



A Systems-Level Perspective on Engine Ice Accretion

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Presented to the ACGSC, Reno, NV
March 6-9, 2013

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

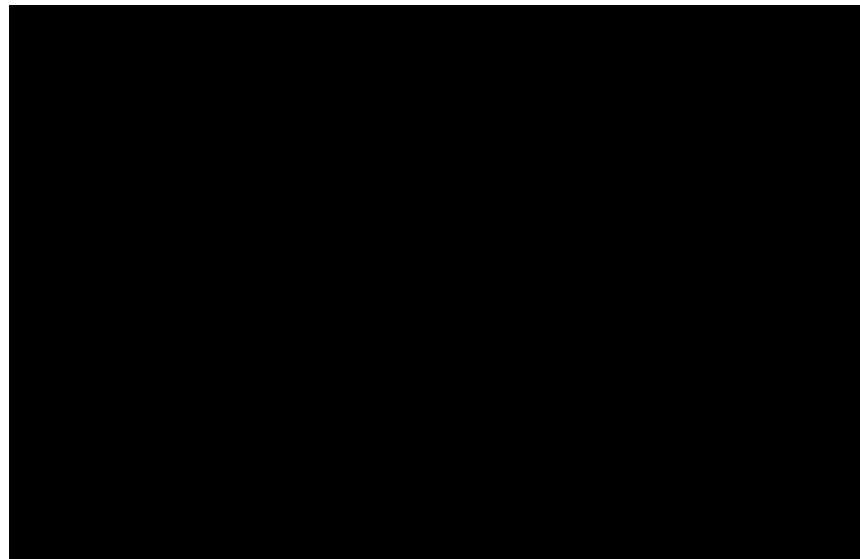


- More than 150 power loss events reported in last 20 years in High Ice Water Content conditions
 - Temporary or sustained power loss, uncontrollability, engine shutdown
- Many possible causes of power loss:
 - Compressor surge
 - Flame-out due to combustor ice ingestion
 - Damage due to ice shedding
 - 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

