Transient Optimization of an Electrified Gas Turbine Engine Using Machine Learning

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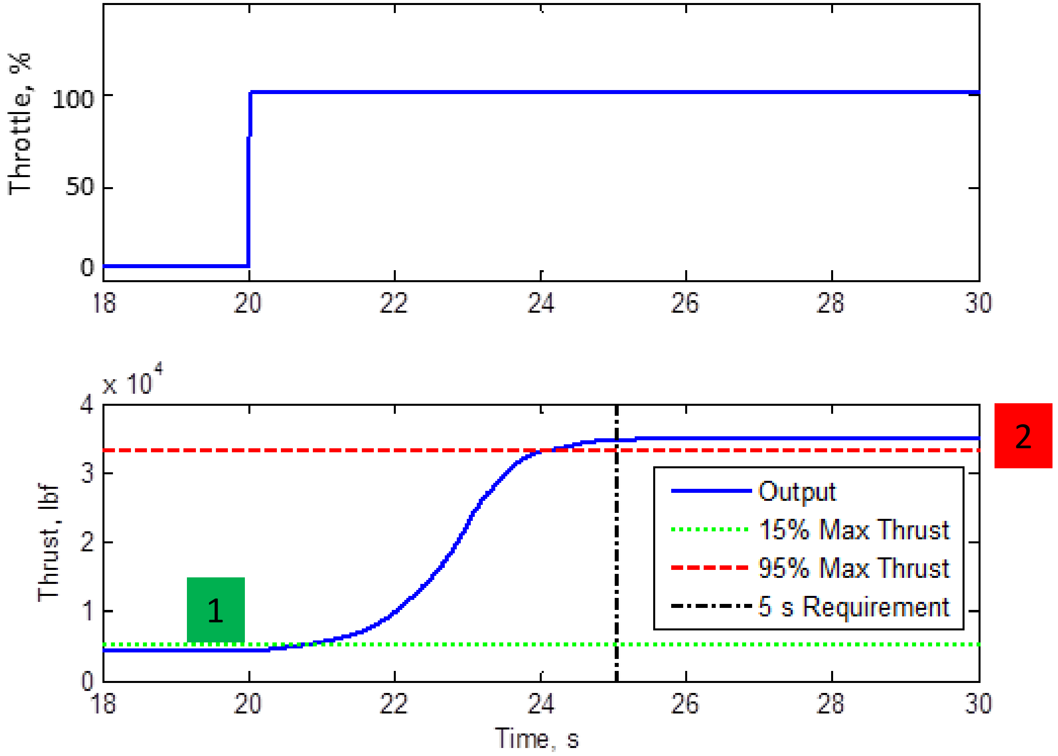
Overview

- Background
- Machine Learning/Genetic Algorithms
- Model Updates
- Results
- Conclusions

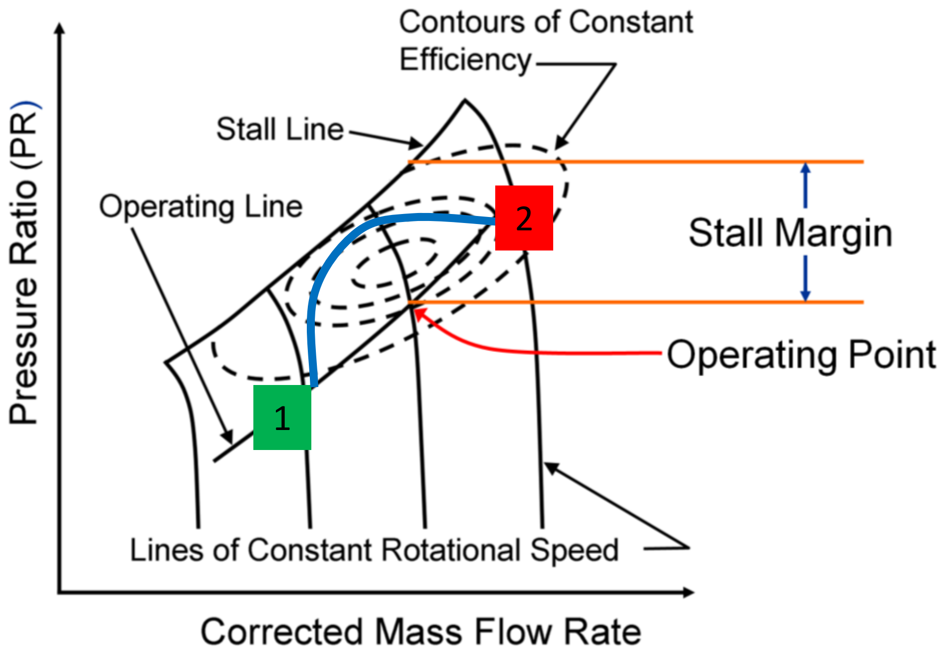
Background

- A 5-second thrust response is an FAA certification requirement
- During transients, compressor operation moves away from the operating line toward stall as engine shafts are temporarily out of sync
- Acceleration and thus deviation from the operating line is limited by an acceleration schedule



