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Model Order Reduction for Thermal Management in Battery and Power Electronics

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Outline

• Motivation of model order reduction (MOR)
• Introduction to ANSYS MOR
• Linear and time-invariant (LTI) based MOR
• Examples
• Conclusion
Motivation of MOR

• CFD as a general thermal analysis tool is accurate.
  • Can be computationally expensive for large cases running transient CFD analysis
• MOR can significantly reduce the model size and simulation time.
Introduction to ANSYS MOR Technology

- Model order reduction (MOR) for linear problems
  - LTI based (aka transfer function based)
  - System matrix based

- Model order reduction (MOR) for non-linear problems
  - Proper orthogonal decomposition (POD)
  - Currently investigating other technologies
Introduction to ANSYS MOR Technology

• Model order reduction (MOR) for linear problems
  • LTI based (aka transfer function based)
  • System matrix based

\[
E \cdot x + K \cdot z = F
\]

\[
E_r \cdot x_r + K_r \cdot z_r = F_r
\]
Output of an 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.

Seek a simple LTI system to represent the original complex LTI system
MOR Using Icepak-Simplorer Coupling

1. Create the CFD model
2. Generate step responses
   - Use Icepak Parameters and Optimization tool
3. Extract LTI model
   - Use Simplorer
4. Simulate inside Simplorer
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.


• 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.

Simplorer 9/10 Limitations

- Simplorer uses a simplified state space model.
  - Can NOT model systems with complex conjugate poles
  - Can NOT model systems with oscillatory step response
  - This limitation does not affect thermal applications
- Simplorer performs the fitting using the time domain LM method.
  - Only robust for lower order state space models
  - Reduces accuracy for more complex problems
- None of the limitations shown are limitations of LTI approach. Rather, they are all limitations of Simplorer 9 current implementation.
- These limitations can be removed by using a better technique, called vector fitting (VF).
For some cooling applications, a higher order LTI model is needed. The current Simplorer 9 implementation gives large numerical error.

Prismatic battery cells example

Electronics cooling example
Introduction of Vector Fitting

• Idea: A signal, for instance impulse response, and its Fourier transform have the same amount of information. So, instead of curve-fitting in the time domain, the curve-fitting is done in the frequency domain for Fourier transform of the impulse response.
Vector Fitting in Simplorer 11

- Provides matrices A, B, C, and D
- Provides tools to plot fitting results
Electronics Cooling

• The vector fitting method gives much more accurate results for the electronics cooling example.

Battery Example with Prismatic Cells

- The battery module has 20 prismatic cells.
- Water cooling is used.
- Average temperature of each cell is monitored.
- The LTI model has 1 input and 20 outputs.

• Using VF only two equations are solved in the reduced model. The run time reduces from 5 seconds to less than 1 second.

MOR for Newman P2D Electrochemistry Model

- Equations are highly non-linear overall.
- However, solid-phase diffusion equations are linear. And solid-phase diffusion is the most time consuming part of the P2D model.
- Use LTI modeling technique to model the diffusion process and keep the rest non-linear equations intact.

\[
\eta = (\phi_i - \phi_F) - U
\]

\[
i_0 = k(c) \alpha^s (c_{s,\max} - c_{s,i})^{\alpha^s} (c_{s,F})^{\alpha^F}
\]

\[
\frac{\partial (\varepsilon_i c)}{\partial t} = \nabla \cdot (D_i \nabla c) + \frac{1 - t^*}{F} j^{Li}
\]

\[
j^{Li} = a_j i_o \left\{ \exp \left[ \frac{\alpha^F F}{RT} \eta \right] - \exp \left[ - \frac{\alpha^F F}{RT} \eta \right] \right\}
\]

- Electrochemical Kinetics
- Solid-State Li Transport
- Electrolytic Li Transport
- Charge Conservation/Transport
- (Thermal) Energy Conservation
Solid-Phase Diffusion Validation of LTI

- Even the 3rd order model gives good accuracy.
- Log scale shows that dynamics near time of zero is captured accurately by the LTI model.

The LTI model reduces the problem size by a factor of 7 and the reduced model runs approximately 6 times faster.

The accuracy is retained by using the LTI approach.

LTI modeling allows for non-spherical particles.

Impact of Particle Shapes on Cell Performance

![Graph showing impact of particle shapes on cell performance](image)

What is LPV Modeling?

• LTI models can only handle one value of a scheduling parameter (think of flow rate).

• LPV stands for linear parameter-varying. LPV models are used to model LTI systems with changing scheduling parameters.

• Methodology: a set of LTI models are identified corresponding to a set of scheduling parameter values. Interpolation is then used for intermediate values.
LPV for Simple Battery Thermal System

• Three sets of LTI models are identified at flow rates of 0.06, 0.075, and 0.09 kg/s.
• Interpolation used for intermediate flow rates.
• A rather random heat source and mass flow rate are applied.

LPV Test Results

Six Cell Battery Example with Changing Flow Rate

- Power 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.

The model gives similar results as CFD. The model runs in less than 20 seconds while the CFD runs a couple of days on 6 CPUs.

Electro-Thermal Coupled Analysis

\[ \text{Voc} = f(\text{SOC}, \text{U1.Temp\_block\_1}) \]
System Model Involving Reduced Thermal Model

Entire powertrain system is simulated including high fidelity sub-system and component simulations.
Conclusion

• LTI based MOR has shown to be applicable to many applications including electrochemistry problems.

• Icepak-Simplorer coupling uses a simplified version of this methodology for thermal problems.

• Vector fitting is shown to be much more flexible than the method implemented in Simplorer 9.

• A natural extension from LTI to LPV is discussed.