In-Flight Engine Shutdown and Restart Modeling

5th Propulsion Control and Diagnostics Workshop
Ohio Aerospace Institute (OAI)
Cleveland, OH
September 16-17, 2015

Team

- Jeffryes Chapman, VPL
- Andy (A.J.) Hamley, GRC intern
- Shane Sowers, VPL
- Karl Owens, Contractor
- Ten-Huei Guo, GRC
- Jonathan S. Litt, GRC

Outline

- Project Background
- Simulation Modifications Shutdown
- Simulation Modifications Re-Start
- Validation
- Summary

Project Background

- In co-operation with NASA Langley, there has been an effort to increase the fidelity of aircraft simulation when one or both engines are operating in the sub-idle region.

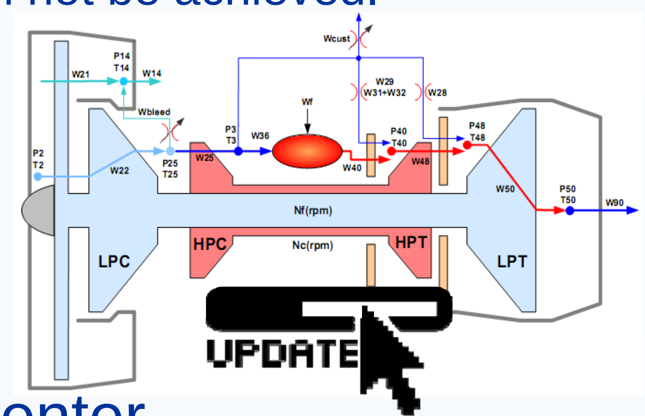
- Engine sub-idle modeling facilitates aircraft simulation during in-flight engine shutdown and/or restart

Potential events:

- Operation post unrecoverable surge
- Combustor blow out
- Loss of engine due to
  - Bird strike
  - Fuel loss
  - Mechanical failure

