Efficient electro-thermal battery pack simulation with model order reduction

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Outline

• Battery simulation introduction
• Model order reduction by projection
• Case studies
  – MIMO, 99 inputs
  – Electro-thermal pack model
  – Expansion pass
  – MOR switch
• Summary
Battery simulation

• Cell level
  – Electrodes design
  – User: Cell producers
• Pack level
  – Battery management systems (BMS)
  – User: OEM, Auto makers
• Vehicle level
  – Complete system integration
  – User: OEM, Auto makers
Battery simulation

• Cell level
  – Electrodes design
  – User: Cell producers

• Pack level
  – Battery management systems (BMS)
  – User: OEM, Auto makers

• Vehicle level
  – Complete system integration
  – User: OEM, Auto makers
Battery pack level: Electrical predictions

- Model for each cell
  - Limiting current
  - Heat generation
  - SOC

- No need of 3D local effects in pack level
  - System level model are indicated
    - P2D, Newman
    - Impedance (circuits)
Battery pack level: Thermal predictions

• Cooling system models
  – CFD, FEM
• Heat sources
  – Battery cells
  – Power electronics
• Cell temperatures
  – Local, 3D
Electro-Thermal simulation for BMS

- Cell electrical model
  - \( f(\text{Temp}, \text{SOC}, I, \ldots) \)

- Battery pack thermal model
  - Hot spots
    - Spatial resolution

Low CPU cost \( \rightarrow \) Reduced order model
Bring 3D thermal model to system level

- ANSYS MOR Techniques for linear problems:
  - Transfer function based (or LTI method)
  - System matrix based

Presentation focus

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MOR for ANSYS

- Projection onto low-dimensional subspace

\[ x = Vz + \varepsilon \]

\[ E\dot{x} + Kx = Bu \]

- Advantage:
  - NO transient solution with the original FEM model is necessary
  - Highly accurate (linear systems)
  - As accurate as the original FEM model

\[ V^T EV\dot{z} + V^T KVz = V^T Bu \]
Implicit Moment Matching

- Padé approximation
- Matching first moments for the transfer function

\[
Ex + Kx = Bu
\]

\[
H(s) = (sE + K)^{-1} B
\]

\[
H = \sum_{i=0}^{\infty} m_i (s - s_0)^i
\]

\[
H_{\text{red}} = \sum_{i=0}^{\infty} m_{i,\text{red}} (s - s_0)^i
\]

\[
m_i = m_{i,\text{red}}, \quad i = 0, \ldots, r
\]

\[
s_0 = 0
\]

\[
V = \text{span}\{\mathcal{Z}(K^{-1}E, K^{-1}b)\}
\]

• Implicit Moment Matching:
  - via Krylov Subspace
Example: battery pack FEM

- Part of a battery pack
  - 4 Cells (pouch)
  - Cooling by 3 air channels
- 3D FEM model in ANSYS
  - Uniform heat generation in each cell
- 1D fluid channels
  - Coupling by heat transfer coefficient
Reduced vs full solution

Step response of 1W per cell

<table>
<thead>
<tr>
<th></th>
<th>Reduced</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation time [s]</td>
<td>4000</td>
<td>4000 (100 time steps)</td>
</tr>
<tr>
<td>Dimension</td>
<td>40 (10 x Input)</td>
<td>48500 elements</td>
</tr>
<tr>
<td>CPU time [s]</td>
<td>&lt;1</td>
<td>~20 min</td>
</tr>
</tbody>
</table>

Error <1%

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Industrial battery pack model

• Pouch cells

• Cooling by Air
  – Rectangular channels

Cutting detail

Simplified CFD domain
How to use 1D CFD element

CFD (CAD cut) 1D CFD + Thermal simulation (complete CAD)

Average film coefficient

3D thermal transient

FLUID116
More complex battery pack model

• 3 layers of 33 cells
  – 99 inputs
• Numerics
  – FEM: 68000 DOFs
  – Dimension of reduced order model: 10*99
• Results (4000s)
  – Simpler: 5min 48s
  – Full solution: 80 min
**Electro-thermal battery modeling: cell model**

- Circuit based (empirical)
  - One model per cell
  - Temperature dependent

Look-up tables from experiments

\[ r_1 = f(SOC, T) \]
\[ r_2 = f(SOC, T) \]
\[ R_1 = f(SOC, T) \]
\[ t_1 = f(SOC, T) \]
\[ t_2 = f(SOC, T) \]
\[ \text{DifFactor} = f(I, T) \]
\[ \text{ButlerVolmerFactor} = f(I) \]

Circuit elements

\[
\begin{align*}
R_1 &= r_1 \cdot \text{ButlerVolmerFactor} \\
R_2 &= r_2 \cdot \text{DifFactor} \\
R_I &= \frac{t_1}{R_1} \\
C_1 &= \frac{t_1}{R_1} \\
C_2 &= \frac{t_2}{R_2} \\
U_{OCV} &= \end{align*}
\]
Electro-thermal battery modeling: Example

Cell model → Heat → Battery pack

Heat → Temperature

Graphs showing voltage and temperature over time for different rates.
Recover the Temperature field

• From system results back to 3D whenever desired
  – Expansion pass

\[ x = \begin{bmatrix} V \\ Z \end{bmatrix} \]

1W/per cell step response, and recovering instants
Recover the Temperature field - Validation

REDUCED

FULL

A

B

C

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When Fluid flow changes

• Co-simulation
  – CFD solver + Simulor

• Transfer function based
  – LTD

• Projection techniques:
  – Parametric MOR
  – ROM switch

Control

Velocity

Temperature
BACKGROUND – ROM switch

\[ x = Vz + \varepsilon \]

\[ E\dot{x} + Kx = Bu \]

\[ V^T EV\dot{z} + V^T KVz = V^T Bu \]

\[ V_I z_I + \varepsilon_I = V_{II} z_{II} + \varepsilon_{II} \]

Assume: \[ V_I z_I = V_{II} z_{II} \]

\[ z_{II} = V_{II}^T V_I z_I \]

ROM = Reduced Order Model
ROM switch example

• Example
  – ROM1: with fluid velocity V
  – ROM2: with fluid velocity V*0.001

• Validation
  • ROM1 (green), ROM 2 (blue), ANSYS (red)
  • Differences are smaller than the line thickness
Summary

• Efficient electro-thermal simulation by reduction of THERMAL models
• MOR with projection techniques by moment matching
  – Automatic MOR from ANSYS to Simploter
• Complex models with more inputs are feasible
• Field values (Temperature) recovering from system solution
• ROM switch for changing conditions in the system matrices (velocity)
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