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Reduced-Order Modeling Method for Fatigue Life Prediction of Hybrid Electric Vehicle Batteries

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Report Documentation Page

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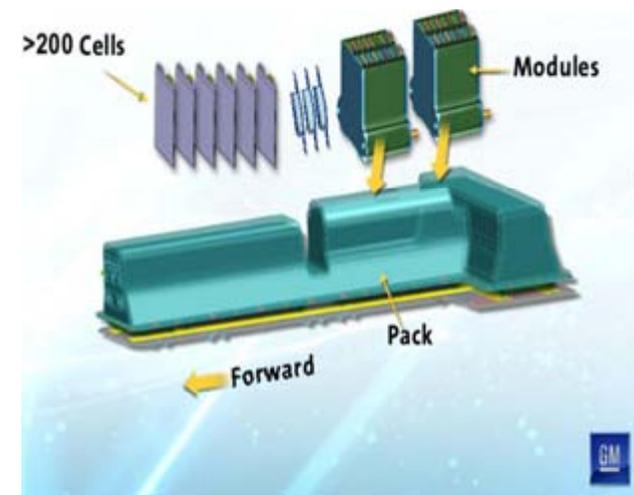
- Objectives
- Structural Battery Model
- Parametric Reduced-Order Models (PROMs)
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 - Full-order models
 - PROMs
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 - Statistical Results
- Conclusions

Objectives

- Gain better understanding of structural dynamics featuring very **high modal density**
 - Special attention to **hybrid electric vehicle (HEV) battery packs**
 - For high modal density, **small cell-to-cell structural variations** have **very large consequences** for the dynamics of the pack
- Develop an **efficient and accurate** computational method for predicting the **structural dynamic response** of HEV batteries
- Enable **fatigue life predictions** by performing **statistical dynamic response calculations**

