Engine Controls for Emergency Aircraft Operation

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  – Pratt & Whitney
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  – U Conn

• Co-Authors
  – George Mink
  – Hoang Tran Van
  – Dr. Link Jaw
Agenda

Motivation
Control Law Development
  Actuation Options
  Emergency Control Modes
  Control Architectures
Results
  Actuation Effectiveness Study
  Fast Response Modes
  Emergency Scenario 2 Study
Summary
Motivation

Aviation Safety Program

Integrated Resilient Aircraft Control

Why Off Nominal Operation?

Loss of Control

United Flight 232 in Sioux City, IA
July 1989

112 Fatalities

American Flight 587 in Queens, NY
November 2001

265 Fatalities

Runway Incursion

USAir 1493 / SkyWest 5569 at LAX
February 1991

34 Fatalities

Comair Flight 5191 in Lexington, KY
August 2007

49 Fatalities

Air Transat 961 from Varadero, Cuba March 2005

What Can The Engines Do To Help?
Project Goal and Objectives

Aviation Safety Program  Integrated Resilient Aircraft Control

Fast-response Engine Research (FastER)

“Arrive at a set of validated multidisciplinary integrated engine control design tools and techniques for enabling safe flight in the presence of adverse aircraft conditions…”

• Improve Flight Safety and Survivability of Aircraft Under Abnormal or Emergency Conditions Such As Faults, Damage or Upsets

• Investigate and Design a Notional Fast-response Engine Controller:
  • Boost (Or Recover) Engine Capability by Relaxing Normal Physical and Operational Limits During an Emergency Until Aircraft Lands Safely
  • Enhanced Engine Capability Is Primarily Increased and Faster Thrust; Produced By Balancing Against Operating Margins and Remaining Life Of Critical Engine Components

Engine Challenges:
• Response Typically Slow as Compared to Aircraft Control Surfaces
• Thrust Levels Typically Limited to Meet Full-Life Specs
Ground Rules

Leading to Fast-response Engine Controller Design

Target Application:
• Generic High-Bypass Turbofan Engine
• Generic Commercial Transport Aircraft

For Research:
• Select and Focus On Two Specific Representative Scenarios
• Study Impact of Over-Thrust Operation on Engine Component Life
• Evaluate Impact of Fast Response on Engine Transient Stability
• Determine Means of Selectively Extending Engine Operation Limits
• Research Use of Traditional and Unconventional Control Modes
• Facilitate Development of New Strategies/Concepts By Other Researchers

Assume:
• No Damage to the Engine, But Do Consider Normal Degradation
• Adverse Condition Indicator Provided to Engine Controller
• Aircraft Scenarios Start from a Stabilized Condition – Don’t Worry About Recovery

Develop and Demonstrate a Notional Controller That Provides Increased and Faster Thrust During Emergency Operations
Requirements Definition

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Scenario 1: Takeoff Runway Incursion

Adverse Condition
Plane Crossing Runway During Takeoff Roll

Operating Conditions
Flight Conditions: 250 feet / 100 kts
Throttle Setting: Full Power

Pilot Action
Snap Full Throttle – Hard Pull Up

Derived Engine Requirements
- Increased Maximum Thrust
- Short Duration (< Minute)
- Ensure Engine Does Not Fail

Durability Analysis for Increased Thrust
Real-Time Trading of Part Life for Thrust
Requirements Definition

Integrated Resilient Aircraft Control

Scenario 2 Loss of Control – Rudder / Tail Failure

Adverse Condition
Sudden Loss of Rudder Control

Operating Conditions
Flight Conditions: 4500 feet / M=0.25
Throttle Setting: 6500 lbf Thrust
Start from Stabilized Condition

Pilot Action
Asymmetric Engine Thrust Modulation

Derived Engine Requirements
- Decrease Accel / Decel Times
- Maintain Adequate Margins / No Stall

Requirements
- Base Engine (τ) $\rightarrow \zeta = 0.2$
- Fast Engine (0.5 $\tau$) $\rightarrow \zeta = 0.3$
- Faster Engine (0.25 $\tau$) $\rightarrow \zeta = 0.4$

Operability Analysis for Fast Response
Real-Time Stability Audit
Three Phase Program Structure

Aviation Safety Program  Integrated Resilient Aircraft Control

Working in a Simulation Environment

Requirements
- Scenario Simulations
- Requirements Definition

Control Law Development
- Theories & Methods
- Available Engine Capabilities
- Simulation Evaluations
- Risk Trade-offs