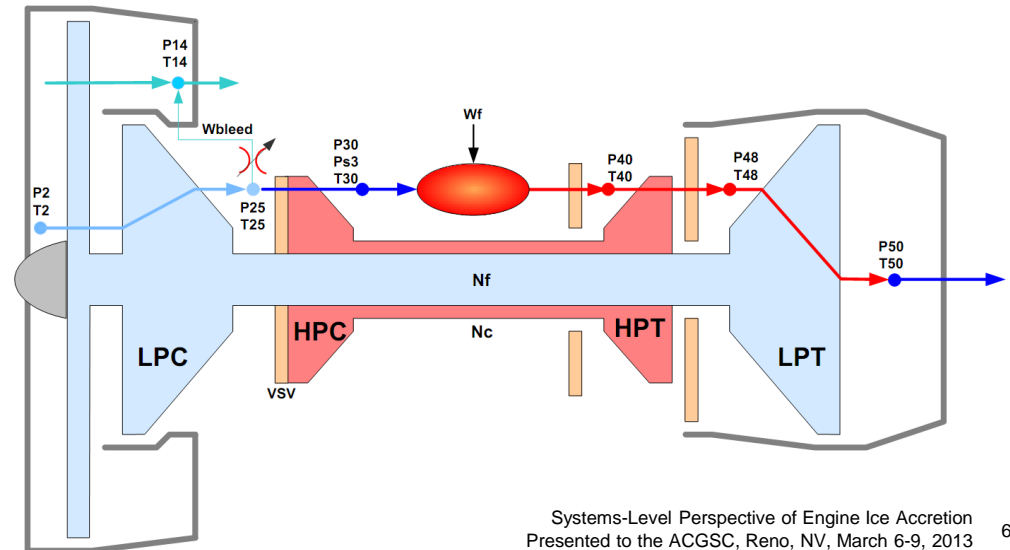
Our Approach

- 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



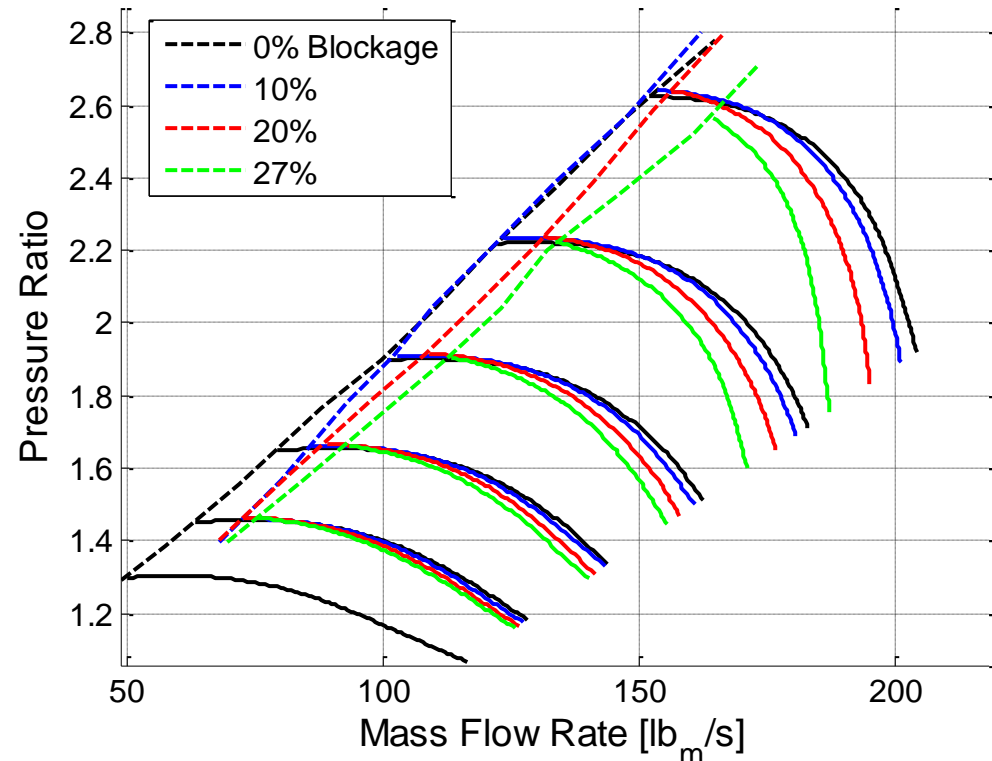
- C-MAPSS40k engine simulation
 - Commercial 40,000lb_f thrust, high-bypass turbofan engine
 - Physics-based model
 - Realistic engine control system & sensor noise
 - Written in MATLAB/Simulink
 - Modular design
 - Publicly available to US citizens



Modeling of Engine Icing Effects



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



Underlying data from:
Jorgenson, P.C.E., Veres, J.P., May, R.D., Wright, W.B.,
“Engine Icing Modeling and Simulation (Part I): Ice Crystal
Accretion on Compression System Components and Modeling
its Effects on Engine Performance,” 2011-38-0025, SAE
International Conference on Aircraft and Engine Icing and
Ground Deicing, Chicago, IL, Jun 13-17, 2011.
doi:10.4271/2011-38-0025

