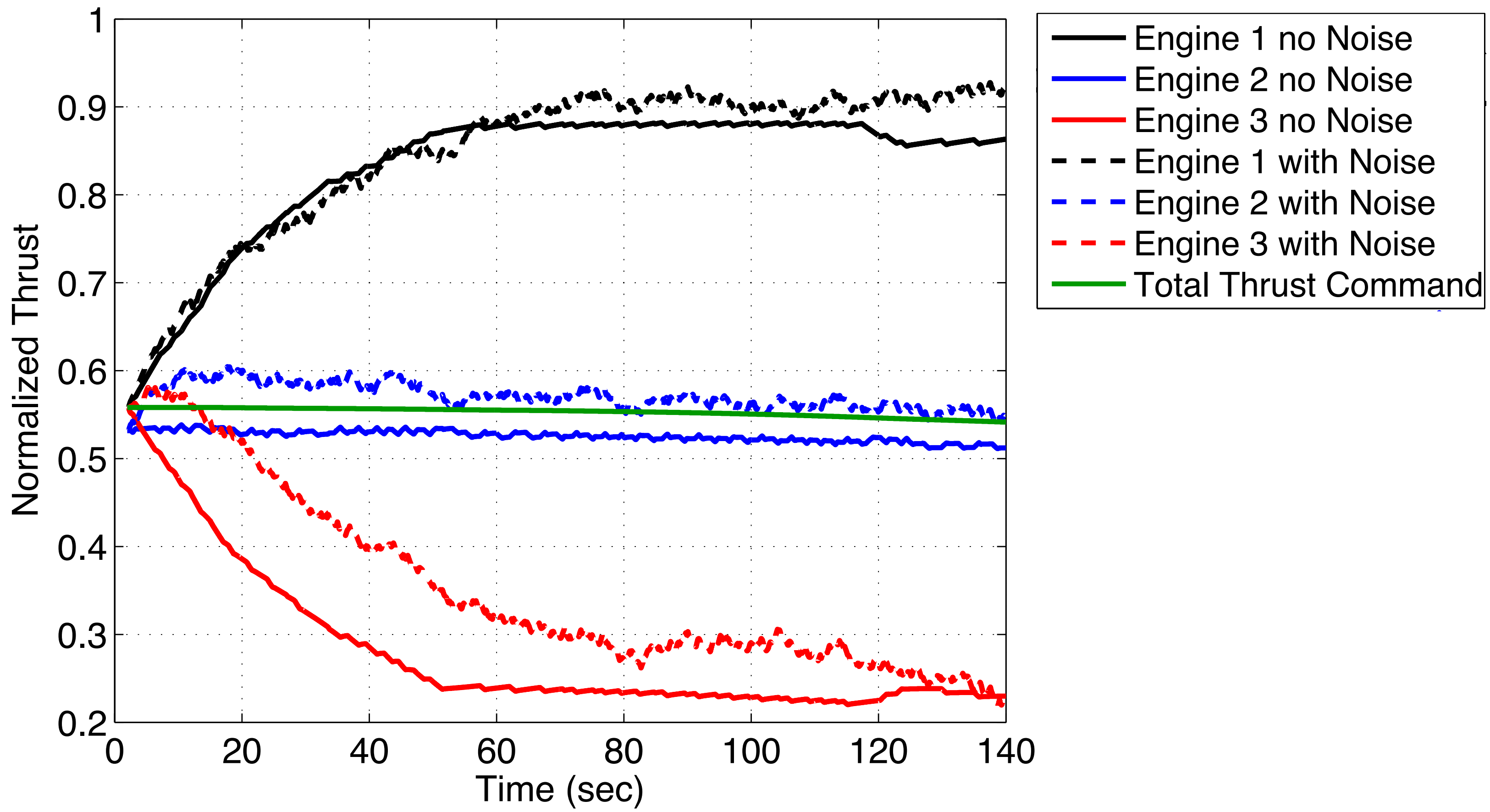
Aerodynamic Modeling Errors

- Split ailerons are still driven to zero deflection
- Convergence time is about 10 sec shorter for +50% error and approximately 30 sec longer for -50% error compared to nominal