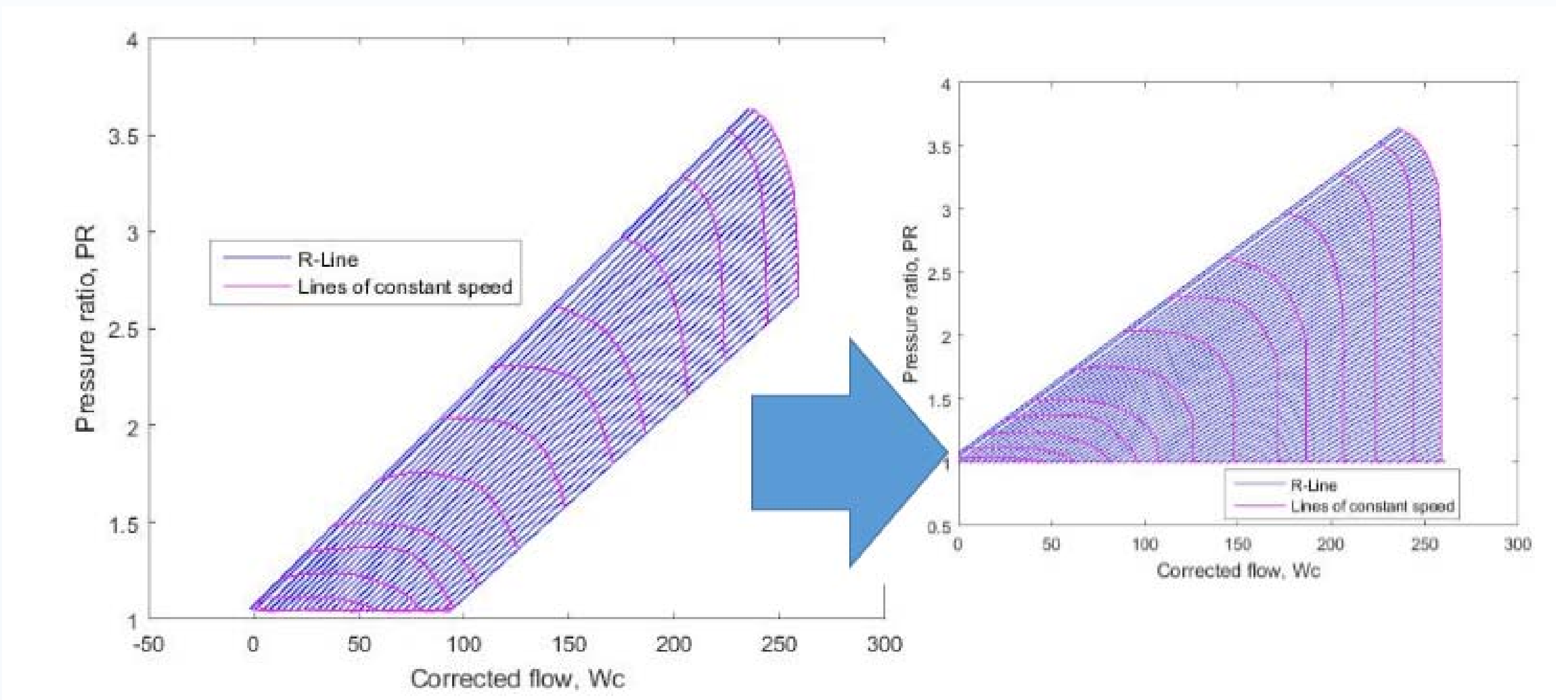
C-MAPSS40k Modifications

- Commercial Aero-Propulsion System Simulation 40k (C-MAPSS40k)
  - All inclusive dynamic high-bypass, dual-spool simulation developed at GRC
  - Energy balance approach centered around compressor and turbine performance maps
  - External solver required for “converging” to a point of operation during any given time step
- Modifications for sub-idle operation
  - Extension of performance maps to increase the operational envelope of the engine simulation
  - Creation of backup empirical model to offer “fail safe” if simulation convergence can not be achieved.



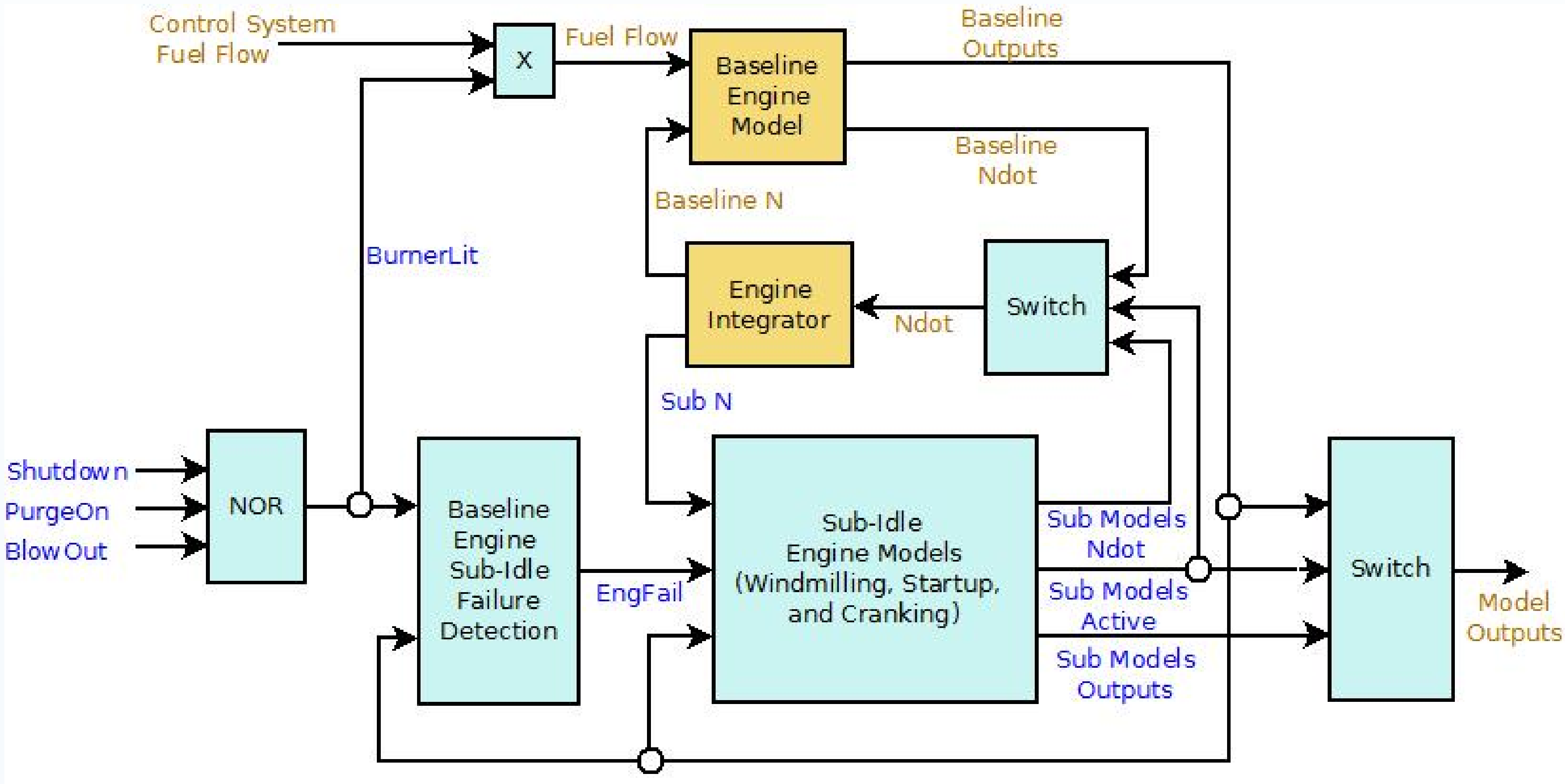
Map Extrapolation

- Compressor and turbine maps were extended to include sub-idle operational points
  - Boundaries: 0 shaft speed, 0 mass flow, and unity pressure ratio
  - Extrapolation into the paddle and turbine regions of the compressor map was avoided due to uncertainty of performance resulting from a lack of engine data.

