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Numerical and Experimental Analysis of the Vibration Response of Lithium-Ion Battery Packs

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A B S T R A C T

This study investigates the dynamic response of a lithium-ion battery pack subjected to environmental vibrations. Considering the widespread use of such packs in electric vehicles and energy storage systems, and the adverse effects of vibrations on their performance and safety, both numerical and experimental approaches are employed. In the numerical simulation phase, a detailed three-dimensional model of the battery pack, including all components and joints, is developed in Abaqus, and a full modal analysis is performed to extract the natural frequencies and mode shapes of the system. In the experimental phase, modal testing is conducted using an impact hammer and an accelerometer on a physical battery-pack sample under free-free boundary conditions to validate the simulation results. A systematic comparison between the two approaches demonstrates a good agreement, with the maximum deviation in the primary natural frequencies being less than 10%. This level of consistency confirms the accuracy and reliability of the proposed model. The developed model can serve as an effective tool during the early design stages for mechanical optimization, dynamic behavior prediction, and mitigation of vibration-induced failures in battery packs. The results of this study mark an important step toward improving the reliability and safety of battery packs in operational environments.

1. Introduction

The fourth industrial revolution and the global transition toward the electrification of transportation systems and the integration of renewable energy sources into power grids have positioned lithium-ion batteries as a cornerstone of modern technologies. At the heart of this transformation lie battery packs, which are formed by connecting tens to thousands of individual cells in series and parallel configurations to deliver the voltage and energy capacity required for applications such as electric vehicles and energy storage systems. While extensive research has focused on material chemistry optimization, thermal management, and battery management algorithms, one critical and relatively less explored aspect is the response of these packs to environmental mechanical loads, particularly vibration.

Vibration is an unavoidable factor in many real-world operating conditions of battery packs. In electric vehicles, the battery pack is directly mounted to the chassis and exposed to a wide spectrum of vibrations originating from road irregularities, bumps, and dynamic loads during acceleration and braking. In aerospace applications, batteries must endure severe vibrations generated

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during launch and flight phases. Even in stationary systems, vibrations transmitted from auxiliary equipment such as cooling pumps, generators, or transformers may affect the structural integrity of the battery pack. Continuous and fatigue-inducing mechanical vibrations can lead to subtle material defects, loosening of internal joints, degradation of electrode structures, and ultimately accelerated battery aging. Such degradation manifests as capacity loss, increased internal impedance, and, in the worst case, thermal instability and fire hazards. Therefore, a thorough understanding of the dynamic response of battery packs to vibrational excitations and the development of rigorous vibration-testing standards are essential for designing reliable, durable, and safe battery systems. Although vibration-related studies on batteries are relatively recent, research activity in this field has grown significantly in recent years.

Sahraei et al. [1] were among the pioneers in this area. In a seminal study, they examined the mechanical response of cylindrical lithium-ion cells under compression and bending and proposed a mechanical model to predict damage initiation. Although their work did not directly address vibrations, it laid the groundwork for understanding the mechanical behavior of battery cells. Williard et al. [2] specifically investigated the effect of vibration on battery health. Exposing lithium-ion cells to sinusoidal excitations at different frequencies, they reported no significant short-term effects on capacity or internal impedance, while highlighting the need for long-term investigations. Zhang et al. [3] extended this research by examining the influence of random vibrations—more representative of real driving conditions—on cylindrical cells. Their results demonstrated that such vibrations could cause gradual degradation of electrical performance and noticeable changes to electrode microstructures.

Lyu et al. [4] elevated the research to the module level by subjecting a battery module to vibration tests according to the automotive standard ISO 12405-3. Their findings revealed loosening of bolted connections and a substantial increase in interfacial contact resistance due to vibrational loading, emphasizing the importance of mechanical design and joint integrity at the module scale. Huang et al. [5] systematically analyzed the failure behavior of welded joints in battery packs under vibrational fatigue loading. They investigated the relationships among vibration amplitude, cycle count, and crack formation and proposed design criteria for reliable welds. Zhu et al. [6] adopted a hybrid approach by developing a finite-element model to simulate the vibrational response of a battery pack and validating the model using experimental data obtained from a shaker-table test. Their work provides a valuable tool for identifying critical regions and optimizing pack design prior to physical prototyping. More recently, Wang et al. [7] explored the connection between vibration-induced structural degradation and safety hazards. Their study showed that microstructural damage caused by long-term vibrations can lower the threshold for thermal runaway, demonstrating that vibration is not merely a mechanical concern but also a critical safety issue.

