Control Design for an Advanced Geared Turbofan Engine

Jeffryes W. Chapman,
Vantage Partners, LLC

Jonathan Litt,
NASA Glenn Research Center

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Outline

• Background and Objective
• Simulation Description
  • Engine Model
  • Controller Design
  • Actuator Hardware Model Design
• Mission Demonstration
• Sample Study
• Details on Model Operation
• Summary
Background

• As preparation for the next generation of aircraft, advanced high-efficiency engine concepts have been developed to demonstrate new technology.

  The Advanced Geared Turbofan, 30,000 lbf (AGTF30) engine simulation was developed to investigate possible next generation engine system designs including:
  1. Ultra-high bypass
  2. Small core
  3. Variable area fan nozzle (VAFN)

• Objective:
  – Detail the generation of a full envelope, classical control system for the AGTF30 engine.
  – Highlight challenges associated with the control system concept of this advanced engine.

• Purpose:
  – To provide a dynamic platform for next generation engine system research.
Modeling Platform

- The AGTF30 was created using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
  - Modular thermodynamic modeling framework created by NASA
  - Built on top of MATLAB/Simulink
  - Package highlights:
    - General thermodynamic simulation design framework
    - Variable input system solvers
    - Advanced turbo-machinery block sets
    - Control system block sets
    - Non-proprietary, free of export restriction and open source with +4500 downloads, [https://github.com/nasa/T-MATS/releases](https://github.com/nasa/T-MATS/releases)
Engine Model Description

- Advanced Geared Turbofan features
  - Variable area fan nozzle (VAFN)
  - Dual spool with low pressure shaft connected to fan via a gear box
- Performance
  - BPR = 24, OPR = 50, TIT = 3000, TSFC = 0.46 at cruise
  - 30,000 lbf takeoff thrust
- Control Effectors: VAFN, fuel flow (Wf), and variable bleed valve (VBV)
Fuel Control Architecture

- **Fuel Control methodology based on literature**
  - Power Management generates fan speed request based on power lever angle (PLA)
  - Fan speed controller generates a fuel flow request
  - Sets of limiters adjust the fuel flow request to operate the engine safely, avoiding engine stall, exceeding structural limits, combustor blowout, etc.
  - Controllers utilize PI method, tuned to meet requirements throughout the envelope

Acceleration limit for stall margin mitigation

Structural limits

Deceleration and Pressure limits for combustor blowout protection
Fuel Control Power Management

- Fuel is the main effector to control the engine, and thrust is the dominant engine output.
- AGTF30 utilizes a classical control strategy
  - Thrust cannot be sensed, so fan speed (Nf) was selected as the thrust surrogate
  - Advantages of using fan speed:
    - Generally linear relationship with thrust (given constant environment and consistent variable geometry positions).
    - Sensor availability and low susceptibility to noise

![Graph showing the relationship between Nf (rpm) and Thrust (lbf)](image)
Fuel Control Tuning

- PI controller gains tuned to ideal values throughout envelope
  - Linear models were generated throughout the envelope and at various power levels
  - PI controller gains were tuned for each defined linear model.
  - Gains were collected into schedules that provide the optimum gain at each operational point.

Operational Envelope

Speed Controller
Setting Fuel Limiters

- Limiters designed to maintain safe engine operation
  - Set to avoid engine stall, structural limits, and engine blow out.
    - Structural limits based on anticipated next generation requirements.
    - Stall mitigated by limiting acceleration with a maximum $W_f/P_s^3$ limit
    - Hypothetical engine blow out mitigated with minimum $W_f/P_s^3$ and $P_s^3$ limits
  - Limiters tuned to allow acceleration from idle to 95% takeoff power within 5 seconds
  - Minimum stall margin requirement set to 8%.
• Variable bleed valve opens to reduce low pressure compressor (LPC) pressure ratio (PR), increasing stall margin.
  – Schedules constructed to maintain 10% stall margin during steady-state operation.

Opening VBV to increase LPC stall margin
• Variable area fan nozzle area scheduled to maintain optimal fan efficiency.
  – Nozzle area increased to reduce fan PR
  – Nozzle area decreased to increase fan PR
Actuator Modeling

- **Fuel metering valve (FMV)**
  - First order actuator with a dynamic response much faster than rotor dynamics

- **Variable bleed valve (VBV)**
  - First order actuator with a dynamic response much faster than rotor dynamics