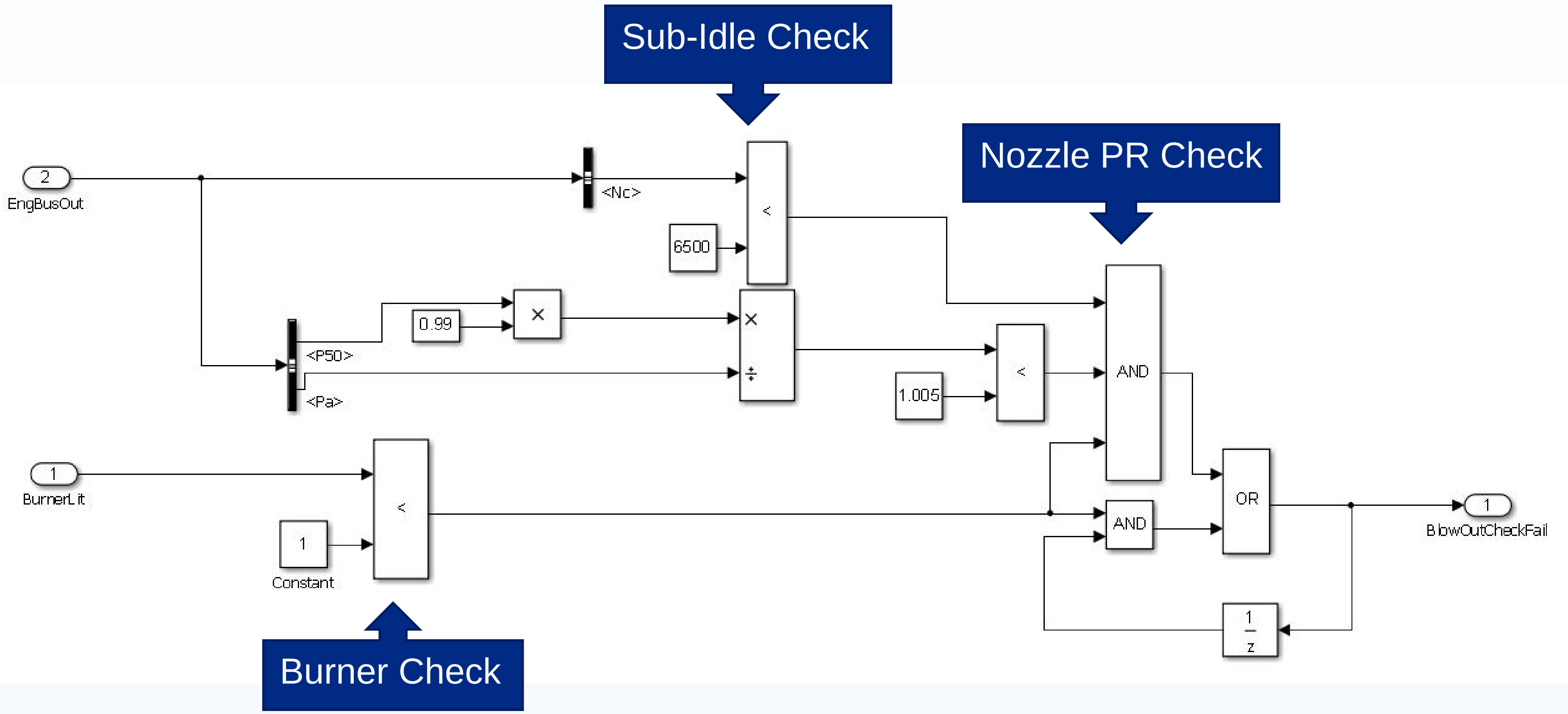


Integrated Architecture

- A Fail-safe model was added to guarantee sub-idle model stability
  - Model switching occurs once a criterion is satisfied

