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

George L. Thomas
N&R Engineering/Vantage Partners, LLC

Dennis E. Culley, Jonathan L. Kratz, and Kenneth L. Fisher
NASA Glenn Research Center

2018 AIAA Joint Propulsion Conference
July 11, 2018, Cincinnati, OH
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
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](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
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
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
NASA hFan – Closed-Loop System

- TTTECTrA 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 = \( f(\text{thrust demand}) \)
  - Additional transient power = \( f(\text{thrust control error}) \)
  - 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%
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
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

• TTTECTrA 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

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
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
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
Acknowledgments

- This work was funded by the NASA Advanced Air Transport Technologies (AATT) project

- Thanks go to others at NASA Glenn Research Center who contributed to this work
  - Jeffrey Csank
  - William Haller
  - Sanjay Garg
  - Thomas Lavelle
  - Scott Jones
Thank You!!

Questions?