Simulation of Engine Performance during Ice Accretion

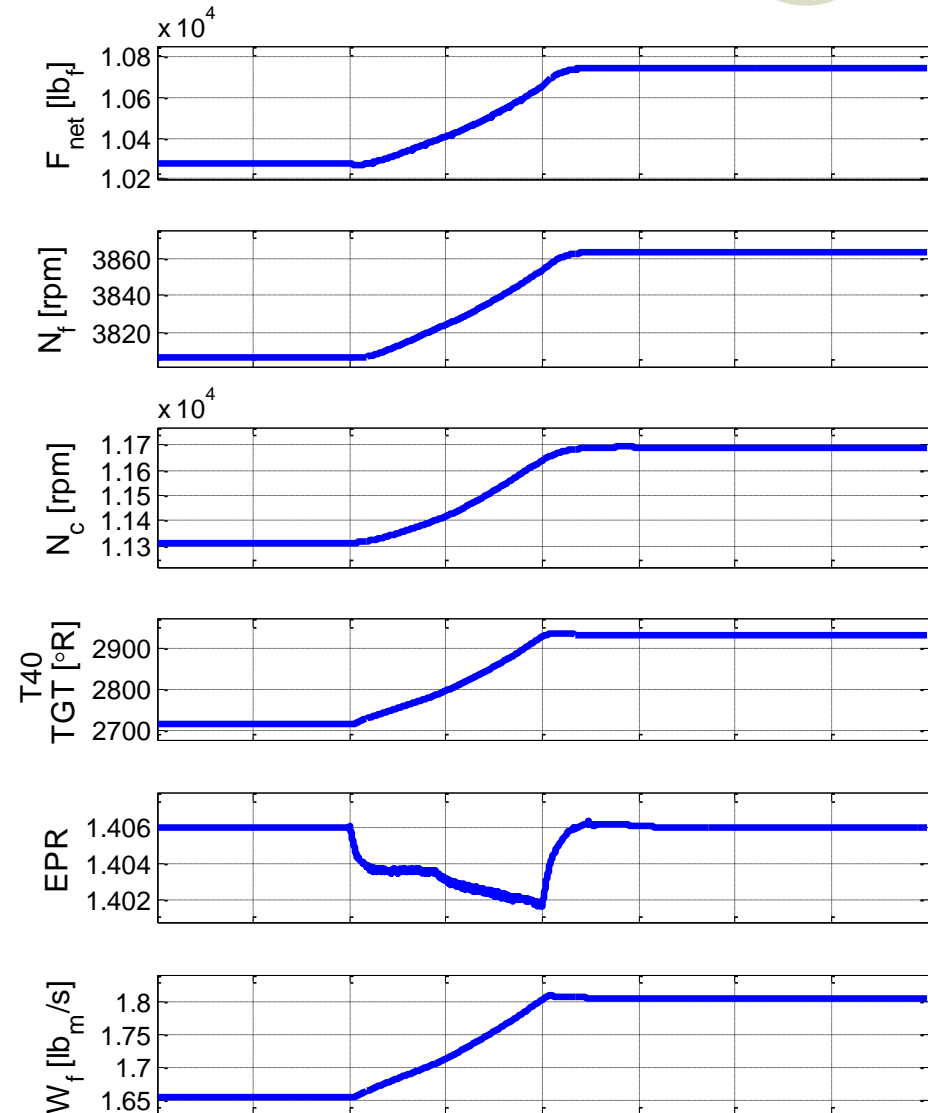


- Impact of Engine Icing

- Start from nominal conditions and increase the blockage level
- Move from nominal LPC map to 20% blocked map

- Effect:

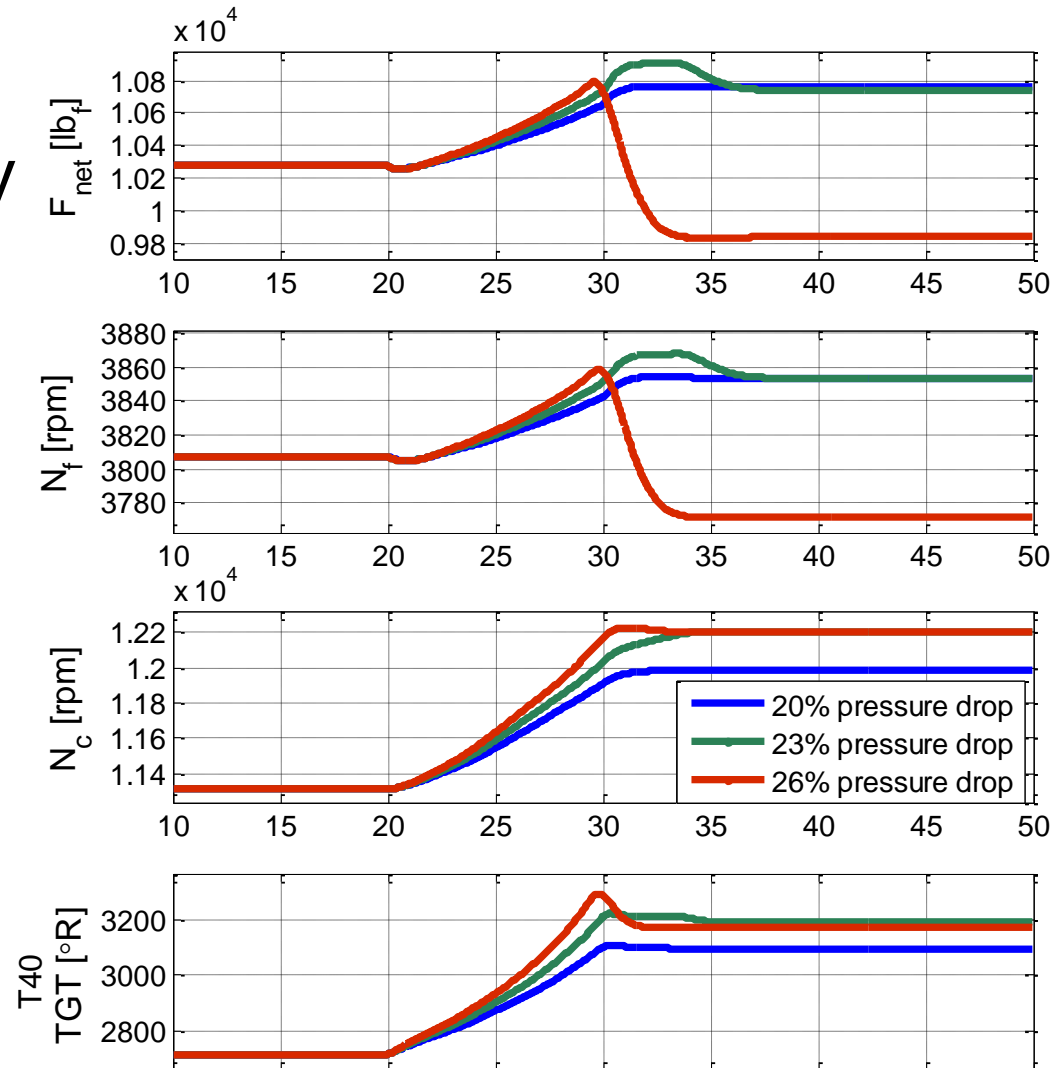
- Higher fuel flow rate required to maintain desired setpoint leads to increase in all other parameters
- No Rollback event