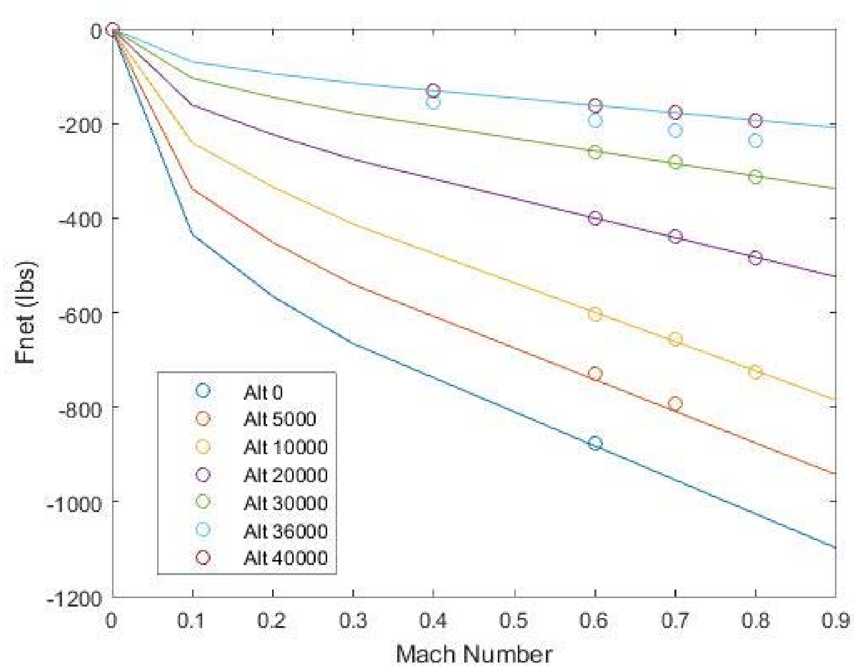


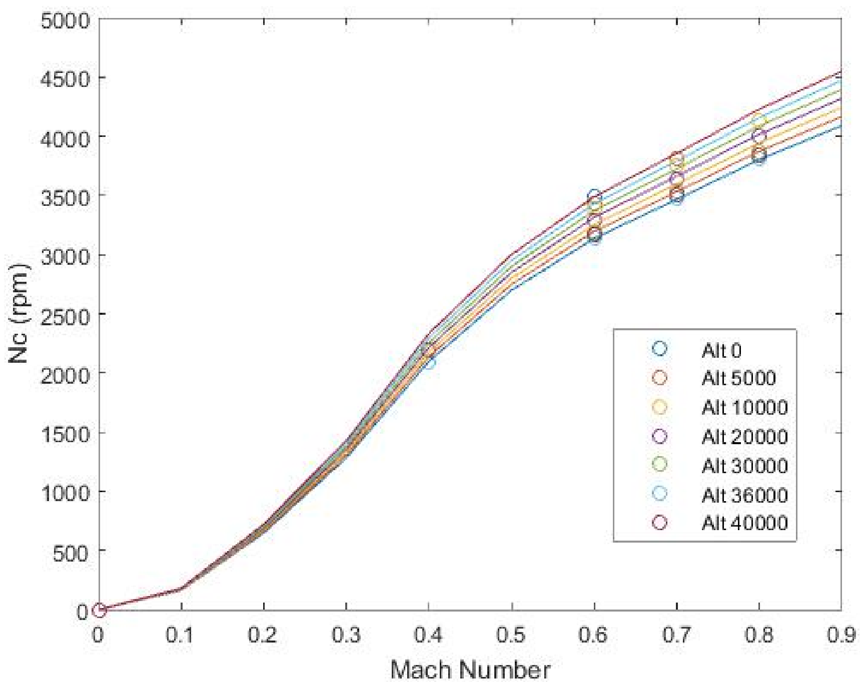
Model Switching



Fail-Safe Windmilling Modeling

- Nc, Nf, and Fnet generated from 2-D table lookups based on Alt. and MN.

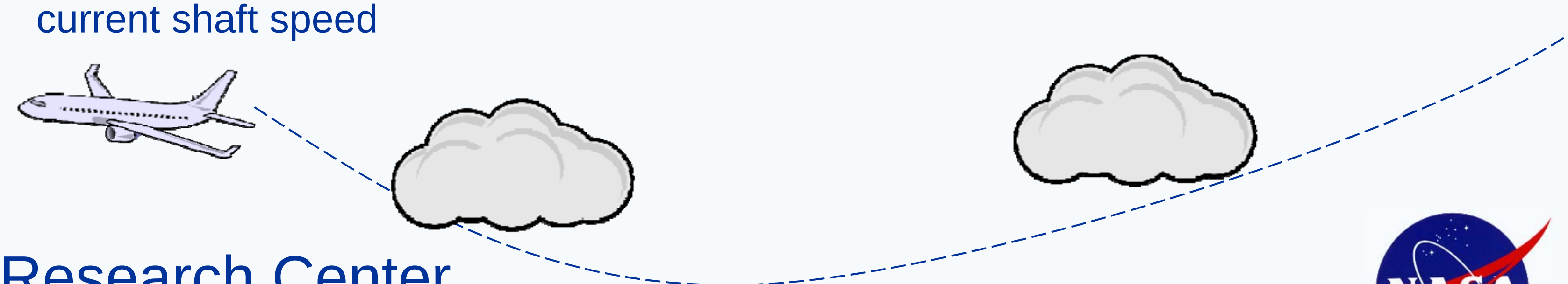




Parameters extrapolated from simulated engine data following typical windmilling parameter curves.