Given the significance of vibration effects on battery packs, the present study investigates a lithium-ion battery pack through both numerical simulation and experimental modal testing to extract the natural frequencies of the system.

2. Numerical Simulation

After creating the geometric model in SolidWorks and importing it into Abaqus, the material properties of each component were assigned. The mechanical properties of the different parts used in the model are listed in Table 1. Since the individual battery cells were not explicitly modeled in the simulation, and the mass contribution of the cells plays a significant role in dynamic analyses, the density of the holders was adjusted such that the mass of each holder represents both its own mass and the equivalent mass of 150 cells. Therefore, a total of 300 cells is accounted for by the pair of holders. For this reason, the density of the holder differs from that of the separators despite both being made of the same base material.

Table 1: Mechanical properties of the model components

Equipment	Poisson's ratio	Young's module (Pa)	Density (kg/m³)
Aluminum	0.334	69×10^{9}	2710
Polyamide (holder)	0.36	4.2×10^{9}	6071
Polyamide	0.36	4.2×10^{9}	1130

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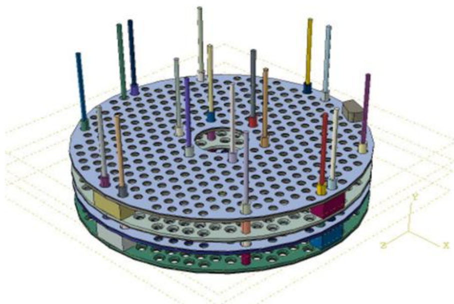

Figure 1: Assembled model

After assigning the mechanical properties, all geometric components were assembled according to the physical configuration of the battery pack. Figure 1 illustrates the assembled model.

In the Step module, a Frequency step was defined to extract the natural frequencies and corresponding mode shapes. The first six modes of the structure were computed. In the Interaction module, the connections between various sub-module components were defined using Tie constraints to simulate bonded contact. Since the modal analysis was carried out under free–free boundary conditions, no specific boundary constraints were applied.

Eight-node solid elements were selected for meshing the components of the battery pack. A sample representation of these elements is shown in figure 2.

After completing the solution process, the first six non-zero natural frequencies were obtained and are listed in Table 2. Because the analysis was conducted under free–free conditions, the first six modes correspond to rigid-body modes with zero natural frequencies. Therefore, Table 2 reports the natural frequencies from the 7th to the 12th modes.

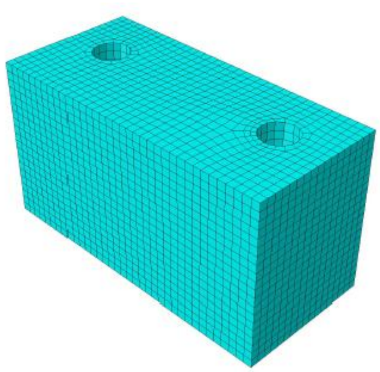

Figure 2: Meshing of the lithium-ion battery pack components

Sample mode shapes corresponding to selected non-rigid modes are shown in Figures 3–5.