Simulation of Engine Rollback

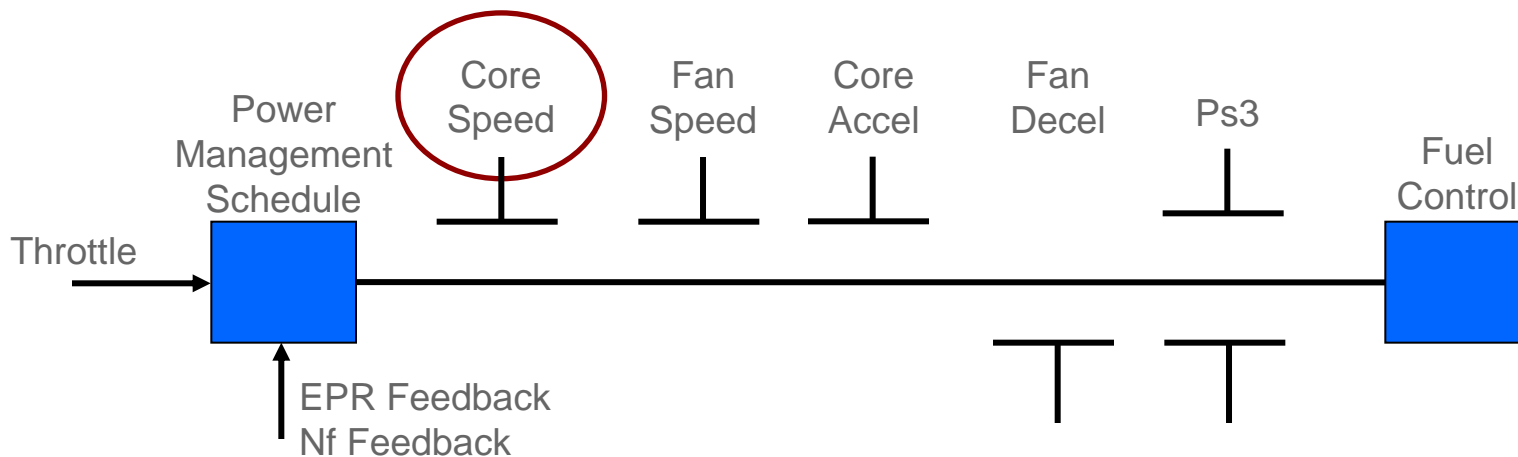


- As blockage increases, eventually a rollback occurs
- Decrease in thrust
- Decrease in fan speed
- Increase in TGT