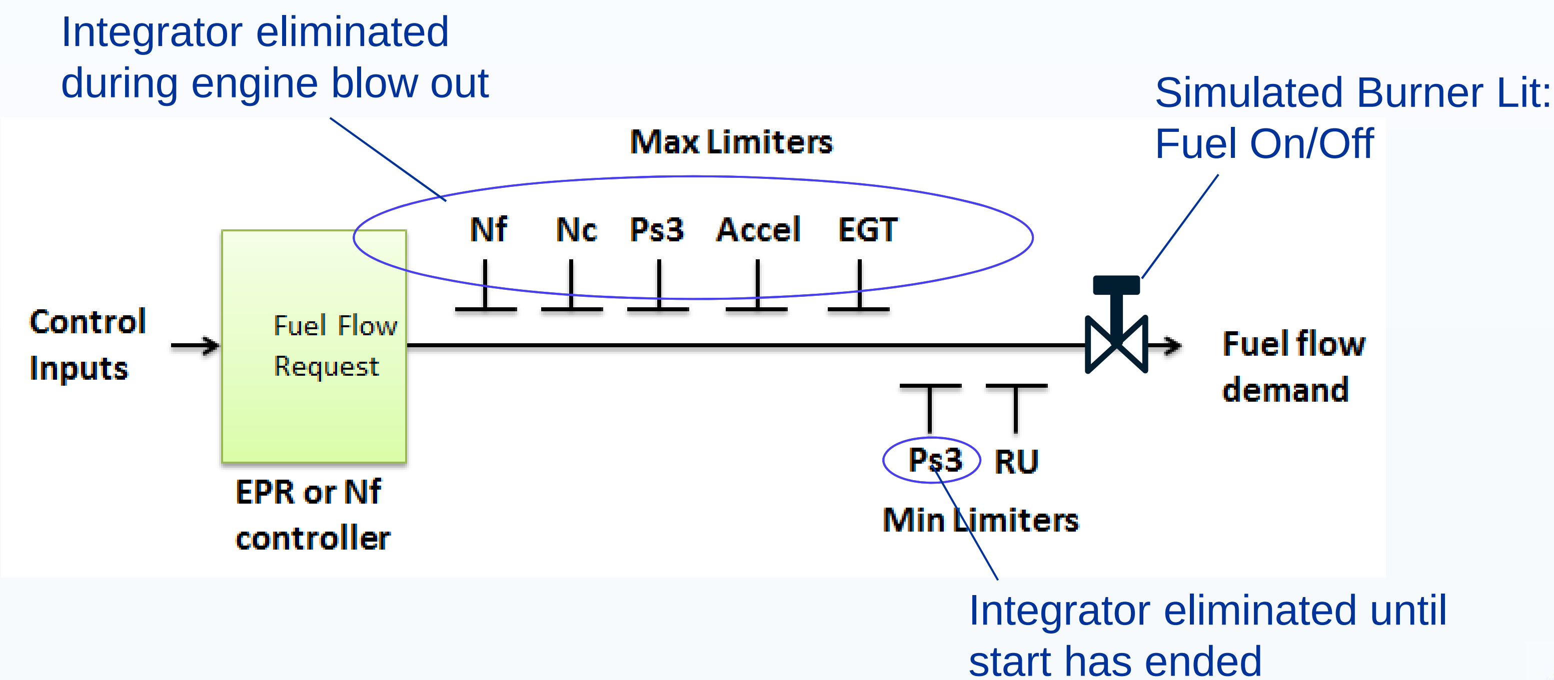
Restart Modeling

- A typical start sequence consists of purging/cranking to get to a predefined speed and clear all un-burnt fuel from the engine
- Modeling restart cases:
  - Engine is operating on the extrapolated maps
    - Cranking will occur if windmilling speeds are within specified limits and is modeled by an external torque on the high pressure shaft.
    - Re-light will occur once shaft speed exceeds 20% max
  - Engine is operating on windmilling tables
    - Low speed cranking engine model (transfer function) will drive the engine to 20% shaft speed
    - Re-light will occur and the model will be transitioned back to the baseline
    - Cranking will continue as an external torque on the high pressure shaft based on current shaft speed



