### Session 6
**Dynamic Modeling and Systems Analysis**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:00 – 1:05p</td>
<td>Overview – Jeffrey Csank</td>
</tr>
<tr>
<td>1:05 – 1:30p</td>
<td>Dynamic Systems Analysis – Jeffrey Csank</td>
</tr>
<tr>
<td>1:30 – 1:55p</td>
<td>T-MATS (Toolbox for the Modeling and Analysis of Thermodynamic Systems) – Jeffryes Chapman</td>
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</tbody>
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**4th Propulsion Control and Diagnostics Workshop**
**Ohio Aerospace Institute (OAI)**
**Cleveland, OH**
**December 11-12, 2013**
Dynamic Systems Analysis

- Preliminary Engine Design
  - Systems Analysis (Steady state)
  - Lack of dynamic performance information
    - Historical data (past experiences)
    - Additional conservatism in the design

- Dynamic Systems Analysis
  - Better predict/account for dynamic operation in PED
  - Allow for trade-offs between performance and operability margins to meet future engine performance requirements
  - Enabled through the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)
T-MATS (Toolbox for the Modeling and Analysis of Thermodynamic Systems)

- Simulation System designed to give a user a library containing building blocks that may be used to create dynamic Thermodynamic systems. Includes:
  - Iterative Solving capability
  - Generic Thermodynamic Component models
    Turbomachinery components (compressor, turbine, burner, nozzle, etc.)
  - Control system modeling (controller, actuator, sensor, etc.)
- MATLAB/Simulink Based
- Open Source (free of proprietary and export restrictions)
- Development of T-MATS is being led by NASA Glenn Research Center
  - NASA’s focus for this project is on the modeling of aerospace applications, however the T-MATS framework is extremely general and can be applied to any thermodynamic model.
Reducing Conservatism in Aircraft Engine Response Using Conditionally Active Min-Max Limit Regulators

- Typical aircraft engine control is based on a Min-Max scheme
- Designed to keep the engine operating within prescribed mechanical and operational safety limits
  - Compares fuel flow to determine the limit that is closest to being violated
  - Conservative
- Improve engine performance by allowing the limit regulators to only be active when a limit is in danger of being violated.
Dynamic Systems Analysis

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4th Propulsion Control and Diagnostics Workshop
Ohio Aerospace Institute (OAI)
Cleveland, OH
December 11-12, 2013
Team Members

• Jonathan Seidel, NASA Glenn Research Center/RTM
• Jeffrey Chin, NASA Glenn Research Center/RTM
• Alicia Zinnecker, N&R Engineering
• Georgia Institute of Technology
Outline

• Preliminary Engine Design
• Systems Analysis
• Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)
• Dynamic Systems Analysis
• Conclusion
Preliminary Engine Design

- Huge commitments are made based on results
- A completely new engine is relatively rare
- Most programs focus on derivative engines

Mission

Weight

Cycle

Scaling

Configuration

Component Test

Component Design

Performance

Manufacture

Performance

Manufacture
Systems Analysis

• Complex process that involves system-level simulations to evaluate system-level performance, weight, and cost (optimize system, compromise component)

• Focus on steady-state design cycle performance

• Dynamic considerations and issues are incorporated through the use of operating margins
  – Stall margin

[Graph showing corrected flow (Wc) vs. pressure ratio (PR)]
Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)

- Capable of automatically designing a controller
- Easily integrates with users engine model in MATLAB/Simulink environment
- Provide an estimate of the closed-loop transient performance/capability of a conceptual engine design
- Requirements:
  - MATLAB®/Simulink® (Release R2012b or later)
    - MATLAB® Version 8.0 (R2012b)
    - Simulink® Version 8.0 (R2012b)
    - Control Systems Toolbox® Version 9.4 (R2012b)
  - Engine Model compatible with Simulink
  - State space linear model in MATLAB
TTECTrA software automatically designs:

- Set Point
- Set Point Controller
- Limit Controller

Simulates different thrust profiles
TTECTRxA - Set Point Function

- Flight condition (altitude, Mach, temperature)
- Define set point bounds and number of breakpoints
  - Fuel flow
  - Thrust

Close figure to accept setpoints
Leave figure open and use GUI to recalculate
TTECTrA – Set Point Controller

- Bandwidth (Hz)
- Phase Margin
- **Feedback filter (Hz)**
- **Throttle Filter (Hz)**
TTETrA – Limit Controller

- **Acceleration Minimum Surge Margin (HPC)**
  - $N_{\text{cdot}}$ vs $N_{\text{cR25}}$

- **Deceleration Minimum Surge Margin (LPC)**
  - $Wf/Ps3$

![Graph showing corrected core speed vs core acceleration]
• **Selector Logic (Min/Max scheme)**
  – Min (Set Point, Acceleration)
  – Max (Min, Deceleration)

