Modal Transient Fatigue Analysis of Battery Pack Assemblies Using Vehicle Road Load Accelerometer Data and Super-element Modeling

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Introduction

Validating battery pack assemblies is critical for ensuring durability performance under real-world conditions. Vibrations during vehicle operation can impact battery lifespan, making dynamic analysis essential. Accelerometers placed at critical points collect data to simulate real-world conditions, enabling evaluations of structural integrity, fatigue life, and performance. These acceleration profiles also support shaker table testing for further validation.

The high computational demands of detailed CAE models, often with millions of nodes, pose challenges due to the need for significant resources and long simulation times. To address this, a hybrid modeling approach was used, combining finite element meshes with super-element modeling to reduce simulation time and storage requirements while maintaining accuracy.

This paper outlines a methodology integrating accelerometer data with advanced simulation techniques to validate battery pack assemblies efficiently, enhancing design processes, and optimizing computational resources.

Modal Transient Fatigue Analysis

When loading excites resonant modes, linear static superposition may fail to accurately predict stress time histories. Transient finite element analysis (FEA) can capture dynamic effects but becomes computationally expensive as model size and time steps increase. Modal Transient analysis offers a more efficient alternative by using a modal representation, reducing CPU time. However, challenges remain in determining the necessary number of modes and managing disk space. Modal superposition within nCode streamlines data handling, improving computational efficiency and making it a practical solution for fatigue analysis.

Super-element Modelling

Modal superposition fatigue analysis requires modal coordinates (from Modal Transient analysis) and modal stress (from Modal analysis). Due to large model size of the battery pack assembly, running Modal Transient analysis for each road load dataset is computationally intensive. To address this, the entire assembly is modeled using a super-element, reducing computation time to just minutes.

In Modal analysis, only one of the battery module is modeled in detail while others are represented by super-elements. Location for detailed representation of module can be determined based on expected worst case scenario. This hybrid FE modeling approach significantly reduces computation time and storage requirements, accelerating the fatigue analysis process in nCode. Using super-elements improves computational efficiency, enabling faster design iterations and optimizations. Figures 01 and 02 illustrate the Battery-Pack assembly modeled with super-elements for Modal Transient and Modal analyses.