Engine Control System

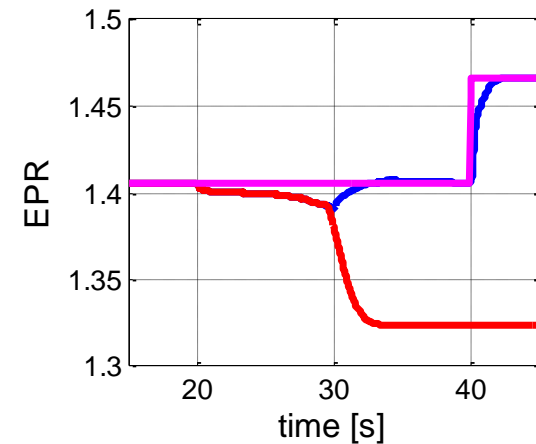
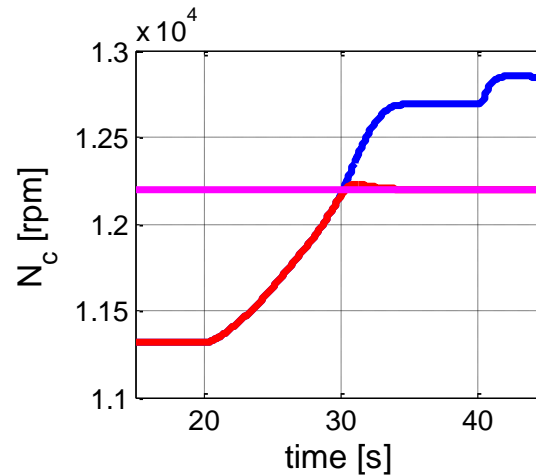
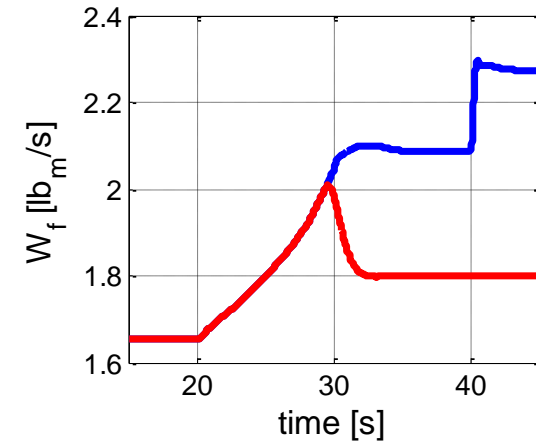
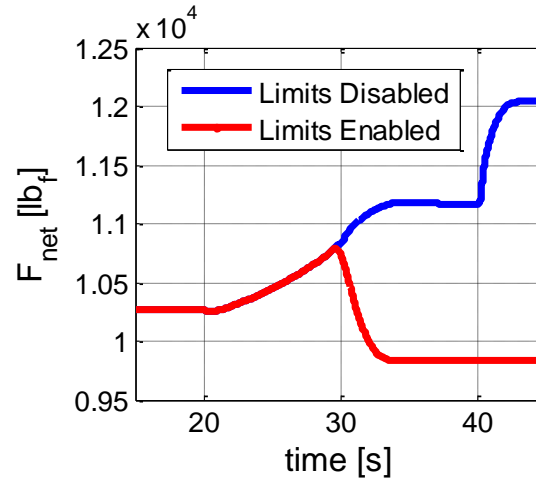
- Power Management
 - Responsible for holding current power level
- Protection Logic
 - Responsible for ensuring safe operation
 - Adjusts Fuel Flow to ensure limits are observed