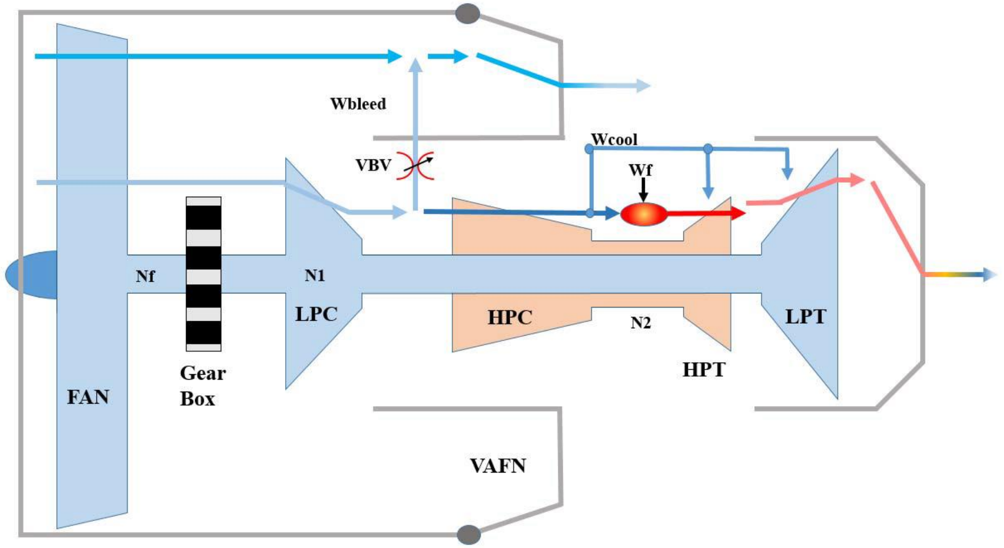
$$\text{Stall Margin}=100\%\times(PR_{\text{Stall line}}-PR_{\text{Operating line}})/PR_{\text{Operating line}}$$

