Dynamic Analysis of the hFan, a Parallel Hybrid Electric Turbofan Engine

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Outline

• Introduction
  – Motivation
  – Engine Design Process (Systems Analysis)
  – Dynamic Systems Analysis
• NASA hFan
  – Engine
  – Closed-loop system
• Simulation Results
  – Baseline Controller
  – Dynamic Systems Analysis
• Conclusions
Introduction – Motivation

• NASA N+3 commercial aviation goals
  – Targeting 2030-2035 time frame
  – Noise, emissions, fuel burn
• Concept architectures developed to meet goals
• NASA performs research work on these concepts
  – Advanced Air Transport Technologies (AATT) project
  – Systems Analysis and Integration (SA&I) subproject
• Particular concept studied: **SUGAR Volt / hFan**
• Studying hFan can answer general hybrid questions
Introduction – Engine Design Process

- Engines are designed using **systems analysis**
  - Steady-state system-level simulations
  - Evaluate system tradeoffs to find optimal designs
- Propulsion systems designed given objectives and constraints
  - Objectives: fuel burn, emissions, noise, cost, performance
  - Constraints: component min/max operating conditions (e.g. stall margins)
  - **Transients** (dynamic) cause engine to run **closer to constraints**
  - Solution is to add **additional margin** to steady-state (design) constraint

**Component**
- Stress
- Stall margin
- Temperature, etc

**Propulsion**
- Thrust
- Fuel-burn
- Weight

**System**
- Performance
- Weight
- Cost
Introduction – Dynamic Systems Analysis

- **Performance** requirement for closed-loop system (Accelerate within 5 seconds)
- Steady-state engine design **operability** constraints include
  - **Uncertainty stack** (how much needed for off-nominal margin debits)
  - **Transient stack** (how much is needed for engine power transitions)
- Controls affects performance vs operability tradeoff

- **DSA workflow:**
  - Design family of controllers parametrically (using TTECTrA)
  - Simulate resulting closed-loop systems to obtain performance metrics
  - Metrics allow performance and operability trade to be assessed
  - Knowledge of trade enables improvements early in design phase
Introduction – Dynamic Analysis Tools

- Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)
  - Developed at NASA Glenn Research Center
  - Enables estimation of the closed-loop transient performance
  - https://github.com/nasa/TTECTrA/releases
    - TTECTrA designs controllers to protect engine during transient operation, preserving desired limits (stall margin (HPC/LPC), Fuel to Air Ratio, T40)

- Integrated TTECTrA with NPSS via S-function interface
- Enables dynamic analysis of future engine concepts
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NASA hFan

- NASA hFan (Parallel Hybrid Electric Turbofan, for SUGAR Volt aircraft)
  - Sized for high L/D, TBW, 150 PAX aircraft
    - 3500 mi max mission
    - 900 mi avg/design mission
  - Direct drive, two spool turbofan
  - N+3 cycle/technology assumptions
  - 1380 HP electric machine (EM) on LP spool
    - Assists driving fan for most of flight
    - Driven by batteries in underwing pods
Q: How does motor make this different from conventional turbofan?
A: If open loop motor power ramped up and fuel flow held constant...

- Fan goes up op-line
- LPC PR goes up
- HPC goes down op-line
- HPT doesn’t really move
- LPT Wc goes down

Takeaways:
- Adding motor power...
  - reduces LPC stall margin, affords some SM control
  - increases fan corrected speed (increases thrust)
- Control design takes this into account
TTTEC TRA control system revised to control thrust directly
- Assumes onboard thrust model (model-based engine control, or MBEC)
- Simplifies control design and analysis, and is appropriate for conceptual study

Fuel control: Gain scheduled PI with...
- Accel limiter: Wf/Ps3 max schedule
- Decel limiter Wf/Ps3 min scalar

Motor control:
- Steady-state power = f(thrust demand)
- Additional transient power = f(thrust control error)
- Saturation and rate limit prevent exceeding motor limits
- Assume maximum assist power delivered instantaneously is best
- Controller designed to do this

Baseline control design vars
- max T4 = 3140 °R
- VAFN variation <= 30% of max
- min HPC stall margin = 14%
- min LPC stall margin = 10%
- min Fan stall margin = 10%
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Simulation Results – Baseline Controller

- Analyze transient response of baseline controller
  - Run 15-100% thrust response (accel and decel) at controller design points (red points)
  - Evaluate off-design closed-loop response with Monte Carlo accel/decel simulations (blue)
- Results show closed loop system is operable throughout envelope
  - Satisfies constraints
- Closed-loop system also meets performance requirements
  - Response time less than 5 s when doing a 15-100% transient at static condition

Given baseline system is operable, next step—conduct DSA to learn more about engine.
Simulation Results – DSA

- **TTECTrA** used to tune accel limiters for different HPC stall margin constraints
  - Controllers designed for 5, 7, 9, 11, 13, and 15% minimum HPC stall margin
  - 15-100% snap accel transients ran at sea-level static for each controller
  - Thrust, stall margin responses shown
  - Response time (15% – 95% thrust) and minimum HPC stall margin metrics obtained

![Graph showing thrust, stall margin responses](image)

Each line represents response obtained with a different controller (accel limiter)

Different controller (time) response gives different minimum HPC stall margin

Compute metrics from response data

Metrics capture info regarding design tradeoffs, informing design process
Simulation Results – DSA

- Engine can accelerate in 5 s while preserving **13.0-13.5% HPC SM**
- However, this assumes baseline motor control design
  - Attempts to apply maximum motor power as soon as the transient begins
- As motor power ramp rate limit was decreased, changes to tradeoff observed
  - Varying both fuel controller accel limiter and motor ramp rate simultaneously yields following metrics

- It turns out if ramp rate chosen such that motor response time is approximately 1 second, we get a better trade (higher stall margin for a 5 second accel)
- Also examined design excursions for motor power rating (not shown; see paper)
  - More transient power not found to be beneficial for hFan system
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Conclusions

• Closed-loop N+3 hFan model demonstrated
  – NPSS model integrated into Simulink-based TTECTra controller via S-Function
  – System is operable throughout envelope

• Dynamic systems analysis conducted
  – TTECTra controllers designed to assess performance vs operability
  – Suggests steady-state HPC stall margin can be reduced, and engine redesigned
  – Conduct DSA at more flight and uncertainty conditions to obtain better estimate

• Trends observed (useful information for future work)
  – Holding other things constant, application of low spool motor power…
    • …pushes fan and HPC up and down along their op-lines
    • …pushes LPC PR up and down
  – Instantaneous application of motor power is not optimal for operability
    • Moderate ramp rate that gives a 1 second rise time is appropriate for hFan
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Questions?