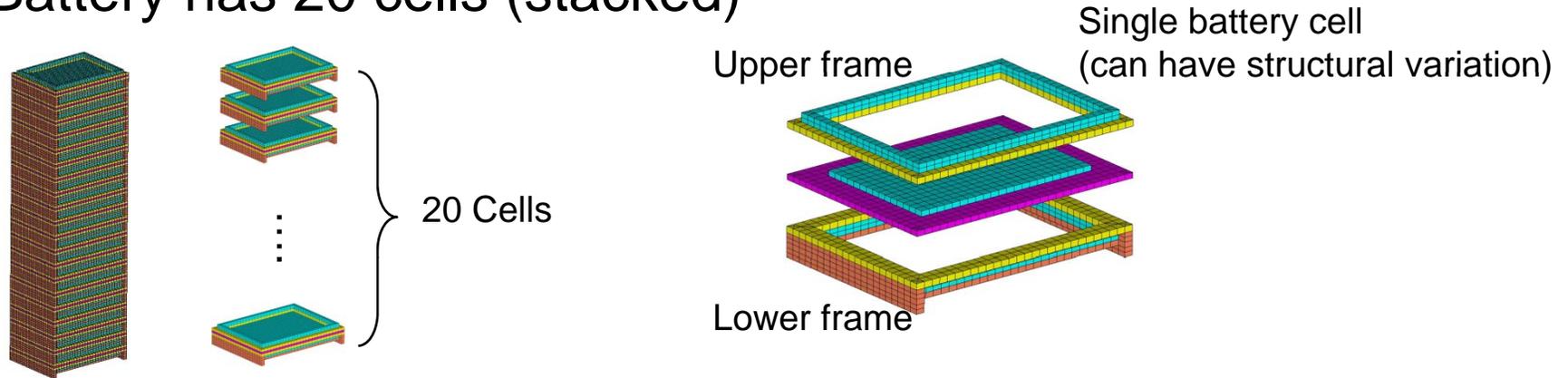


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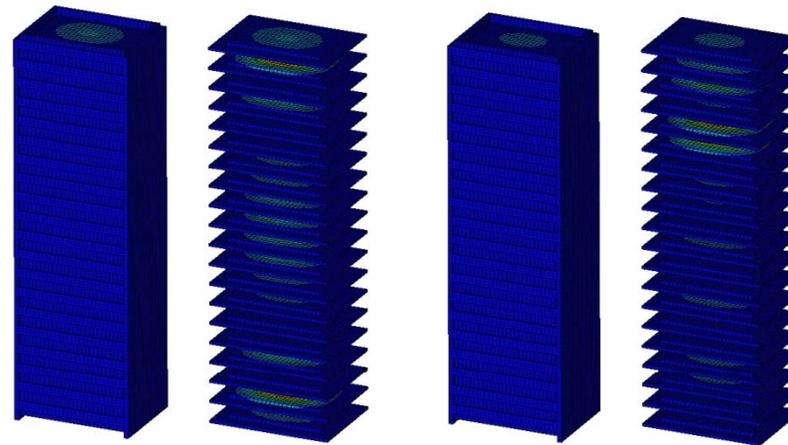
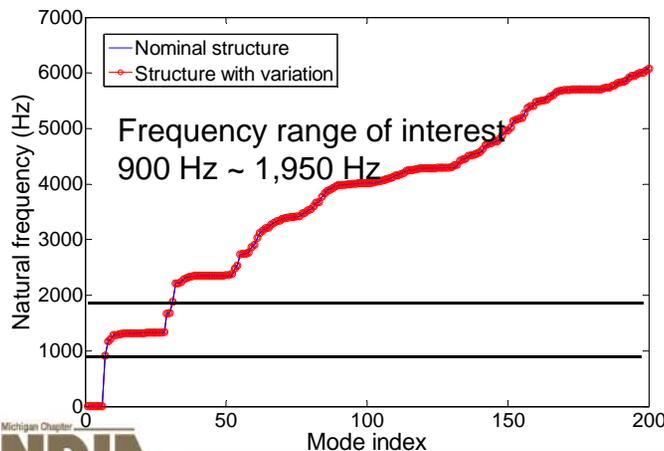


Academic Battery Model

- Battery has 20 cells (stacked)



- Dynamic response (natural frequencies and mode shapes)



Mode shapes are sensitive to variations, but natural frequencies are not

Parametric Reduced-Order Models (PROMs): Key Ideas

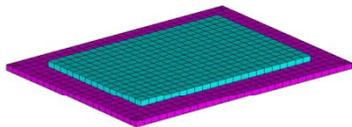


- Modes (Φ_M) of a **structure with small parametric variations** and high modal density (e.g., a batter pack) can be approximated using a **linear combination of modes (Φ_T) of the structure with nominal parameters**

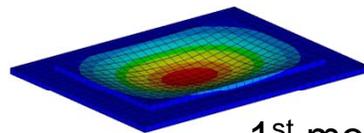
$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F} \rightarrow \Phi_T \text{ (Mode for nominal structure)}$$

$$(\mathbf{M} + \mathbf{M}^\delta)\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + (\mathbf{K} + \mathbf{K}^\delta)\mathbf{x} = \mathbf{F} \rightarrow \Phi_M \text{ (Mode for structure with variations)}$$

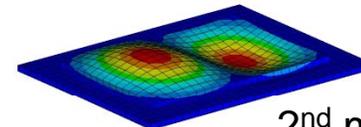
- The **motion in each of the cells** is plate-like with fixed boundary



Single battery cell
with fixed boundary
(nominal)