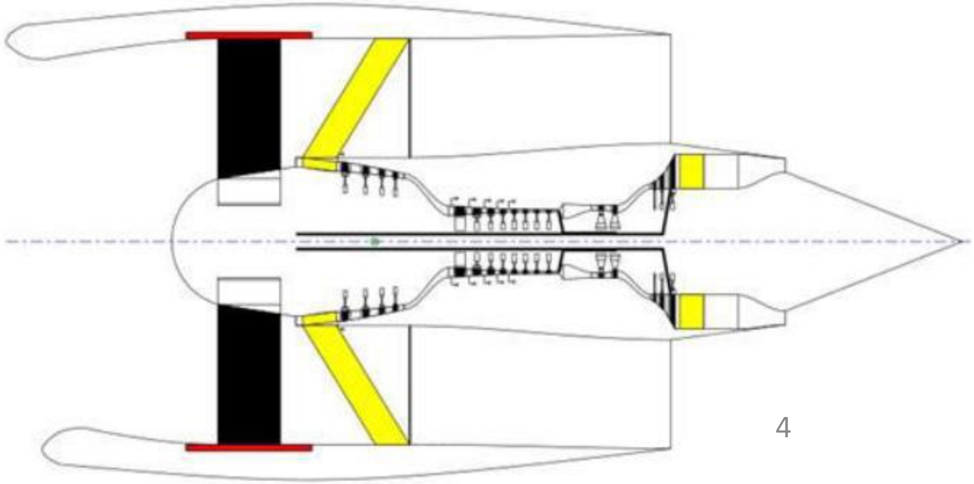
at a constant mass flow rate



Model—Advanced Geared Turbofan 30,000

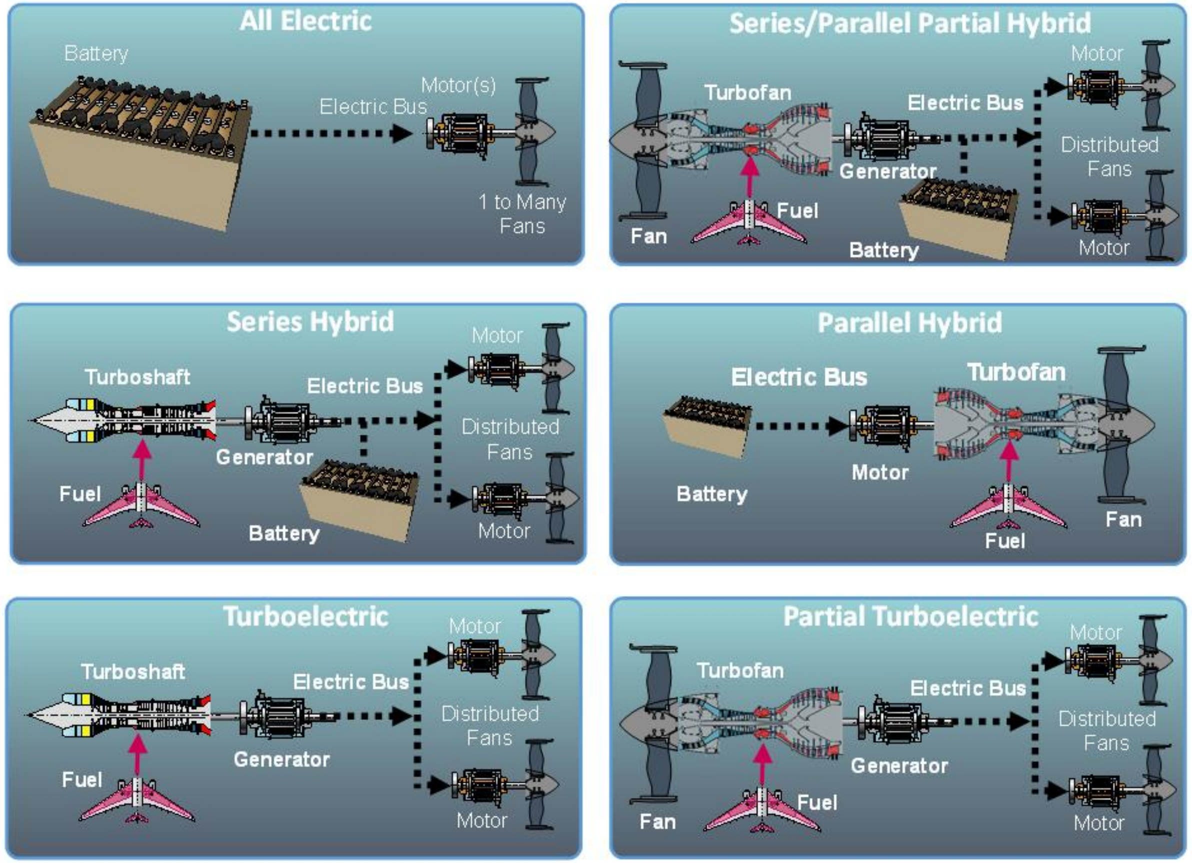
- Advanced Geared Turbofan 30,000 (AGTF30)
  - Conceptual two-spool geared turbofan
  - Produces ~30,000 lbf at sea level static conditions
  - Included advanced technologies
    - Compact core
    - Variable area fan nozzle
  - MATLAB/Simulink® model developed with the Toolbox for the Modeling & Analysis of Thermodynamic Systems (T-MATS)





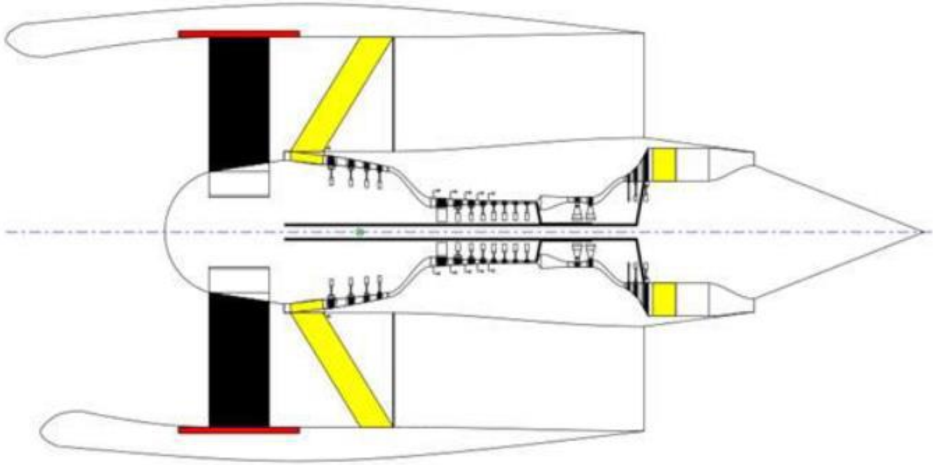
Electrified Propulsion

- In an all-electric architecture, a battery provides the power
- Otherwise, a gas turbine engine provides power for electric fans and potentially thrust to propel the aircraft
- Power is extracted by generators attached to the engine shafts
- Hybrid architectures have a battery and a gas turbine engine