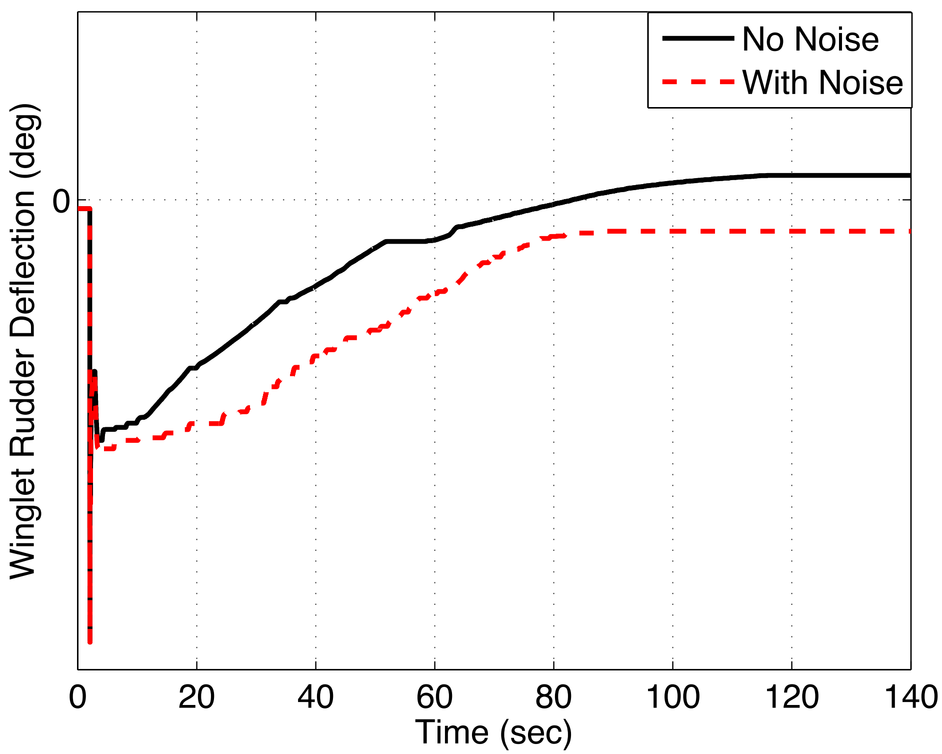
Instrumentation Noise

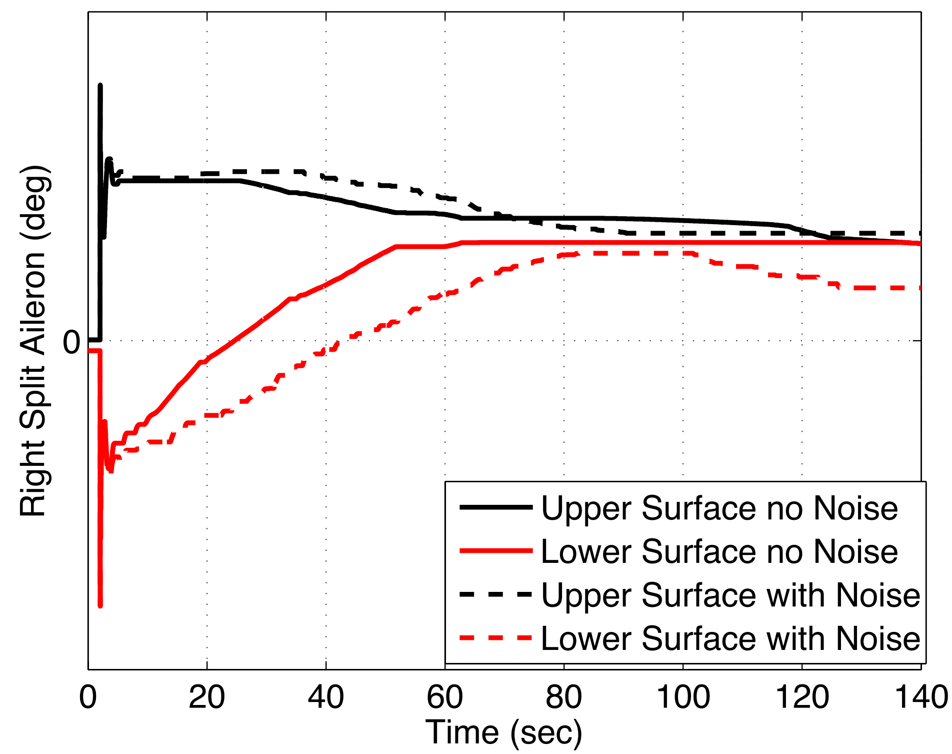
- Noise added to measured RPM signals equal to 5% of the maximum
- Low pass filters (0.5 rad/s) on all of the signals from the sensors
- Increased noise in the thrust commands, but similar steady state values