- **Variable area fan nozzle (VAFN)**
  - Research into VAFN actuation is ongoing
  - Thermally activated shape memory alloy is being considered as a solution
    - Advantages
      - High power-to-weight ratio
    - Challenges
      - Maximum area reduction may not meet ideal nozzle requirements
      - Slew rate may not meet engine transient requirements.
      - Low technology readiness level (TRL)
  - Due to uncertainty in actuator characteristics the AGTF30 utilizes an idealized actuation system as default, settling time equivalent to 0.8s. This value will be updated as more research becomes available.
VAFN response study

- The AGTF30 was used for a simple study to find the minimum settling time requirement for a hypothetical shape memory alloy actuator.
  - Traces show acceleration from Idle to Full power then a deceleration back to idle
  - Plots b and c show divergence from ideal actuation (tracks control request perfectly)

Settling times greater than 9.8s, generate large losses of thrust
Model Validation

- Engine Model validation
  - Simulation of an abbreviated mission profile
    - Engine idling
    - Acceleration from idle to full power followed by a take off at sea level static conditions
    - Engine climbs to cruise at 35,000 ft
    - Deceleration and descent
    - Aircraft lands then returns to idle
Model Validation, full profile

For the validation profile, all parameters remain within acceptable parameters and the engine performs as expected.
During acceleration and climb to altitude the control regulators act to maintain stall margin and maximum T45 limit.
During approach and landing the control regulators act to maintain stall margin, maximum Nf limit and minimum Ps3 limit.
Simulation Operation

- AGTF30 class definition
- Folder containing setup files
- Engine Model
- Steady-State, Dynamic, and Linearization models, all use the same Engine Model file
- Link to input definitions
- Excel spread sheet for quick input definition
- Plotting scripts
- Simulation setup and clean up scripts
Setup Everything

MWS =

    engName: 'AGTF30'
    top_level: 'C:\AGTF30'
    POp: '\'
    Cntrl: [1x1 struct]
    iDesign: 2
    Inlet: [1x1 struct]
    FAN: [1x1 struct]
    LPC: [1x1 struct]
    HPC: [1x1 struct]
    HPT: [1x1 struct]
    LPT: [1x1 struct]
    VBV: [1x1 struct]
    Burn: [1x1 struct]
    NozByp: [1x1 struct]
    NozCor: [1x1 struct]
    Duct: [1x1 struct]
    GearBox: [1x1 struct]
    Sensor: [1x1 struct]
    Act: [1x1 struct]
    Shaft: [1x1 struct]
    In: [1x1 struct]

Setup_everything.m - Loads bus objects and MATLAB Workspace (MWS) structure containing all simulation inputs
### Input File

**Enter inputs manually**

```matlab
%% Set default time vector name
DefTVNm = 't';
%% Set default time vector values
MWS = SetInput(MWS,DefTVNm, [0 10 20 20.1 50],inputs);

%% PLA or Power Code (40 to 80.5)
MWS = SetTVec(...
    MWS, 'PLA',...
    [40 40 40 80 80],...
    DefTVNm,inputs);
```

**Or use an excel spread sheet**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Input Variable</td>
<td>Associated Time Vector</td>
<td>Data:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>time (s)</td>
<td>t</td>
<td>NA</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>20.1</td>
<td>50</td>
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<tr>
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<tr>
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<tr>
<td>Delta Temperature (degF)</td>
<td>dT</td>
<td>t</td>
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<tr>
<td>PLA (deg)</td>
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<td>40</td>
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<td>40</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>
Dynamic AGTF30
Advanced Geared Turbofan Engine System
Data Presentation

Data gathered in an output structure.

```
>> out_Dyn

out_Dyn =

    act: [1x1 struct]
    cntrl: [1x1 struct]
    eng: [1x1 struct]
    loop: [1x1 struct]
    sen: [1x1 struct]
    in: [1x1 struct]
```

Formatted to make use of T-MATS auto plotting tools.
Summary

• A simulation of a next generation engine has been presented
  – Advanced Geared Turbofan 30,000lbf (AGTF30)
  • Ultrahigh bypass, small engine core, VAFN design
  • Full envelope dynamic control system
  • Built with the Toolbox for the Modeling and Analysis of Thermodynamic systems (T-MATS), https://github.com/nasa/T-MATS/releases
  • Simulation awaiting approval to be made publically available

• Control system design described
  – Fuel control based on classical architecture
  – Variable geometries scheduled

• Sensitivity study on VAFN slew rate
  – Shape memory alloy is currently being considered for use as the VAFN actuator, and actuator slew rate has been shown to be a limiting factor.
  – Analysis of ideal and potential slew rates show significant performance degradation at actuator settling times greater than 9.8s

• AGTF30 simulation meets all requirements
  – Simulation provides a realistic and dynamic platform for research into advanced geared turbofan technologies.
Acknowledgments

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