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

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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>
</thead>
<tbody>
<tr>
<td><strong>Steady-State</strong> (system convergence may be required)</td>
<td>Gas turbine cycle model</td>
</tr>
<tr>
<td></td>
<td>• e.g., performance models</td>
</tr>
<tr>
<td><strong>Dynamic with Quasi-steady-state variables</strong> (multi-iteration simulation; time and system convergence)</td>
<td>Gas turbine model with spool dynamics only. (real time running capability)</td>
</tr>
<tr>
<td></td>
<td>• e.g., control models</td>
</tr>
<tr>
<td><strong>Fully Defined Dynamic Simulation</strong> (iteration over time)</td>
<td>Dynamic gas turbine model with spool and volume dynamics (typically runs more slowly)</td>
</tr>
<tr>
<td></td>
<td>• e.g., near stall performance models</td>
</tr>
</tbody>
</table>
## 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>
</tr>
</thead>
<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>
</tr>
<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>
</tr>
<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>
<td>Medium</td>
<td>Low</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>$1340</td>
</tr>
<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

![Diagram of Turbo-machinery blocks]
Blocks: Controls

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

- Sensors:

- Actuators:

- PI controllers:
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

- **Outer Loop Effectors**
- **Inner Loop Plant**
- **Do While**
  - Iteration Condition
- **Iterative Solver**
  - Iteration to ensure convergence, n
- **Outer Loop Plant**
  - Iteration over time, t

Outputs:
- y(t)
- f(x(n))
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**
  - Iteration to ensure convergence, n
  - Iterations
- **Outer Loop Plant**
  - Iteration over time, t
  - $X_{ol}(t+dt)$
  - $X_{ll}(n+1)$
  - $f(x(n))$
  - $y(t)$
Dynamic Gas Turbine Example: Solver

- Simulink While Iterator block
- Inner Loop Plant from previous slide
- Iterative Solver

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

Outer Loop Effectors

Inner Loop Plant

Outputs

Do While

Iteration to ensure convergence, n

Outer Loop Plant

y(t)
f(x(n))

X_ol(t+dt)

Iteration over time, t

X_il(n+1)

f(x(n))

T-MATS Block

Simulink Block

Do While

Iterations

X_il(n+1)
Dynamic Gas Turbine Example: Outer Loop Plant

Environmental conditions

Shaft speed integration

Simple Control System

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

\[
O + CH \leftrightarrow H + CO
\]