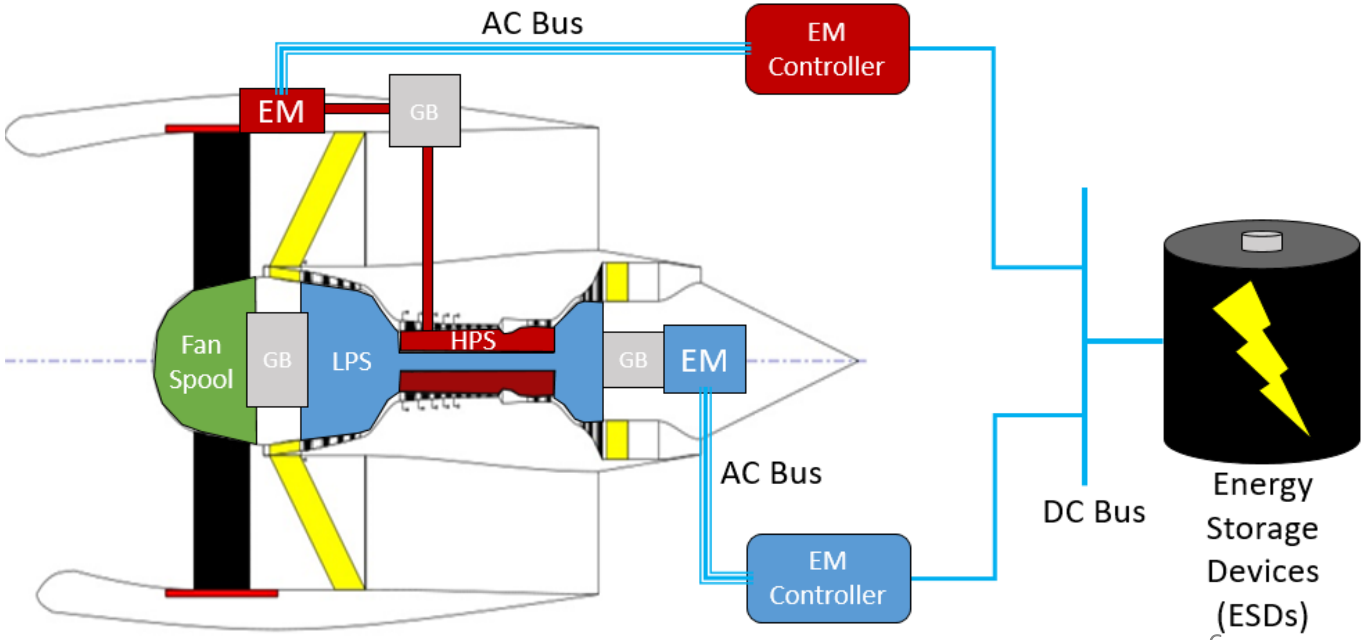


TEEM Control

- Turbine Electrified Energy Management (TEEM) control
  - Utilizes the existing electric machines on the engine shafts
  - Extracts or injects power strategically during transients to help keep the engine spools in sync
  - Benefits greatly from having an energy storage device such as a battery to source and/or sink power