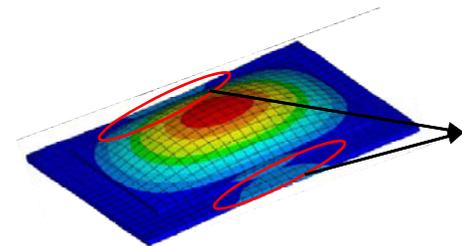
1st mode of cell



2nd mode of cell

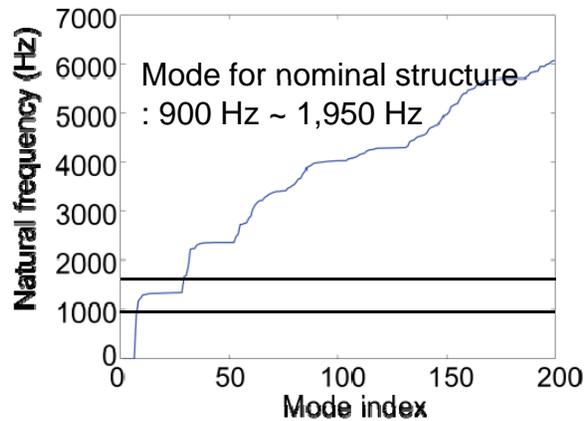
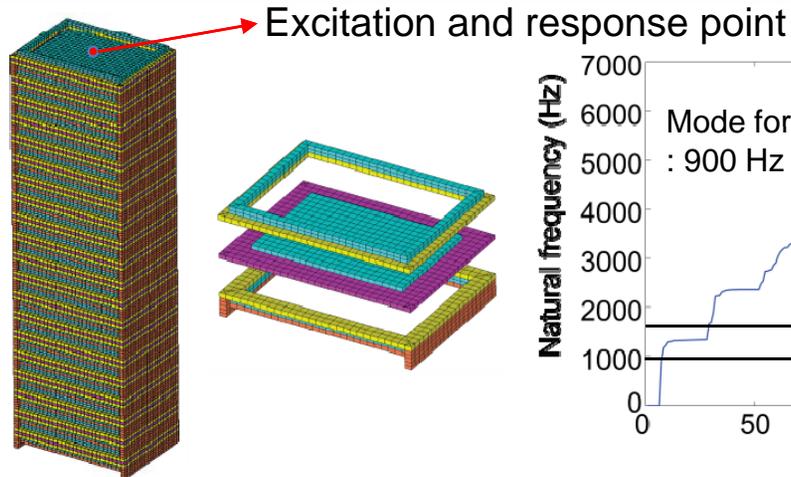
The effects of parameter variability are captured by **cantilevered plate modes**

- To capture the effect of the motion of the boundary of battery pack, cantilevered plate mode with **boundary (frame) displaced as in the nominal modes** are used



Boundary displacement

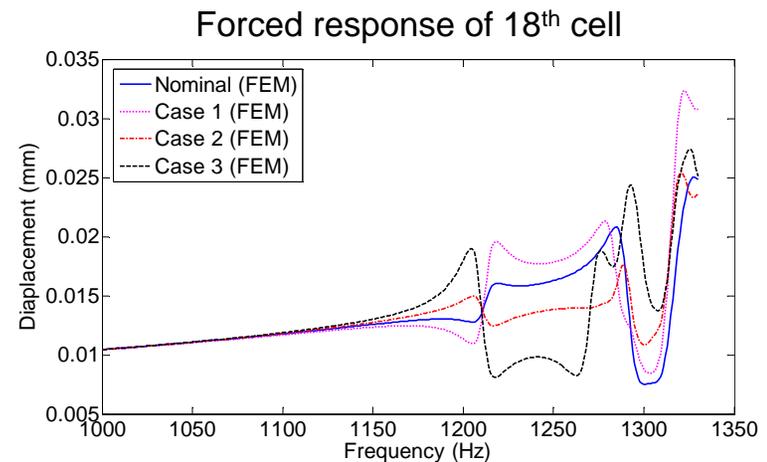
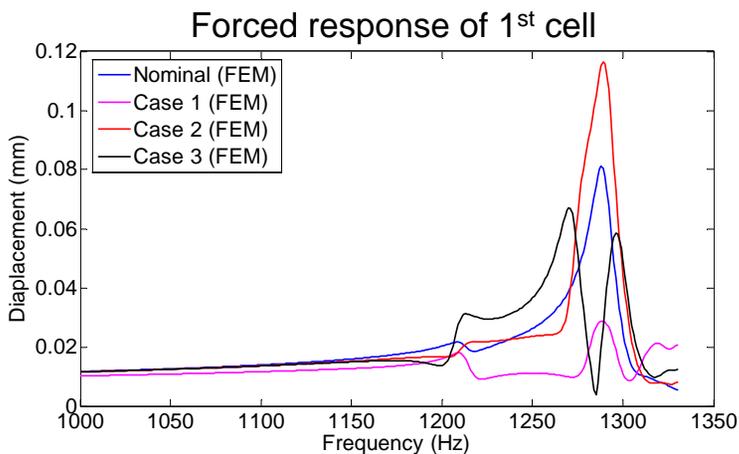
Numerical Results: Full-Order Models



Three cases of Young's modulus variations in various cells

Case 1		Case 2		Case 3	
Cell	Variation	Cell	Variation	Cell	Variation
1	5%	4	10%	3	3%
5	-7%	7	-8%	9	-5%
12	1%	10	3%	13	2%
16	3%	19	-5%	20	-5%