• **Actuators**
  – Currently only models fuel flow
  – First order filter
Commercial Modular Aero Propulsion System Simulator 40,000 (C-MAPSS40k)

- 40,000 Lb Thrust Class High Bypass Turbofan Engine Simulation
- Matlab/Simulink Environment
- Publically available
- Realistic controller
- Realistic surge margin calculations
Burst and Chop Thrust Profile

- Idle (14% of max thrust) to Take-off thrust profile to test the TTECTrA controller
- Compare the thrust response to the Federal Aviation Administrations (FAA) Federal Aviation Regulation (FAR) Part 33, Section 33.73(b)
Burst and Chop Thrust Profile

Graphs showing:
- HPC SM, %
  - Time, s
- LPC SM, %
  - Time, s
- Nc_{dot}
  - NcR25
- Wc/Pr3
  - Time, s
Engine Deterioration

- Thrust, lbf
- Control Variable
- HPC SM, %
- LPC SM
The Benefit of TTECTrA

Do we have enough margin? Too much margin?

<table>
<thead>
<tr>
<th>Stack</th>
<th>%</th>
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<tbody>
<tr>
<td>Uncertainty</td>
<td>11</td>
</tr>
<tr>
<td>Reynolds Number</td>
<td>2</td>
</tr>
<tr>
<td>Distortion</td>
<td>4</td>
</tr>
<tr>
<td>Tip Clearances</td>
<td>1.5</td>
</tr>
<tr>
<td>Deterioration</td>
<td>1.5</td>
</tr>
<tr>
<td>Random</td>
<td>2</td>
</tr>
<tr>
<td>Transient Allowance</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
</tr>
</tbody>
</table>
The Benefit of TTTECTrA

- Combustor Stability
- Low Pressure Compressor
- Turbine life
Future Work

• NPSS Model in Simulink
  – Georgia Institute of Technology

• Integrate TTECTrA with the NPSS Simulink model
  – NASA/RHC

• Integrate TTECTrA/NPSS Simulink with a larger systems analysis optimization algorithm
  – NASA/RHC and NASA/RTM
Conclusion

• Dynamic systems analysis:
  – Enables engine transient performance to be accounted for in the optimization of the engine design and early in the preliminary design of turbine engines.
  – Allows trading of overly conservative surge margin for better performance through system redesign (or opline).

• Developed the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)
  – Capable of automatically designing a controller at a single flight condition.
  – Easily integrates with users engine model in MATLAB/Simulink environment.
  – Open source
Thank you

Questions?
Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

Jeffryes W. Chapman
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4th Propulsion Control and Diagnostics Workshop
Ohio Aerospace Institute (OAI)
Cleveland, OH
December 11-12, 2013
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Outline

• T-MATS Description
• Background
• Framework
• Block Sets
• Examples
• Conclusion
• Future work
T-MATS Description

• Toolbox for the Modeling and Analysis of Thermodynamic systems, T-MATS
  – Modular thermodynamic modeling framework
  – Designed for easy creation of custom Component Level Models (CLM)
  – Built in MATLAB®/Simulink®

• Package highlights
  – General thermodynamic simulation design framework
  – Variable input system solvers
  – Advanced turbo-machinery block sets
  – Control system block sets

• Development being led by NASA Glenn Research Center
  – Non-proprietary, free of export restrictions, and open source
    • Open collaboration environment
Background

• Thermodynamic simulation examples

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Examples</th>
</tr>
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<tbody>
<tr>
<td><strong>Steady-State</strong></td>
<td>Gas turbine cycle model</td>
</tr>
<tr>
<td>(system convergence may be required)</td>
<td>• e.g., performance models</td>
</tr>
<tr>
<td><strong>Dynamic with Quasi-steady-state variables</strong></td>
<td>Gas turbine model with spool dynamics only. (real time running capability)</td>
</tr>
<tr>
<td>(multi-iteration simulation; time and system convergence)</td>
<td>• e.g., control models</td>
</tr>
<tr>
<td><strong>Fully Defined Dynamic Simulation</strong></td>
<td>Dynamic gas turbine model with spool and volume dynamics (typically runs more slowly)</td>
</tr>
<tr>
<td>(iteration over time)</td>
<td>• e.g., near stall performance models</td>
</tr>
</tbody>
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## Background: Industry Study