Demonstration of Capability
- Integ. of Engine and A/C Models
- Integ. of Engine and A/C Controls
- Simulation Evaluations
Technical Challenges

- Establish the Baseline Engine Control System
- Flow down the aircraft, engine and control requirements
- Identify Engine Control System Actuation Options
  - Consider Both Existing and New Actuation Approaches
  - Rank Actuation Options Based on Effectiveness and Impact
- Develop Engine Control Modes for Emergency Maneuvers
  - Down select to Three High Potential Modes
- Design Control Laws for High Potential Emergency Control Modes
  - Use Both Classical and Modern Design Methods
  - Take Into Account Time/Event-Varying Constraints
  - Incorporate Risk Evaluation in Design
- Evaluate Designs Through Simulation
  - Evaluate rapid acceleration and fan bleed modes
  - Incorporate fan bleed in C-MAPSS40k – (Incorporated in C-MAPSS40k* Simulation)
  - Integrate C-MAPSS40k with the aircraft General Transport Model (GTM) – (C-MAPSS40k* integrated with scaled GTM)
  - Incorporate differential thrust - yaw control in GTM
  - Evaluate differential thrust control mode
- Develop control design methods that trade performance and risk metrics, while maintaining engine safety limits
Control Law Development

Potential Actuation Options
Compressor Example

<table>
<thead>
<tr>
<th>Existing Commercial Engine Actuation</th>
<th>Higher Resp Actuation (in Existing Package)</th>
<th>New or Advanced Actuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>CGV, RCVV, BV, ACC</td>
<td>ACC, ASC, Aspirated Tip, water injector, gas injector</td>
</tr>
<tr>
<td></td>
<td>CGV, RCVV, ABV, ACC</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>active clearance control</td>
</tr>
<tr>
<td>ABV</td>
<td>active bleed valve</td>
</tr>
<tr>
<td>ASC</td>
<td>active stall/surge control</td>
</tr>
<tr>
<td>BV</td>
<td>bleed valve</td>
</tr>
<tr>
<td>CGV</td>
<td>compressor guide vane</td>
</tr>
<tr>
<td>RCVV</td>
<td>rear compressor variable vane</td>
</tr>
</tbody>
</table>

Can our objectives be achieved without substantial, new actuator development?
## Control Law Development

### Aviation Safety Program  Integrated Resilient Aircraft Control

Potential Emergency Engine Control Modes

<table>
<thead>
<tr>
<th>Emergency Control Mode</th>
<th>Thrust Objective</th>
<th>Technology Challenge</th>
<th>Operability Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stall Margin Feedback</td>
<td>Response</td>
<td>Reliable Stall Margin Estimation</td>
<td>Compressor Stall/Surge</td>
</tr>
<tr>
<td>Variable Thrust Reverser</td>
<td>Response, Increased Delta</td>
<td>Reliable, low weight actuation</td>
<td>Weight, Complexity</td>
</tr>
<tr>
<td>Reduced Temperature Margin</td>
<td>Maximum</td>
<td>Improved turbine engine life estimation</td>
<td>Blade Melt, Disk Failure</td>
</tr>
<tr>
<td>High Speed Flight Idle</td>
<td>Response</td>
<td>Thrust &quot;dumping&quot;</td>
<td>Localized Overheating</td>
</tr>
<tr>
<td>Rotor Torque Augmentation</td>
<td>Response</td>
<td>Actuator and power source for additional engine rotor torque</td>
<td>Weight, Complexity</td>
</tr>
<tr>
<td>Improved BOM Modes</td>
<td>Response, Maximum</td>
<td>Higher Response versions of existing actuation</td>
<td>Heavier Actuation</td>
</tr>
</tbody>
</table>

### Risk Assessment

- **High**
- **Medium**
- **Low**
Fast Response Engine Control Architecture

Adaptive Flight Control

Thrust Target

Control Adapter

Selected Mode

Selected Actuators

Control Law

Actuators

Sensors

Engine or Simulator

Vehicle Risk Mgt.

Vehicle Health Mgt.

Eng. Risk Assessment

Health Assessment

Engine Control

Situational Risk Tolerance

EHM

EHM Sensors

Vehicle Risk Mgt.