AGTF30



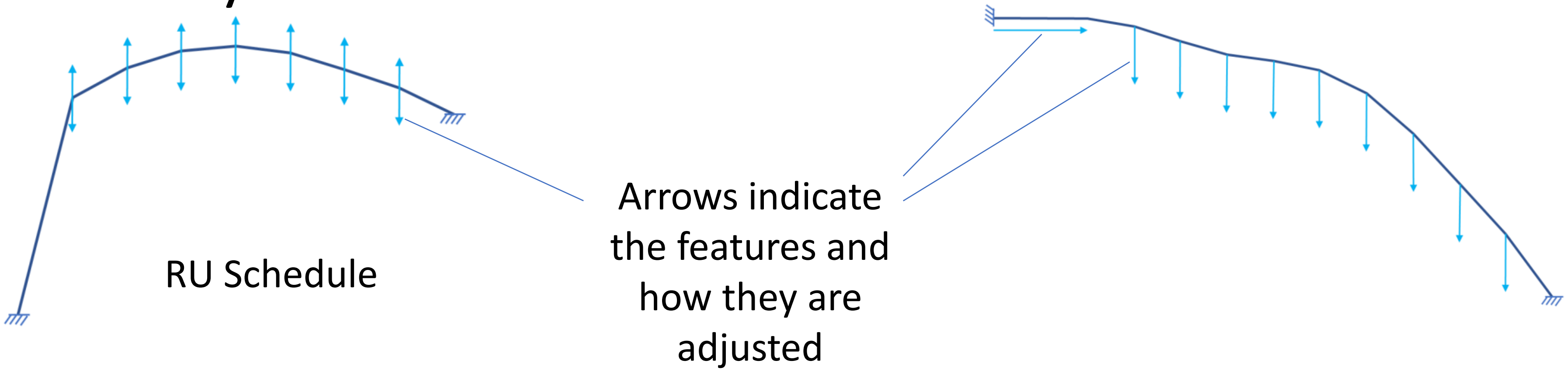
Electrified AGTF30

Differences From Past Work

- Simultaneous optimization of fuel flow acceleration schedule and torque shape used to implement TEEM
- Updated AGTF30 model includes effects for added realism
  - Heat soak
  - Tip clearance

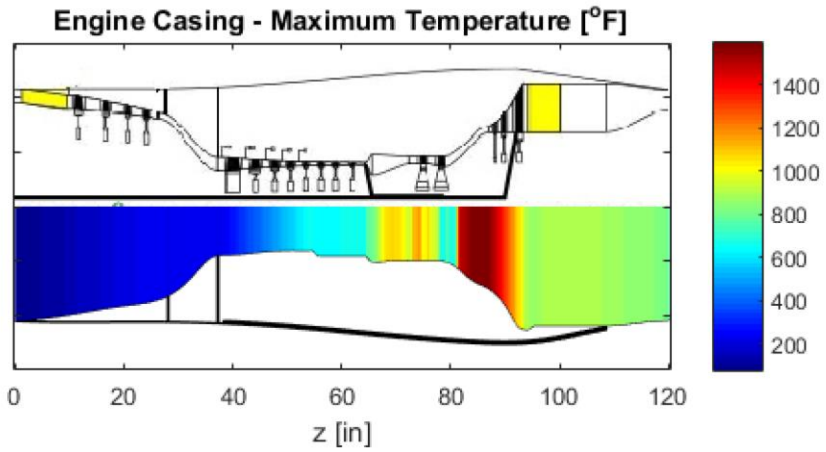
Machine Learning/Genetic Algorithms

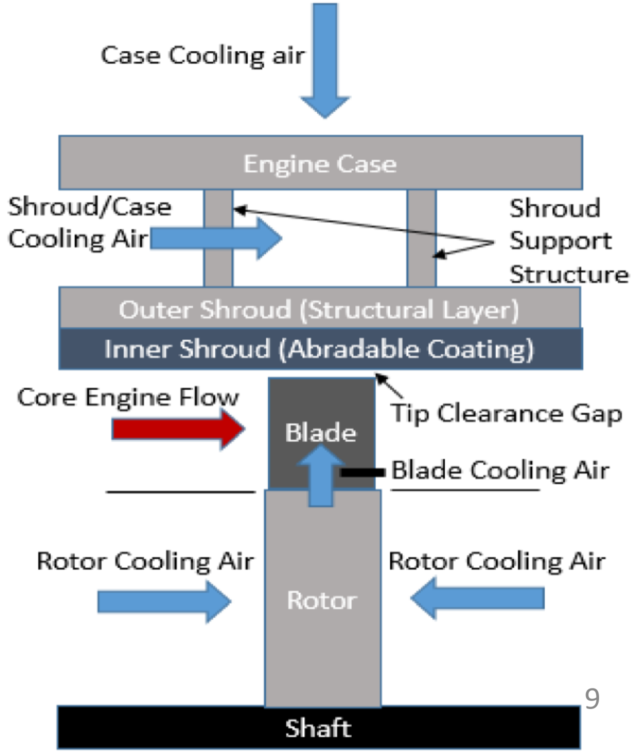
- A genetic algorithm is a type of ML based on natural selection. It starts with a population of potential solutions and evolves them over multiple generations to determine the best features
- The fuel flow schedule is determined as a ratio unit (RU) limit schedule (Wf/Ps3) vs corrected fan speed
- The power schedule starts at the maximum value and drops monotonically to zero