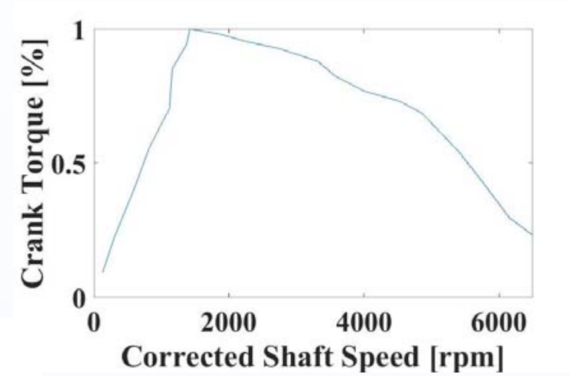
Updating Fuel Control

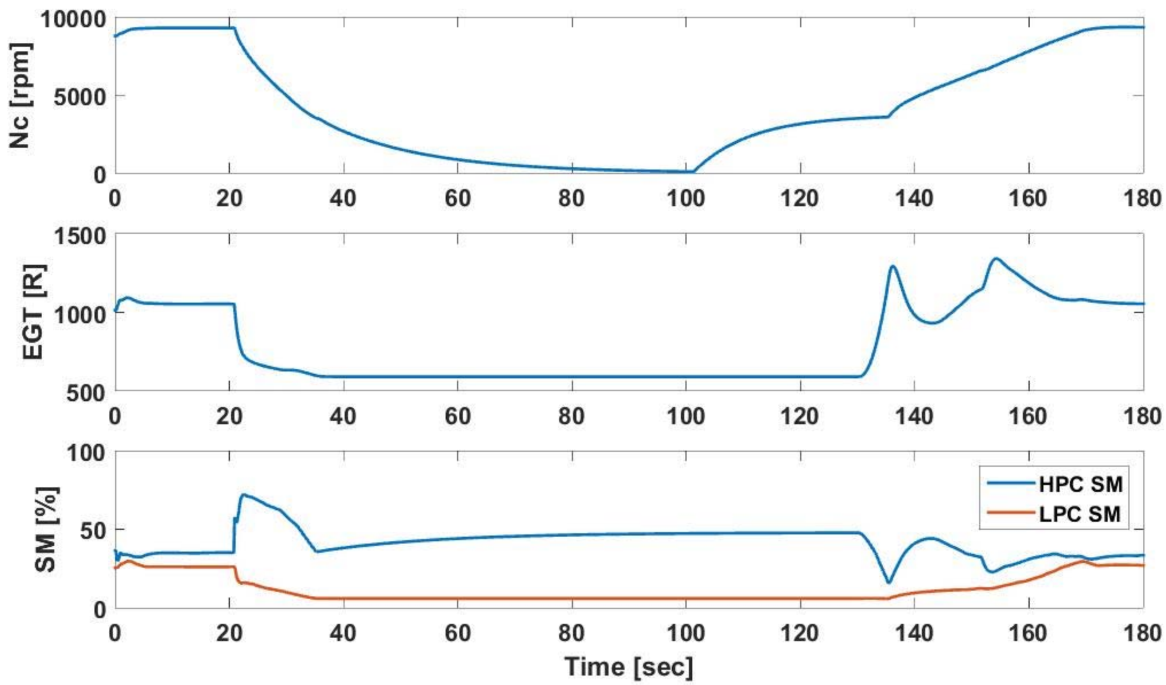
- Shutdown simulated by removing fuel from the engine
- Eliminating controller windup:
  - PI feedback for limiters removed during blow out
  - Integration in min limiters removed during start



Starter Assist

- Torque assist on high pressure shaft at low engine speeds
  - Derived from typical crank torque curves
  - Designed to reduce idle time to roughly 1 min
  - Increase Stall Margin to acceptable values
  - Decrease Engine Exhaust Temperature to acceptable values