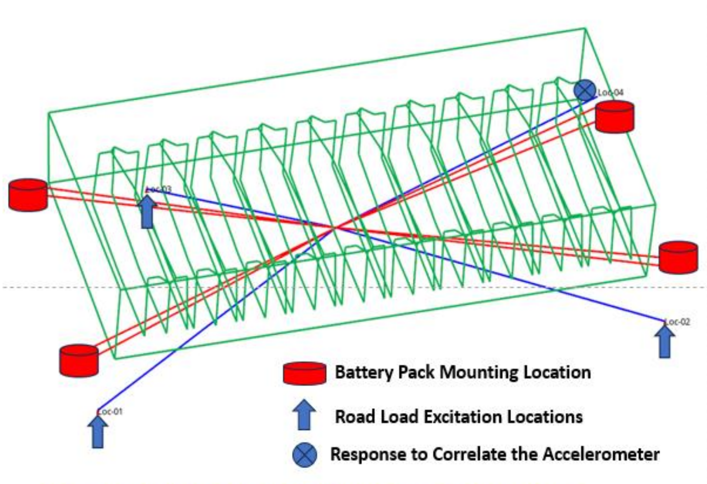

Figure 01: Full DMIG Model for Modal Transient Analysis

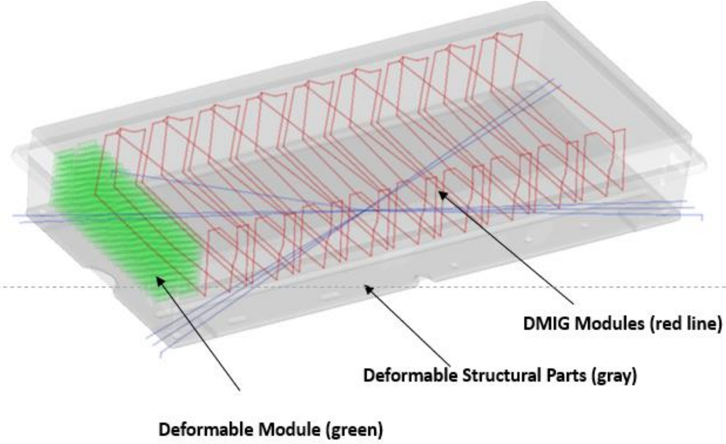

Figure 02: Partial DMIG Model for Modal Analysis

Accelerometer loads and Correleation

The battery pack assembly in the vehicle is mounted at four frame locations, with accelerometers placed near the mounting points to collect data during testing. For transient analysis, the frame is modeled with rigid elements, applying excitation at three accelerometer locations (Loc-01, Loc-02, Loc-03) at one end, while the other end connects to the battery pack bracket. Acceleration at Loc-04 is compared against test data for validation of FE model.

For shaker table testing, acceleration loads are developed for the three locations, and results at Loc-04 are adjusted and correlated. Figure 03 depicts road load excitations and response locations. Acceleration at Loc-04 from the analysis closely matches vehicle test readings, demonstrating strong correlation across road load conditions. This approach reinforces confidence in the FE model and applied loads.

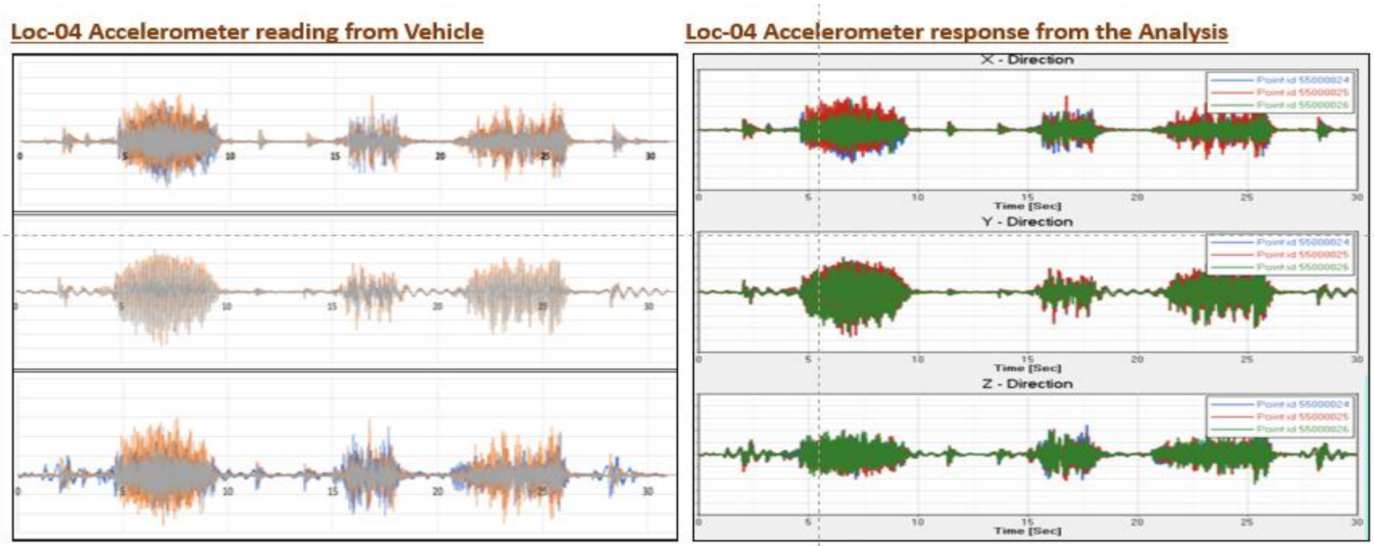

Figure 03: Comparison of Acceleration from measurement and CAE analysis

Modal Superposition Fatigue

Modal superposition offers an efficient method to approximate the dynamic response of a structure by utilizing a select number of eigenmodes. This approach is commonly applied in fatigue analysis, where the stress history is computed by multiplying modal stresses (obtained from modal analysis) with modal participation factors (derived from modal transient analysis).

