A Systems-Level Perspective on Engine Ice Accretion

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Overview

• Problem of Engine Power Loss
• Modeling Engine Icing Effects
• Simulation of Engine Rollback
• Icing/Engine Control System Interaction
• Detection of Ice Accretion
• Potential Mitigation Strategies
• Future Work
Problem of Icing Induced Power Loss

• More than 150 power loss events reported in last 20 years in High Ice Water Content conditions
  • Temporary or sustained power loss, uncontrollability, engine shutdown

• Many possible causes of power loss:
  • Compressor surge
  • Flame-out due to combustor ice ingestion
  • Damage due to ice shedding
  • Sensor icing
  • Engine rollback
Problem of Icing Induced Power Loss

• Ice crystals are believed to enter the core, melt, and accrete on engine components
• No pilot reports of weather radar returns
• No observations of airframe icing

Video courtesy of NASA GRC
Our Approach

• Accept that ice does accrete in the engine core
• Focus on the impact of the icing on the engine’s performance
  ▪ Collaborative effort across NASA Glenn Research Center
    » Controls and Dynamics Branch
    » Turbomachinery Branch
    » Icing Branch
• Develop models to study the conditions in which ice accretes (COMDES+NPSS+GlennICE)
• Use some of these results to develop “simplified” models
Modeling of Effect of Engine Icing

• C-MAPSS40k engine simulation
  ▪ Commercial 40,000lb₉ thrust, high-bypass turbofan engine
  ▪ Physics-based model
  ▪ Realistic engine control system & sensor noise
  ▪ Written in MATLAB/Simulink
  ▪ Modular design
  ▪ Publicly available to US citizens
Modeling of Engine Icing Effects

- Low Pressure Compressor (LPC) maps with various quantities of ice blockage in the 2\textsuperscript{nd} row stator
- Integrated into C-MAPSS40k
  - Linear interpolation between maps

Underlying data from:
Simulation of Engine Performance during Ice Accretion

- **Impact of Engine Icing**
  - Start from nominal conditions and increase the blockage level
  - Move from nominal LPC map to 20% blocked map

- **Effect:**
  - Higher fuel flow rate required to maintain desired setpoint leads to increase in all other parameters
  - No Rollback event
Simulation of Engine Rollback

- As blockage increases, eventually a rollback occurs
- Decrease in thrust
- Decrease in fan speed
- Increase in TGT
Engine Control System

- Power Management
  - Responsible for holding current power level

- Protection Logic
  - Responsible for ensuring safe operation
  - Adjusts Fuel Flow to ensure limits are observed
Controller Response To Icing

- Core speed limit prevents fuel flow rate from continuing to increase

- Normal operation of controller in the presence of blockage results in rollback
Detection of Engine Icing

- Typically 5 – 7 control sensors present in an engine
- Icing causes a change in the LPC operational characteristics
- Operate in conjunction with airframe devices to reduce chance of false-positive
Detection of Engine Icing

- Estimate the change in LPC “health” based on fan and core shaft speeds and look for a decrease in the flow capacity
- Linear estimator approach
  - Uses simple 1D interpolation
  - Low memory usage
  - Should be capable of operating real-time in typical FADEC

- Early Sim. Results:
  - False-Positive = 0.0%
  - True-Positive = 100.0%
  - Average Blockage Level at Detection = 6.80%
Mitigation of Engine Icing

• Ideally, completely avoid ice accretion

• If we can detect accretion can the engine controller act to mitigate the impact of the ice blockage?

• Potential mitigation strategies:
  ▪ Operate actuators off-nominally to change operating point
    » Close inter-compressor bleed valve or move HPC inlet guide vanes off schedule
  ▪ Use existing airframe integration in novel ways
    » Power take-off, Customer air bleed
  ▪ Change shaft speed to cause ice to shed

• All of these approaches require iteration with an icing code to determine the effect of the new condition on ice accretion!
Future Plans

• Upcoming testing at NASA Glenn’s Propulsion System Laboratory promises to provide validation of models and detection algorithm

• Develop mitigation strategies – iterate with the NASA GRC icing code to determine how the change in operating point impacts the accretion of ice & possible testing in PSL
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References


Detection of Engine Icing

- Linear estimator – optimal unbiased least squares
  \[ y = Hx + \omega \]
  \[ \hat{x} = (H' R^{-1} H)^{-1} H' R^{-1} y \]

- Detection threshold can be chosen to obtain a desired false-positive rate

- As threshold increases, the detection latency also increases