Model Updates

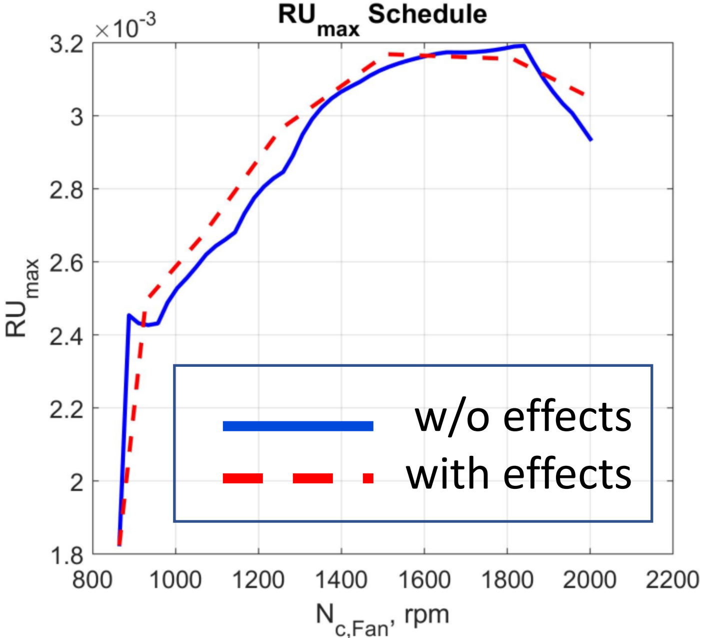
- Added two realistic features to the AGTF30
  - Heat soak (HS)
    - Engine carcass absorbs and holds heat
    - On hot restart, the heat transfer has the effect of adding fuel
    - On cold soaked starts the heat transfer has the effect of reducing fuel flow
  - Tip clearance (TC) effects
    - Tip clearance is impacted by thermal expansion and contraction and centrifugal forces at high rotational speed
    - Reducing the High-Pressure Turbine (HPT) tip clearance improves efficiency and reduces fuel burn
    - For a large commercial turbofan engine, a change of 10 mils of HPT tip clearance correlates to
      - approximately a 1% difference in SFC at cruise
      - 10˚C (18˚R) difference in exhaust gas temperature at takeoff

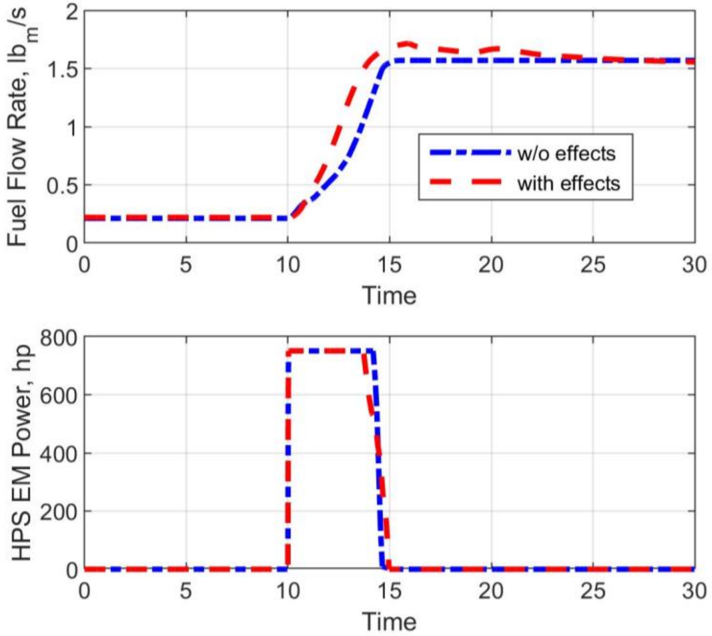




Results—Schedules

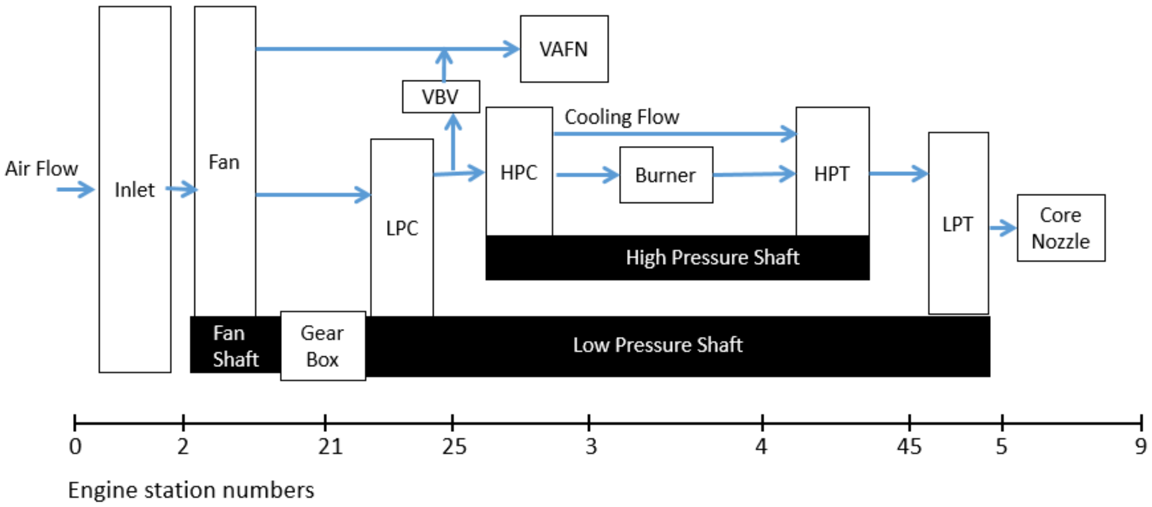
- The RU limit fuel flow schedule for the new model with TC and HS effects is more aggressive
- Acceleration takes energy from the flow to heat the engine carcass, so additional fuel is required
- The power schedules are similar in both cases due to the constraints that cause the motor to saturate. With a larger motor, the shapes could be significantly different.