<table>
<thead>
<tr>
<th>Package</th>
<th>User Friendly*</th>
<th>Flexibility*</th>
<th>Export Restricted</th>
<th>Source code available</th>
<th>Dynamic</th>
<th>Control System</th>
<th>Cost</th>
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<tbody>
<tr>
<td>C-MAPSS40k, NASA</td>
<td>High</td>
<td>Low</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>MATLAB</td>
</tr>
<tr>
<td>Matlab: Thermlib toolbox, Eutech</td>
<td>High</td>
<td>Medium</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>MATLAB + $4900</td>
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<tr>
<td>Cantera, Open source</td>
<td>Low</td>
<td>High</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>None</td>
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<tr>
<td>Gas Turbine Simulation Program (GSP), NRL</td>
<td>Medium</td>
<td>Medium</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>$4,000</td>
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<tr>
<td>GasTurb, Nrec</td>
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<td>Yes</td>
<td>Yes</td>
<td>$1340</td>
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<tr>
<td>T-MATS, NASA</td>
<td>High</td>
<td>High</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>MATLAB</td>
</tr>
</tbody>
</table>

**Definitions:**

1* User Friendly, Controls Perspective
   - Low: Code based
   - Med: Model based
   - High: Model based with package implemented in a platform that is an industry standard

2* Flexibility
   - Low: Plant configuration set
   - Med: Object oriented, objects difficult to update
   - High: Object oriented, objects easily adaptable by user
T-MATS Framework

- T-MATS is a plug-in for a MATLAB/Simulink platform
  - additional blocks in the Simulink Library Browser:
    - Added Simulink Thermodynamic modeling and numerical solving functionality
  - additional diagram tools for model development in Simulink:
    - Faster and easier model creation
T-MATS Framework

- **Dynamic Simulation Example:**
  - Multi-loop structure
  - The “outer” loop (green) iterates in the time domain
    - Not required for steady-state models
  - The “inner” loop (blue) solves for plant convergence during each time step
Blocks: Numerical Solver

• Many Thermodynamic models are partially defined and require a solver to ensure model conservation (e.g., mass, energy, etc.).
  – In many gas turbine simulations, component flow will typically be solved by an independent solver.

• T-MATS contains solvers that perform in two main steps:
  – Automated Jacobian (system gradient) Calculation

\[
J = \begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\
\vdots & \ddots & \vdots \\
\frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_n}
\end{bmatrix}
\]

  • Each plant input is perturbed to find the effect on each plant output.
  – Newton-Raphson method is used to “converge” the system.

\[
x(n + 1) = x(n) - \frac{f(x(n))}{f'(x(n))}
\]

where,

\[
f'(x(n)) = J
\]
Blocks: Turbo-machinery

- **T-MATS contains component blocks necessary for creation of turbo-machinery systems**
  - Models based on common industry practices
    - Energy balance modeling approach
    - R-line compressor maps in Compressor model
    - Pressure Ratio maps in Turbine model
    - Single fuel assumption
    - Flow errors generated by comparing component calculated flow with component input flow
  - Includes blocks such as: compressor, turbine, nozzle, flow splitter, and valves among others.
  - Built with S-functions, utilizing compiled MEX functions
Blocks: Controls

- **T-MATS contains component blocks designed for fast control systems creation**

  - **Sensors:**
    
    ![Sensors Diagram]

  - **Actuators:**
    
    ![Actuators Diagram]

  - **PI controllers:**
    
    ![PI controllers Diagram]
The T-MATS Simulation System is a highly tunable and flexible framework for Thermodynamic modeling.

- T-MATS block Function Block Parameters
  - fast table and variable updates

- Open source code
  - flexibility in component composition, as equations can be updated to meet system design

- MATLAB/Simulink development environment
  - user-friendly, powerful, and versatile operation platform for model design
Dynamic Gas Turbine Example: Objective System

Simple Turbojet
Dynamic Gas Turbine Example: Creating the Inner Loop
Dynamic Gas Turbine Example:
Inner Loop Plant

Turbojet plant model architecture made simple by T-MATS vectored I/O and block labeling
Dynamic Gas Turbine Example: Creating the Solver

- **Outer Loop Effectors**
- **Inner Loop Plant**
- **Outputs**
- **Do While Simulink Block**
- **Iterative Solver**
- **Outer Loop Plant**
Dynamic Gas Turbine Example: Solver

Plant flow errors driven to zero by iterative solver block in parallel with While Iterator
Dynamic Gas Turbine Example: Creating the Outer Loop
Dynamic Gas Turbine Example: Outer Loop Plant

Environmental conditions

Simple Control System

Shaft speed integration

Shaft integrator and other Outer Loop effectors added to create full system simulation
Verification and Release

• Verification was performed by matching T-MATS simulation data with other established simulations.
  – Models chosen for verification
    • NPSS steady-state turbojet model
    • C-MAPSS – High bypass turbofan engine model
  – In all cases differences in simulation performance were within acceptable limits.