Total DOFs: **208,752**, 20 battery cells are stacked
Material: Steel

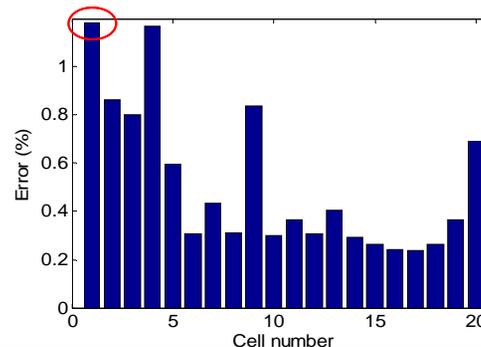
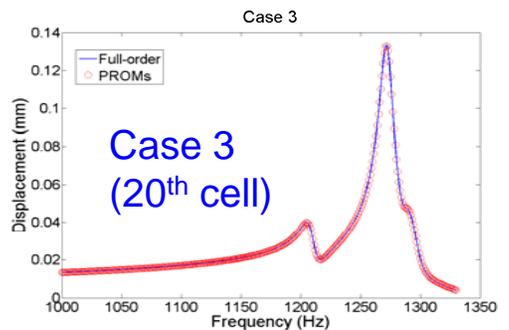
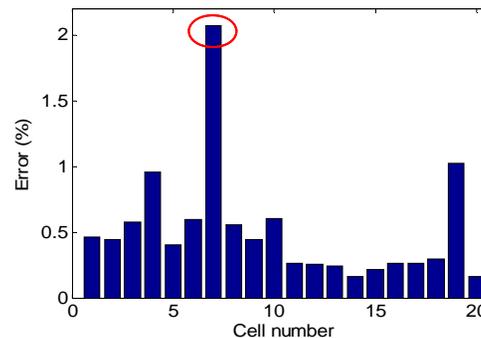
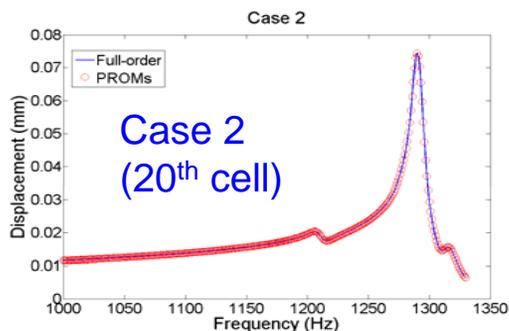
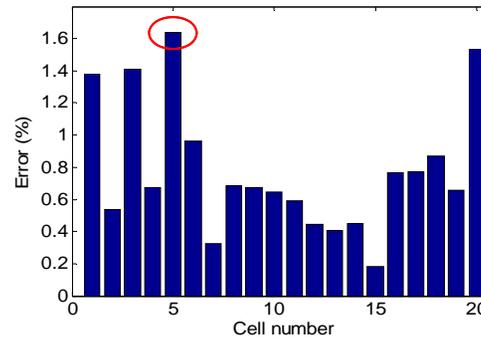
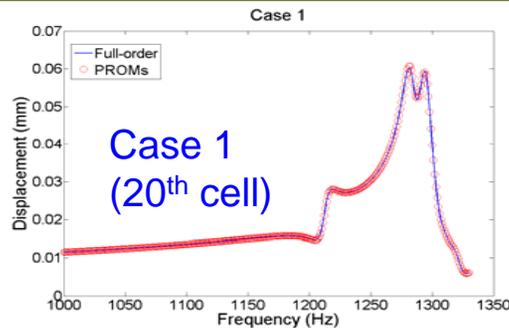


CPU time for reanalysis: 105 min 50 sec ~ 110 min 25sec (NASTRAN sol 108)