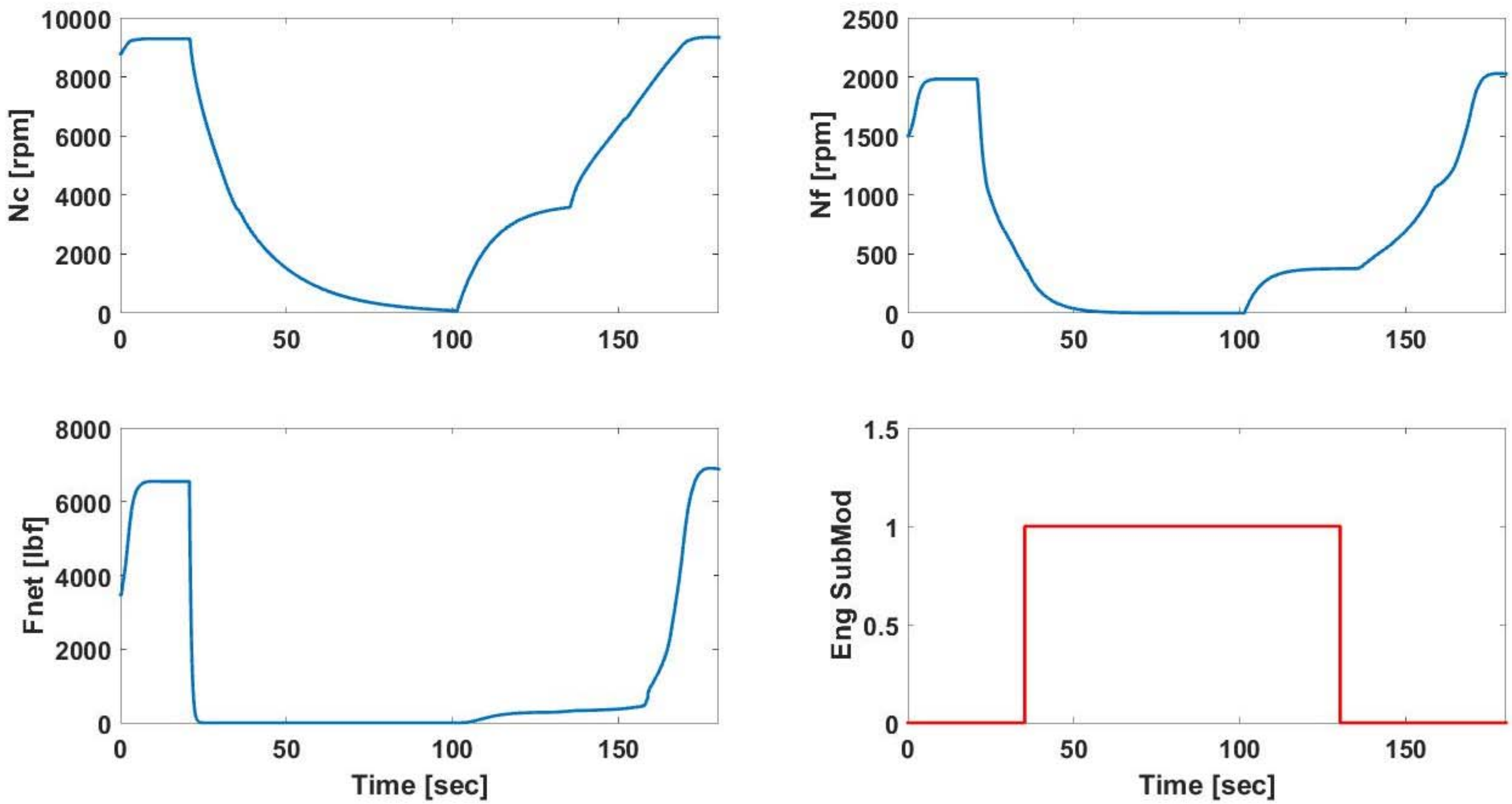


EGT < 1500 R

SM > 5%

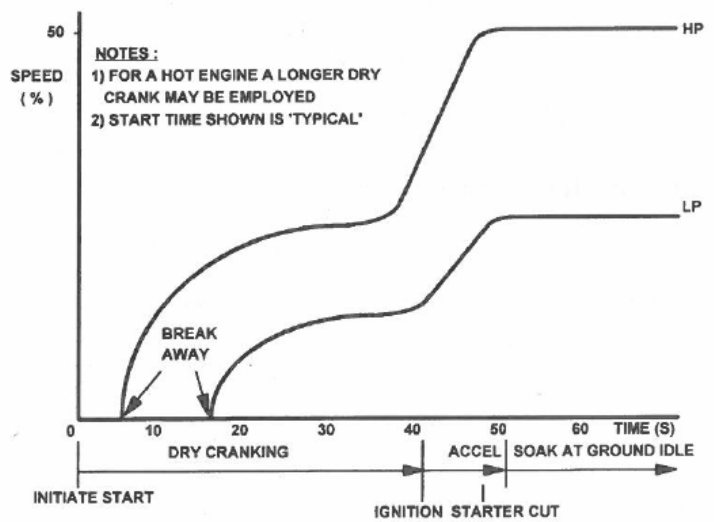
Sub-Idle Model Operation

- Engine Simulated Shutdown and Restart at Sea Level Static conditions



Performance Validation

- Validation challenging due to generic nature of model
- Comparison to textbook performance and pilot in-flight performance confirmation



(b) Two spool turbojet or turbofan

Fig. 9.1 Key engine start phases and speeds versus time.