$$\boldsymbol{\sigma_{ij}(t) = \sum_{n} P_n(t) * \sigma_{ij}(n)}$$

Where,

$\boldsymbol{\sigma_{ij}(t)}$ is the stress histroy for a given time interval of an element
$\boldsymbol{P_n(t)}$ is the modal participation factor (modal coordinates) per mode at time t
$\boldsymbol{\sigma_{ij}(n)}$ is the Modal stress of an element per mode
n is the mode number

One key advantage of this analysis is the significant reduction in computational time. The model's response is represented through modal shapes and modal participation factors, where mode shapes are calculated once during the modal analysis, and participation factors can be quickly derived for any new loading definition in a modal transient analysis. Additionally, a limited number of mode shapes often provides an accurate approximation, particularly when the loading lacks high-frequency content.

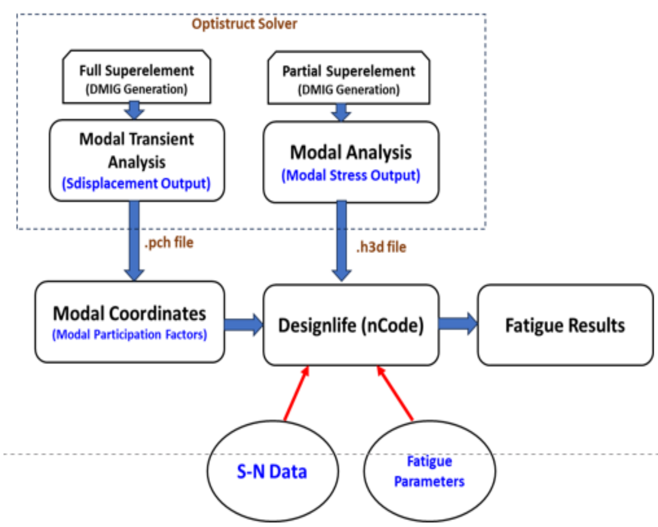

Figure 04: Modal Superposition Workflow

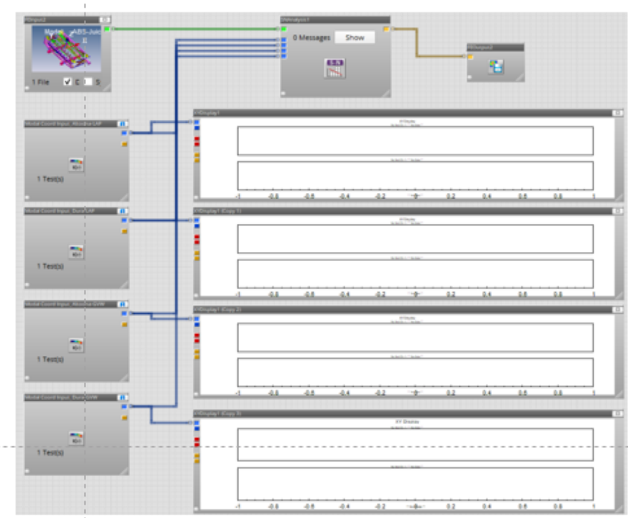

Figure 05: nCode (Designlife) Flow file for Modal Superposition Fatigue

Summary

This paper outlines a simulation process that leverages measured accelerometer data from vehicle testing to validate the durability of battery-pack assemblies and other subsystems. The use of super-element modeling significantly enhances computational efficiency, reducing both solving time and storage requirements for modal and modal transient analyses.

A full analysis using traditional deformable elements can take up to a day to simulate the complete motion. In comparison, super-element-based analysis is over 100 times faster, enabling rapid validation of structural components. This approach accelerates design iterations, facilitates optimization, and ensures quicker validation of critical subsystems, ultimately supporting faster product development cycles while maintaining accuracy and reliability.

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