Numerical Results: PROMs

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Reduced-DOFs: 25

Maximum error: ○

Case 1: 1.64%

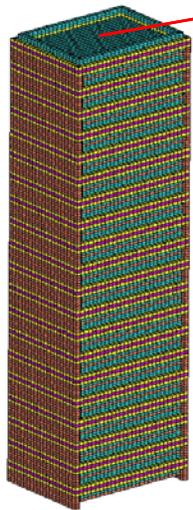
Case 2: 2.07%

Case 3: 1.18%

CPU time for reanalysis:
0.71 - 0.85 sec

PROM reanalysis is
9,000 times faster than
that of full-order model

Numerical Results: Detection of Highest Vibrating Cells

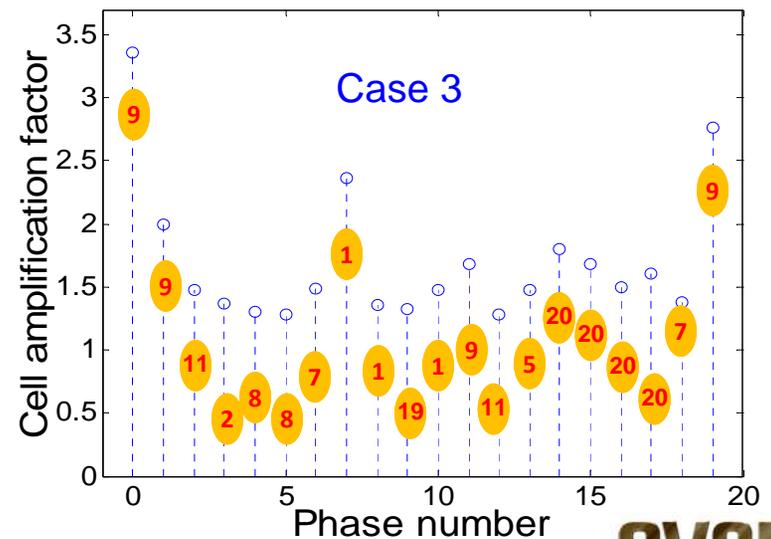
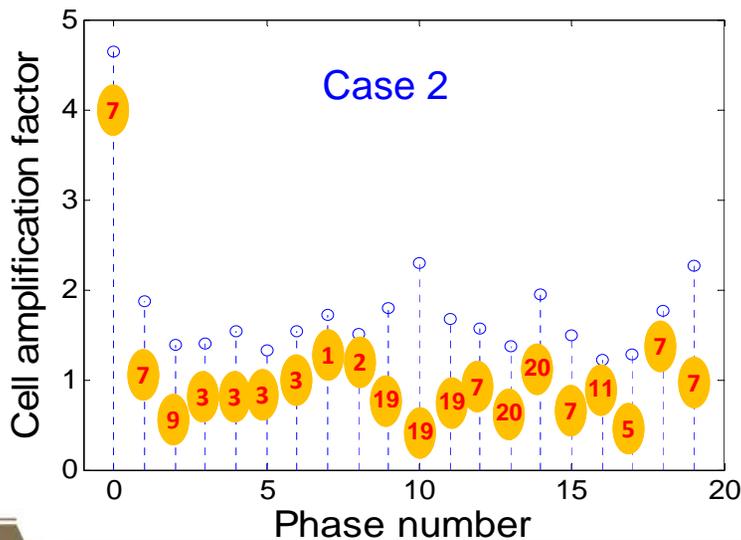
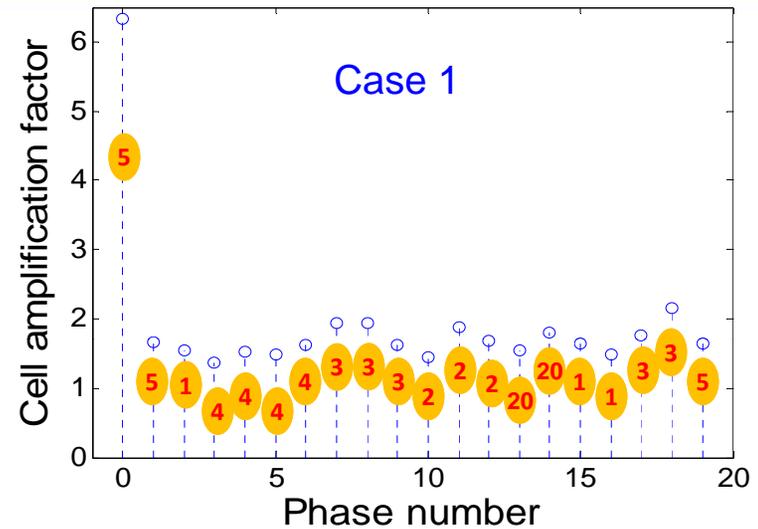


Traveling wave excitation to the center nodes of each battery cell

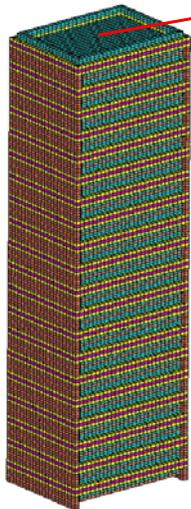
Cell amplification factor (CAF)

$$CAF_k^j = \max_{i=1, \dots, 20} \left(\frac{\max_{\omega} (|A_i|^{\Delta p})}{\max_{\omega} (|A_i|^{\text{Nominal}})} \right)$$