• Expected Release: Q4, 2013 or Q1, 2014.
  – Pre-built examples will include:
    • Newton-Raphson equation solver
    • Steady state turbojet simulation
    • Dynamic turbojet simulation
Conclusions

• T-MATS offers a comprehensive thermodynamic simulation system
  – Thermodynamic system modeling framework
  – Automated system “convergence”
  – Advanced turbo-machinery modeling capability
  – Fast controller creation block set
Future Work

• Increase thermodynamic modeling capability
  – Introduce Cantera to T-MATS
    • “Cantera is a suite of object-oriented software tools for problems involving chemical kinetics, thermodynamics, and/or transport processes”
    • Open source
    • Increases thermodynamic modeling capability to include:
      – Non-fuel specific gas turbine modeling
      – Fuel cells
      – Combustion
      – Chemical Equilibriums

\[
O + CH \Leftrightarrow H + CO
\]
Reducing Conservatism in Aircraft Engine Response Using Conditionally Active Min-Max Limit Regulators

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4th Propulsion Control and Diagnostics Workshop
Ohio Aerospace Institute (OAI)
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December 11-12th, 2013
Overview

• Introduction
• Baseline Control Architecture
• Conditionally Active Limit Regulator Approach
• Simulation Examples
• Conclusions & Future Work
Introduction

• The primary task of an engine control system is to deliver the guaranteed performance while ensuring safe operation throughout operating envelope over the life of the engine.

• Guaranteed performance is defined as meeting the FAA certification requirements for engine responsiveness – maximum allowed 95% rise time for idle to max thrust command.
Baseline Control Architecture

- Typical aircraft engine control is based on a Min-Max scheme
- Designed to keep the engine operating within prescribed mechanical and operational safety limits
Engine Response with Baseline Control

- C-MAPSS40k Full throttle burst at sea-level static conditions with an end-of-life engine

- Acceleration limit regulator is active immediately even though it is far from the limit - Conservative Response
Is the Conservative Response an issue?

- **No:**
  - Not during normal flight as long as it meets the FAA response requirements

- **Yes:**
  - On aircraft where primary flight control surfaces are damaged (e.g. UAL 232, Bagdad DHL, AA 587)
  - On aircraft with integrated flight/propulsion control

- Can we improve the engine response while maintaining the current architecture?
The Case for Conditionally Active Limit Regulators

• The baseline Min-Max selection control approach is inherently conservative
• Every limit regulator is capable of limiting fuel flow to engine – regardless of proximity to current limit
• Depending on how the individual PI regulators are tuned, the regulator may intervene when there is no danger of a limit being violated
• To reduce conservatism, limit regulators should become active only when a limit is in “danger” of being violated.
Conditionally Active Limit Regulators

• For operation with reduced conservatism while still ensuring safety, following two criteria must both be satisfied to enable a limit regulator:
  1) The regulated variable must be “close” to the specified limit
  2) The rate of change of the regulated variable is such that the regulated variable will reach the limit within a specified number of control update time steps
Conditionally Active Limit Regulators

• The conditions for the limit regulator to be active can be stated as:

For a maximum limit variable $y_1$ with limit $y_{1\text{max}}$:

$$y_1 \geq (1 - \alpha_1) \times y_{1\text{max}}$$

–where $\alpha_1$ and $\beta_1$ are positive design parameters

• Similar equations can be developed for minimum limit variables
Conditionally Active Limit Regulators

Graphical interpretation:

- Criteria 1 is satisfied at $t_A$
- Criteria 2 is satisfied at $t_B$
- Therefore the limit regulator is enabled at $t_B$
CA Architecture Modifica

Uses the existing Min-Max architecture, but each regulator’s output is only considered if the associated criteria are satisfied.
Choice of CA Design Parameters

• We currently do not have an analytical approach to selecting the CA limit regulator design parameters $\alpha$ and $\beta$
• The CA parameters are tuned empirically
  – - $\alpha$ value selected first to ensure limit is not violated for operation under worst case conditions
  - With a fixed $\alpha$, the $\beta$ value is selected to provide fastest possible response without violating limit
• Numerical optimization algorithm has been developed
Simulation Results

- Full throttle burst at sea-level static conditions with an end-of-life engine

- Reduced conservatism resulting in much faster response
Simulation Results

- Case when a limit (Nc) is reached
Conclusions

• The use of properly tuned Conditionally Active limit regulators can improve the engine response without compromising safety
• This approach should simplify the tuning and validation of the limit regulator gains as the regulators are only active in a small number of possible cases
• The CA limit regulator does not require modifications to any other aspect of the well established control architecture
Future Work

• Formulate the CA limit regulator approach in a proper mathematical framework
• Investigate development of analytical approach to determining the CA design parameters so as to satisfy performance and safety requirements
References