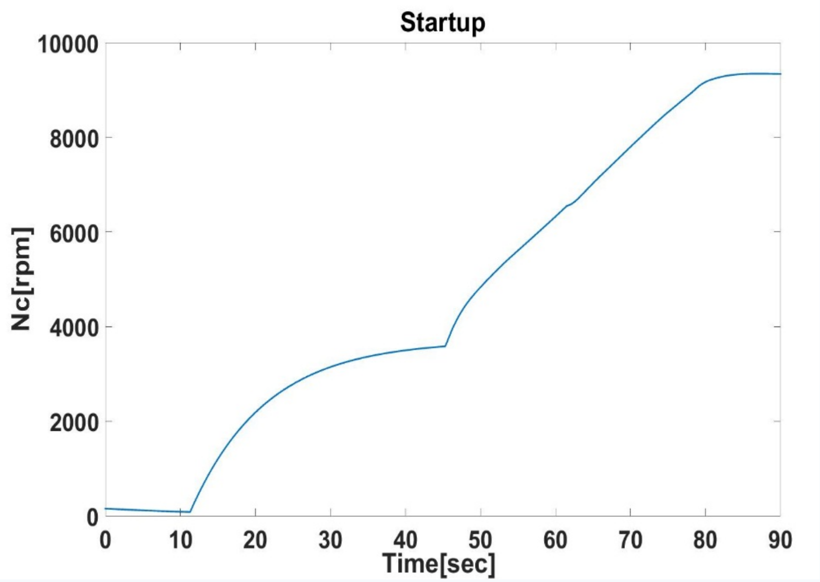
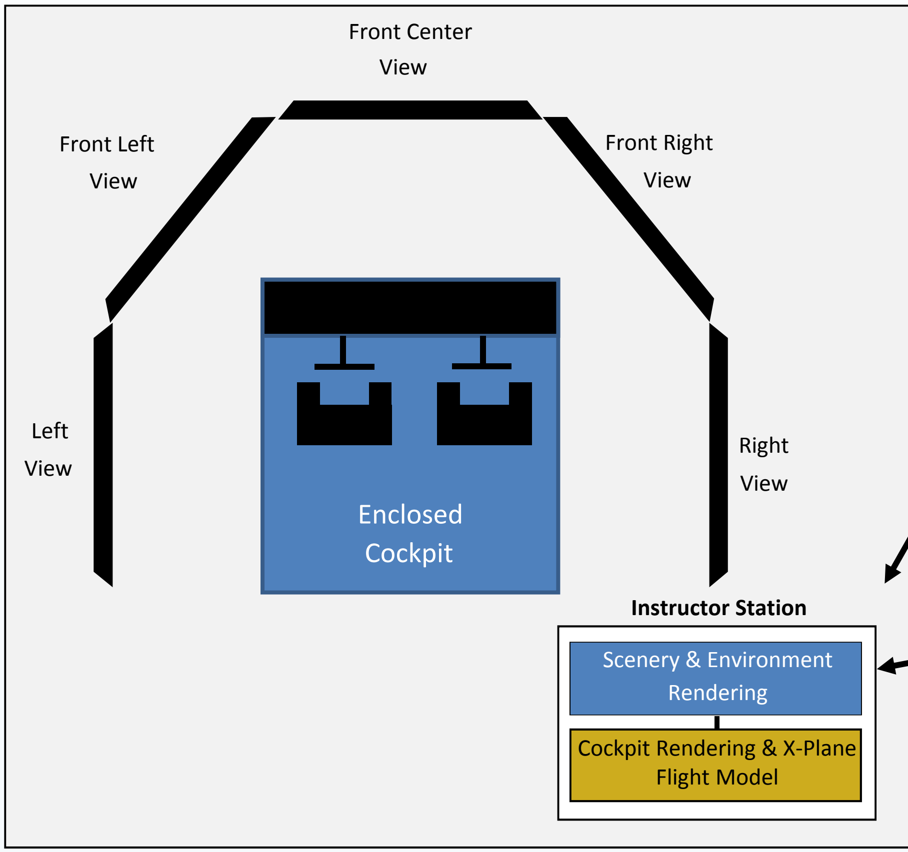


Figure from Walsh and Fletcher, *Gas Turbine Performance,* 2 ed

Modeling Platform

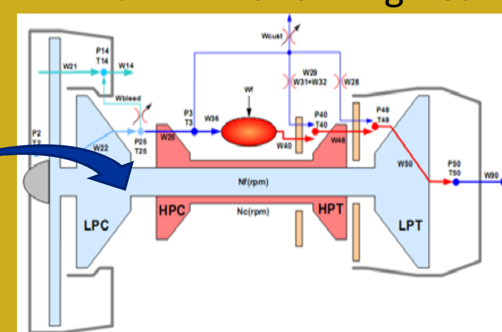
Integrate new requirements into existing NASA Glenn flight simulator



Modular Flight Deck

GRC flight simulation:
-TCM Airframe

-2 x C-MAPPS40k Engines



In-flight shutdown and restart

Summary

- An in-flight shutdown and re-start model was developed and integrated into C-MAPSS40k for use in the NASA Glenn flight simulator
- Two main techniques were used to extend the engine simulation envelope
  - Performance map extrapolation
  - Alternate Sub-Idle model fail-safe
- A restart model was created using a two tiered crank simulation
  - External torque source
  - Alternate cranking model fail-safe
- Engine control system was adjusted to account for integrator wind-up
- Model results show plausible results that allow for smooth transitioning between engine shutdown and idle.

References

- Chapman, J.W., Hamley, A.J., Guo, T.-H., Litt, J.S., “Extending the operational envelope of a turbofan engine simulation into the sub-idle region”, AIAA Science and Technology Forum and Exposition, San Diego, CA, Jan. 2016—to appear.