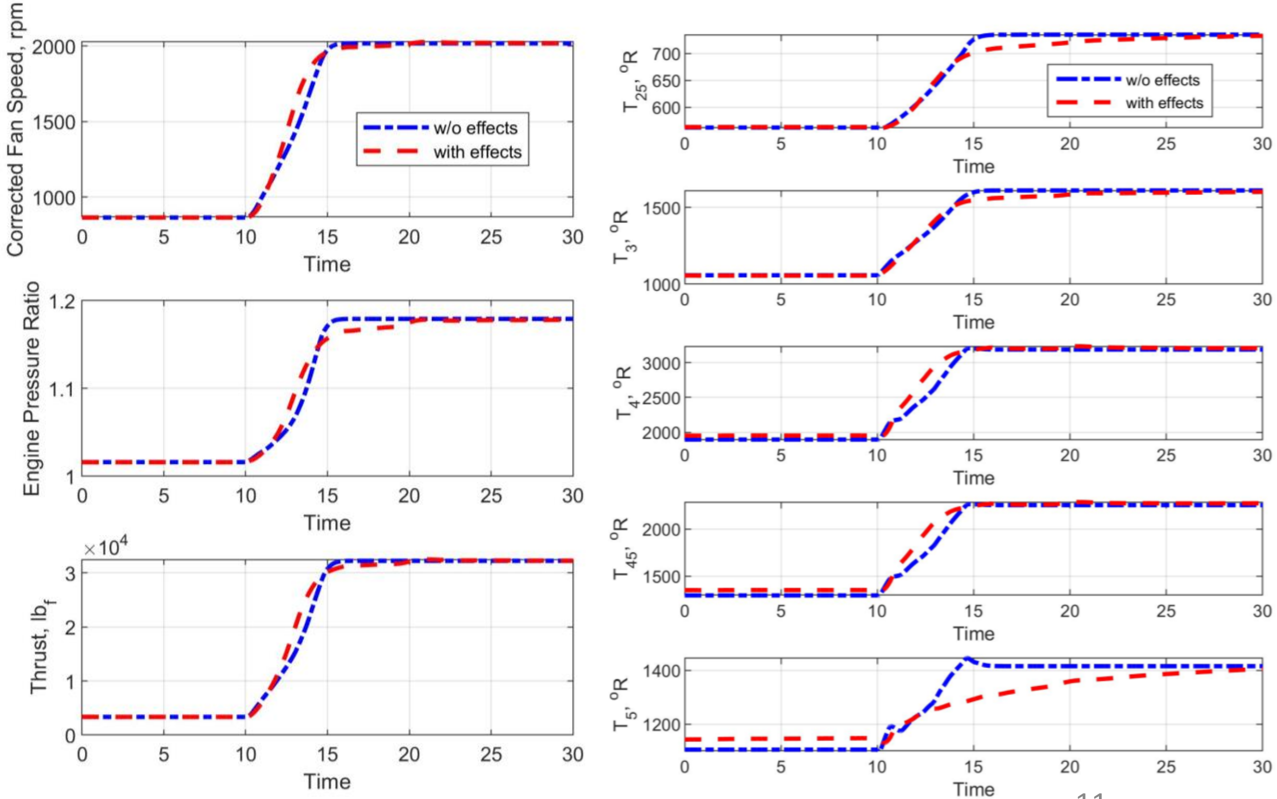




Results—Responses

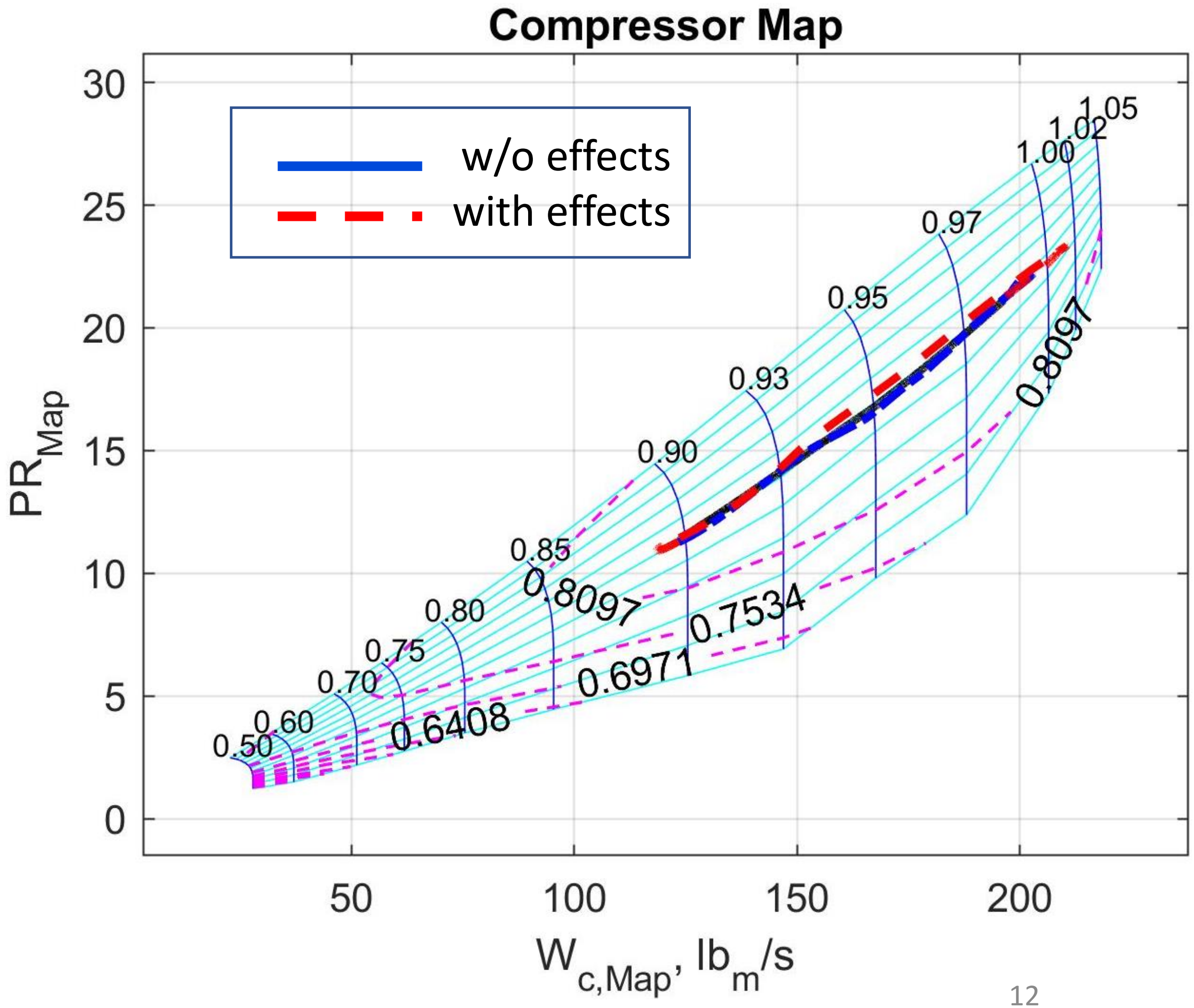
- Aggressive fuel flow due to HS effects causes initial faster responses
- Pressures (not shown) exhibited similar responses
- TC effects account for steady state temperature discrepancies at station 4 and beyond





Results—Responses

- In the previous work without TC and HS effects, the transient was collapsed onto the operating line
- In the current work with the effects, the transient excursion was still suppressed but not as much
- The greater deviation is attributed to the more aggressive fuel flow schedule



Conclusions

- The heat soak and tip clearance effects were significant, the simultaneous optimization had less effect on the results
- The new RU schedule is similar to the previous one, but more aggressive, likely due to heat soak effects
- The power schedule was only slightly changed, and only at the end of the transient; power constraints here certainly restricted the possibilities
- A major advantage of a data-driven solution is that other components of the stall margin stack can be estimated
  - ML's ability to extract patterns from data could allow an algorithm (perhaps a neural network) to estimate an engine's actual stall margin, accounting for the uncertainties that comprise the stall margin stack
  - This could be used not only to develop highly robust acceleration schedules, but also for stall avoidance as part of an advanced control scheme

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