Instrumentation Noise

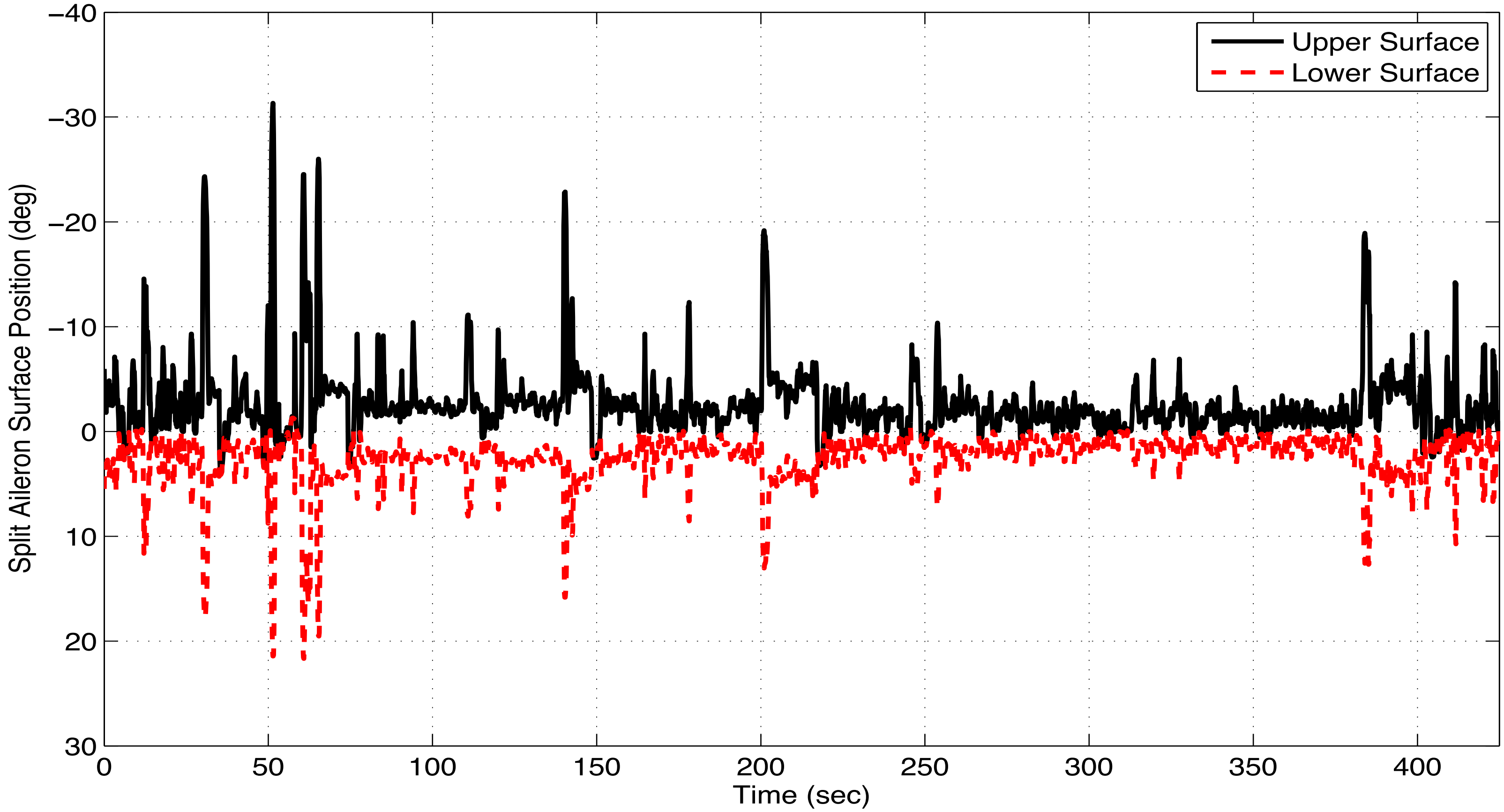
- Convergence time is approximately 25 seconds slower with noise on the measured RPM signals
- Right split aileron is still driven to zero deflection