Controller Response To Icing

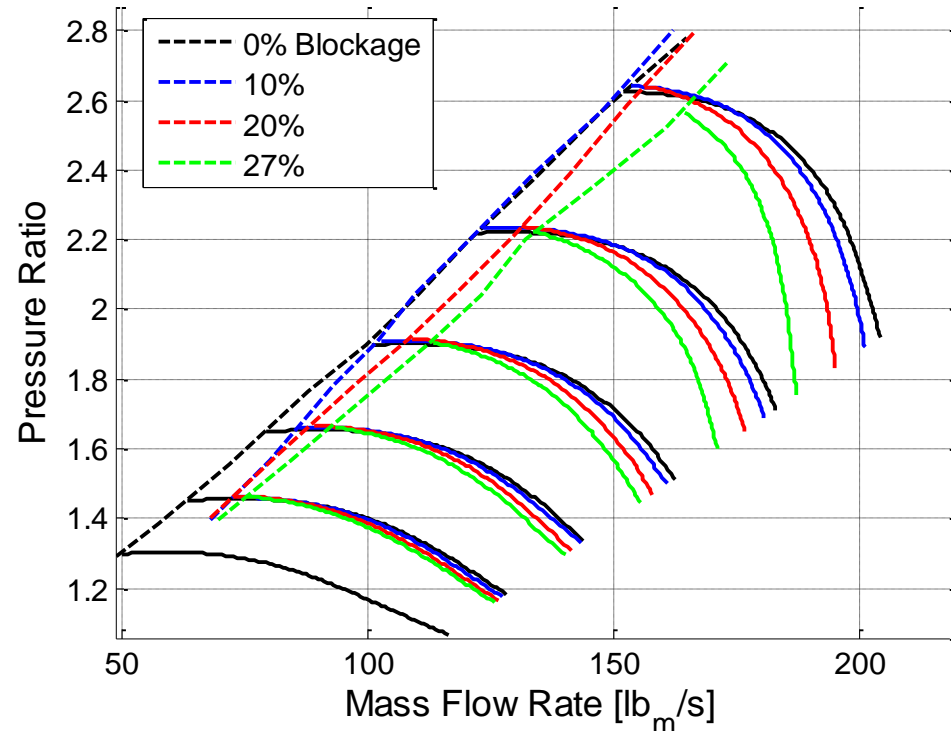


- Core speed limit prevents fuel flow rate from continuing to increase
- Normal operation of controller in the presence of blockage results in rollback



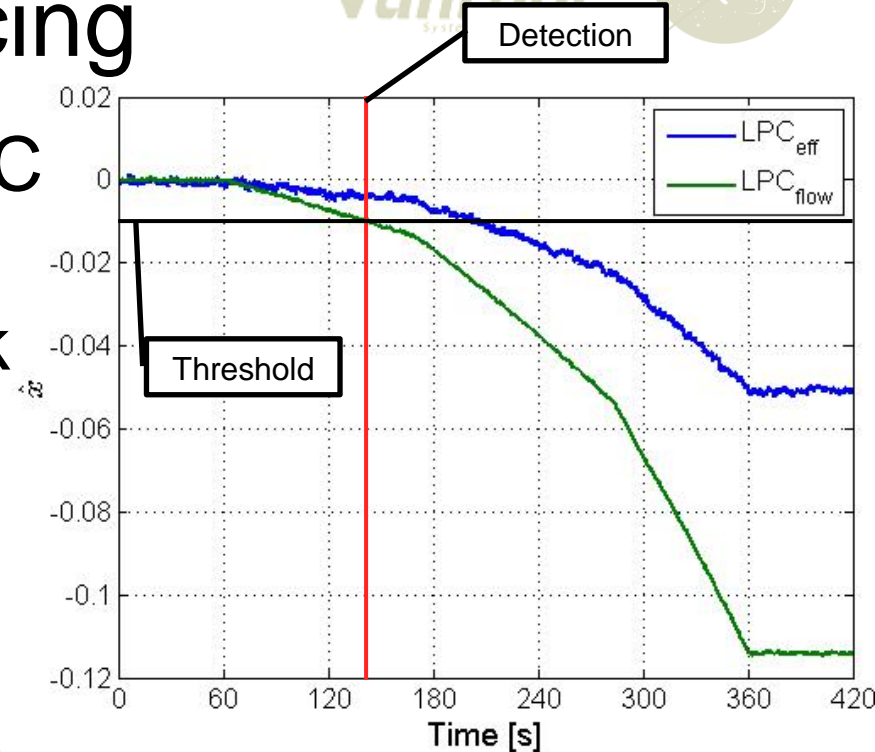
Detection of Engine Icing

- 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

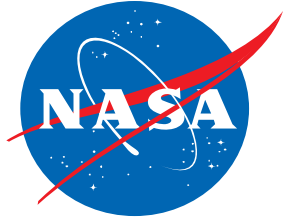
Acknowledgements

- This work was funded by the NASA Aviation Safety Program's Vehicle Systems Safety Technologies Project

References



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- May, R.D., Guo, T-H., Veres J.P., Jorgenson, P.C.E., “Engine Icing Modeling and Simulation (Part 2): Performance Simulation of Engine Rollback Phenomena,” 2011-38-0026, SAE International Conference on Aircraft and Engine Icing and Ground Deicing, Chicago, IL, Jun 13-17, 2011. doi:10.4271/2011-38-0026
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- May, R.D., Guo, T.H., Simon, D.L., "An Approach to Detect and Mitigate Ice Particle Accretion in Aircraft Engine Compression Systems," ASME-GT2013-95049, to be published at the ASME TurboExpo 2013, San Antonio, TX, June 3-7, 2013.



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