Engine Risk Assessment

Health Assessment
Preliminary Results - Flight Idle
Preliminary Results-Flight Idle

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Graph showing the comparison of HPC Surge Margin and Fan Bleed between two scenarios (4a and 4b) over time.
Preliminary Results - Throttle Advance

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![Throttle Advance Graph](image)

- Baseline
- Schedule & Bleed
- Sched, Bld & VSV

**Thrust (lbf)**
- 0
- 10000
- 20000
- 30000
- 40000

**HPC Surge Margin (%)**
- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35
- 40
- 45
- 50

**Time (seconds)**
- 0
- 5
- 10
- 15
- 20
- 25
- 30
Preliminary Results - Throttle Advance

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Graph showing LPC Surge Margin (%) and LPC Bleed Flow (lbs) over time (seconds) for three conditions: Baseline, Schedule & Bleed, and Sched, Bld & VSV.
Yr 2 Technical Approach

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- Define response requirements for engine and aircraft in emergency situations – (Replicated Boeing/PW results using GTM)
- Develop fan bleed engine mode – (Incorporated fan bleed and actuation logic in C-MAPSS40k* simulation)
- Develop the differential thrust yaw mode – (control incorporates PI mode and thrust splitter logic)
- Compare yaw control performance for – (Evaluated performance using GTM/C-MAPSS40k* simulation)
  - conventional rudder control
  - engine throttle modulation for differential thrust
  - fan bleed modulation for differential thrust
- Assess engine operation capability & life usage
The GTM Design Model
- Simulation represents the AirSTAR T-series vehicles
- 5.5%-scale model of a generic twin engine transport
- Aerodynamic database derived from polynomial fit to wind tunnel data. Data include
  - high-angle-of-attack conditions
  - high-sideslip conditions
  - aerodynamic and mass effects on selected damage conditions

Simulation is in the public domain
- Released under NASA's open-source license
  - which allows the software to be modified and extended by end users
- Simulation development continues
  - Updates to be provided on a regular basis as issues are found and data refined though experimental testing and system calibration.
- GTM-Design simulation availability – contact Melissa.A.Hill@nasa.gov
Yaw Control using Fan Bleed Modulation

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Yaw Control

Yaw Command

Left Fan Bleed Command

Right Fan Bleed Command

Yaw Command

Yaw Feedback

Air Speed

Altitude

Yaw Attitude Controller

L Engine Bleed

R Engine Bleed

L Engine Thrust

R Engine Thrust

Differential Thrust

[50/50 Thrust Splitter]

PI Control

Left Engine

Right Engine

Yaw Command

Yaw Feedback
Yaw Control Comparison

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![Graph showing Yaw Angle (deg) vs Time (Sec) for various control inputs: Demand, Rudder, Throttle, Fan Bleed (300in²), Fan Bleed (800in²).]

<table>
<thead>
<tr>
<th>Altitude(ft)</th>
<th>Mach</th>
<th>Throttle Range</th>
<th>Nominal Thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>1110</td>
<td>0.14</td>
<td>50-58</td>
<td>16750</td>
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Yaw Control Comparison

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</table>
Yaw Control under Wind Disturbances

Rudder OK – Yellow
Rudder Failed – Magenta
Fan Bleed - Cyan
Summary and Conclusions

Aviation Safety Program
Integrated Resilient Aircraft Control

- There is a need for Continuous Aircraft Safety Improvements
  - FastER Engines can substantially contribute to the need

- Demonstrated to Date
  - Requirements Definition Scenarios Selected
  - Advanced/New Actuation Proposed
  - Emergency Control Modes Proposed and Selected
  - Initial Control Mode Simulation Results Quite Encouraging
  - Actuator Effectiveness Quantified
  - Yaw attitude control can be achieved through left & right engine differential thrust modulation
  - Differential thrust can be achieved using either fan bleed or throttle lever modulation
  - Yaw attitude control via fan bleed is more effective than via throttle modulation due to faster engine response
  - Stability Margin and Life Usage are not factors due to relatively small thrust changes

- Next Steps
  - Integrate Fan Bleed into C-MAPSS40k
  - Integrate C-MAPSS40k into GTM
  - Additional Evaluation of Fan Bleed Control Mode
  - Elaboration of Risk Models
  - Formalize Design Approach
NASA Propulsion Controls Workshop

Backup Material
Actuator Effectiveness

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Normalized effectiveness

Fan Bleed Case
Fuel Flow Case
VSV Case
Actuator Effectiveness-Fbld vs VSV

Aviation Safety Program
Integrated Resilient Aircraft Control

Normalized effectiveness

Fan Bleed Case
VSV Case
Actuator Effectiveness-Fbld vs VSV

- EGT
- P25
- P30
- Wf/P3
- DWfP3max
- DWfP3min
- VSV
- Fan Bleed
- Net Thrust

Normalized effectiveness

Fan Bleed Case
VSV Case