Drag Reduction

- Potential to reduce drag by 2 – 4% depending on flight condition
- Estimated from the maximum yaw capability of the engine add-on and the amount of split aileron required to create the same moment
- 2.8% drag reduction for this case seen in flight:

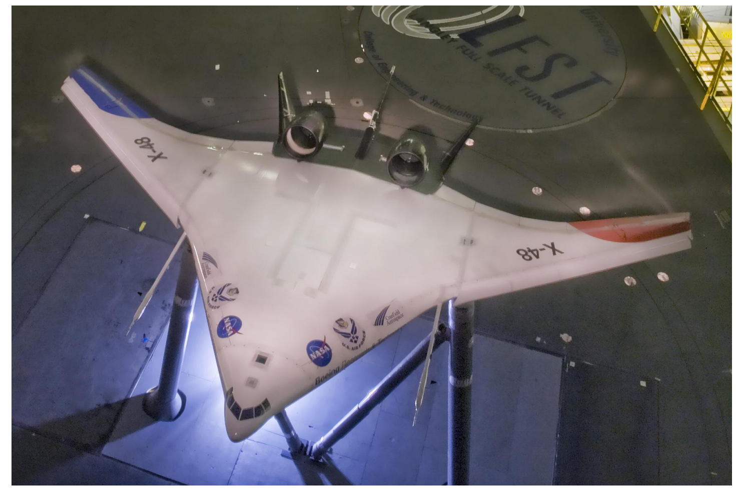


Design Considerations

- Potential drag reduction from engine yaw add-on
- Operates engines off-nominal condition which may increase the amount of fuel used even though drag is reduced
  - Application dependent
    - Amount of closed-loop yaw stability and control needed and the type of surfaces used
    - Thrust and location of engines
    - Specific fuel consumption for off-nominal operation
  - Can implement fuel flow as the second objective in the cost function instead of yaw moment to take into account the effect of operating engines off-nominal conditions
- Additional tool and trade-off for aircraft designers

Conclusions

- Add-on to baseline control laws
- Asymmetric engine thrust was used to reduce deployment of aerodynamic surfaces
  - Objectives:
    - Preserve baseline aircraft control characteristics
    - Reduce drag



- Optimal control allocation techniques:
  - Track total thrust command
  - Generate yaw moment to drive split ailerons to zero
  - Keep individual engines close to PLA
- Robust to aerodynamic modeling errors and RPM noise
  - Convergence time differences, but similar steady state
- Drag reduction of 2 – 4%
- Planned for flight research on X-48C in 2012

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