: Highest vibrating cell for each phase



Numerical Results: Statistical Analysis



Traveling wave excitation applied to center nodes of each battery cell

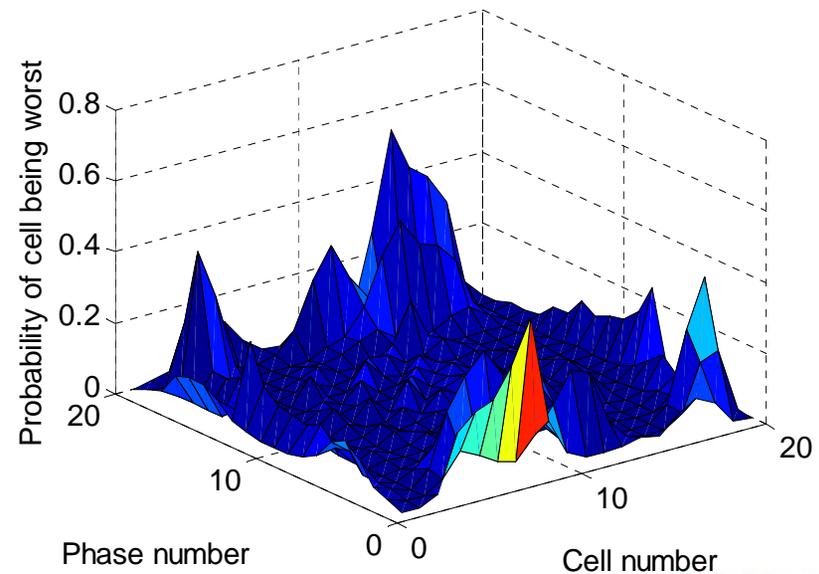
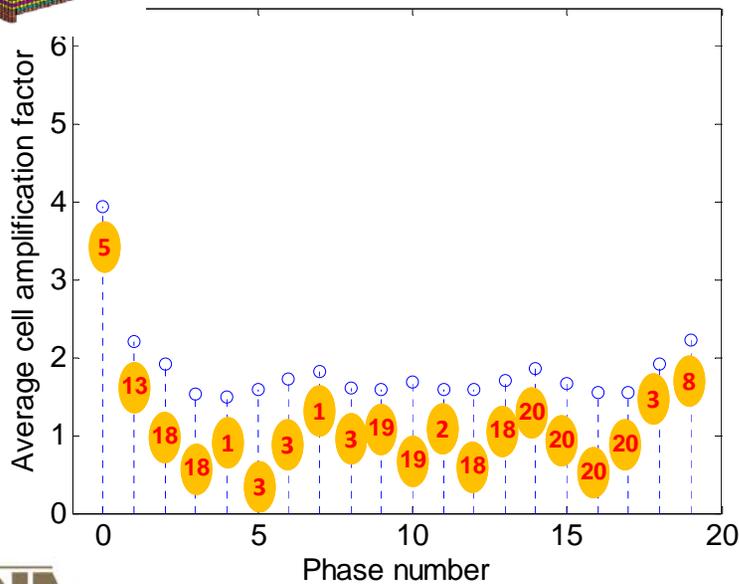
Average CAF:

$$CAF_k^j(\text{AVG}) = \max_{i=1, \dots, 20} \left(\frac{1/10,000 \sum_{j=1}^{10,000} \max_{\omega} (|A_i|^{\Delta p})}{\max_{\omega} (|A_i|^{\text{Nominal}})} \right)$$

10,000 cases of elastic modulus variation to all 20 cells

Analysis time: 0.8 sec × 20 phases × 10,000 cases = 160,000 sec (44 hours)

: Statistically highest vibrating cell for each phase





Conclusions

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- **Introduced efficient structural dynamic simulation** capability for HEV batteries
 - Enables **fatigue life prediction**
- **Developed parametric reduced-order models** (PROMS) to capture dynamic response very quickly for structures featuring **high modal density**
 - **Reanalysis time** of new PROMs for each variation is **9,000 - 10,000 times faster** than that of full-order models
- Identified the **weakest cell (highest vibration)** by using **statistical analysis** based on cell amplification factors