Reduction of Model Order Based on LTI for Battery System Thermal Simulation

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Motivation of Using Model Order Reduction

- CFD as a general thermal analysis tool is accurate but
  - Can be expensive for large system level repeated transient CFD analysis
  - Can be cumbersome to couple with electrical circuit model for large system analysis
Motivation of Using Model Order Reduction

• Seek reduced order models for system level transient analysis
  – Thermal network (use thermal resistors and capacitors, etc)
    • Compromised accuracy
    • Needs careful calibration and calculation of thermal resistance, capacitance
  – LTI method (state space)
    • Can be as accurate as CFD or even testing
    • No need to calculate thermal resistance, capacitance
    • Rely on linearity and time invariance
What is an LTI system?

• A LTI system is a **Linear Time Invariant (LTI)** system
  • Output of such a system is completely characterized by its impulse (or step) response in that the output of the system under any input is simply the convolution of the impulse response and the input.

• Battery cooling problem can be treated like a system, in which the inputs are the power dissipation by individual batteries and the outputs are temperatures at user specified locations.
Characteristics of LTI Systems

Output of a LTI system is completely characterized by its impulse or step response*!

If two LTI systems have the same impulse or step response, the two systems are equivalent!!

Use the simple state space LTI model to represent the complex thermal LTI system.

* Under the condition of initial rest
State Space Approach for One Input One Output System

- State space model is an LTI system

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{align*}
\]

\(x\) : internal states, no physical meaning

\(u\) : heat dissipated, input

\(y\) : temperature, output

- Goal: Find coefficient matrices \(A, B, C,\) and \(D\) such that the state space model gives the same step response as the thermal system.
An One Input and One Output LTI Battery Thermal System

Battery Heat $\rightarrow$ LTI $\rightarrow$ Battery Temperature

- CFD results shown are pressure contour and velocity vectors
State Space Model vs FLUENT CFD

- Identical results obtained between FLUENT CFD calculation and state space model
- State space takes a fraction of second to compute
Multiple Inputs/Outputs LTI System

For multiple inputs and outputs, use superposition since the system is linear. A matrix of state space is used.

\[
\begin{bmatrix}
\dot{x} &= Ax + Bu \\
y &= Cx + Du \\
\dot{x} &= Ax + Bu \\
y &= Cx + Du \\
\vdots \\
\end{bmatrix}
\]

Represents the relationship between 2\textsuperscript{nd} input and 1\textsuperscript{st} output

\[
\begin{bmatrix}
\dot{x} &= Ax + Bu \\
y &= Cx + Du \\
\dot{x} &= Ax + Bu \\
y &= Cx + Du \\
\vdots \\
\end{bmatrix}
\]

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Reduced Order Model Extraction Process Using Simplorer 9.0

1. Create step responses
   • From CFD / Test
2. Generate .simpinfo file
3. Extract equivalent thermal model
   - Use Simplorer
4. Simulate inside Simplorer
Six-Cell Module Test Case
Geometry/Mesh

- Inputs: heat source to each battery
- Outputs: battery volume average temperature
State Space vs FLUENT

- State space and Fluent give identical solution under arbitrary sinusoidal power inputs
  - State space model runs in a few seconds while the full CFD model could take a couple of hours to run.
LTI Model Extraction for a General Motors Battery Module Example

State space model gives the same results as CFD. State space model runs in less than 5 seconds while the CFD runs 2 hours on one single CPU.

Example: A Battery Module Coupled Analysis

\[ V_{oc} = f(SOC, U1.Temp\_block\_1) \]
LTI Approach for Flow Rate Change of 100%

- Heat dissipation inputs are sinusoidal functions
- Flow rate changes at time of 1000 second.
- Results are excellent for the entire duration. A small difference is seen during transition period.
• Non-linear CFD: Ideal gas law plus temperature dependent properties are used. Full Navier-Stokes equations are solved

• LTI: Assumes the system is linear and time invariant.

• A speed-up factor of 10,000 is observed. Huge time saving if the error, which is about 2%, is acceptable.
• Non-linear CFD: Ideal gas law plus temperature dependent properties are used. Full Navier-Stokes equations are solved.

• LTI: Assumes the system is linear and time invariant.

• A speed-up factor of 10,000 is observed. Huge time saving if the error, which is about 1.4%, is acceptable.
Conclusion

• Battery system level thermal management can be greatly simplified by using state space model.

• Results show that the state space approach gives identical solution compared with the Fluent CFD calculation under LTI assumption.

• State space approach, however, is much faster than CFD calculation. Seconds rather than hours of run time has been shown on a few test cases.

• Multiple flow rates can be handled with multiple sets of state space model with good accuracy.

• Non-linearity is not strong to affect thermal performance for the temperature range seen in battery application.
Thank you !!