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
• **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

\[
J = \sum_{i=1}^{3} (T_i - u_i) + \epsilon \|v - Bu\| + \gamma \sqrt{(T_1 - u_1)^2 + (T_2 - u_2)^2 + (T_3 - u_3)^2}
\]

Subject to: \( u_{i_{\text{min}}} \leq u_i \leq u_{i_{\text{max}}} \)
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

![Amplitude Ratio and Phase Angle Graphs](image)
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

Engine 1 ramped to maintain asymmetric thrust
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:

![Graph showing time vs. split aileron surface position for upper and lower surfaces.](image-url)
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