Table 2: First six non-zero natural frequencies

Mode No.	Natural frequency (Hz)
7	42.84
8	58.83
9	59.90
10	65.00
11	73.60
12	84.90

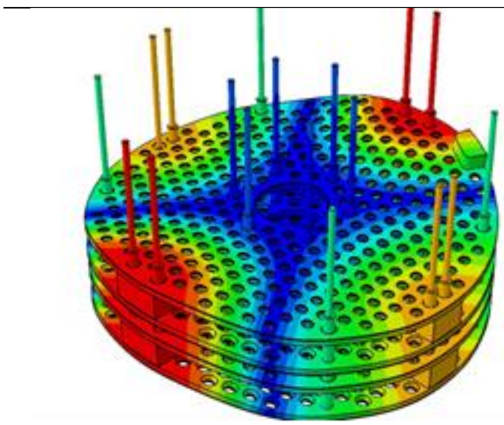

Figure 3: Mode shape of the 7th mode

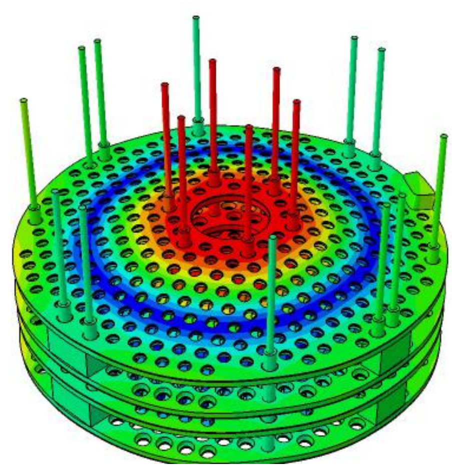

Figure 3: Mode shape of the 8th mode

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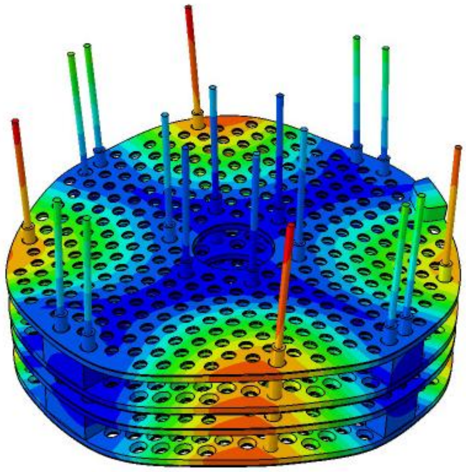

Figure 3: Mode shape of the 9th mode

3. Method

Modal testing is an experimental technique used to obtain the modal model of a linear time-invariant vibratory system. The theoretical basis of this technique lies in the relationship between the vibration response at one point of a structure and the excitation applied at the same or another point, expressed as a function of the excitation frequency. This relationship, often represented as a complex mathematical function, is known as the Frequency Response Function, or simply the FRF.

By considering different combinations of excitation and response points on the structure, a complete set of FRFs is obtained, which can be represented in the form of the system's FRF matrix. This matrix is often symmetric, reflecting Maxwell's reciprocity principle in the structure.

Overall, experimental modal analysis consists of three stages: test preparation, frequency-response measurement, and modal parameter extraction.

The data acquisition system (DAS) used for vibration analysis and modal testing includes a data acquisition card, which is its main and essential component. The DAQ card used in this study is the NI 4431 model, which converts analog signals into digital form. One channel of the DAQ card is allocated to a miniature accelerometer, and another channel is assigned to a force sensor (instrumented hammer). The hammer has an aluminum tip and contains a force transducer connected to the DAQ card. It is a 2-kN force hammer, and the accelerometer has a measurement range of 500 g and a sensitivity of 10 mV/g. The sampling

Figure 6: Data acquisition card and impact hammer used for modal analysis testing

frequency is set to 5 Hz, and the maximum measurable frequency is 2560 Hz.

Due to human error, three hammer impacts were applied to the "battery module system," and the data acquisition system used the average of these three impacts. During modal testing, care must be taken to avoid striking nodal points of the structure. The software used for recording modal test data is LabVIEW.

To approximate free–free boundary conditions during testing, two hoists were used based on the available equipment, allowing this boundary condition to be achieved to a reasonable extent. After this step, the sensor of the testing device was placed at various points on the system, and impacts were applied to different locations using the modal testing hammer. Since multiple tests were performed, various plots were obtained. Figure 7 shows one of the extracted plots, from which the first and second natural frequencies can be identified.

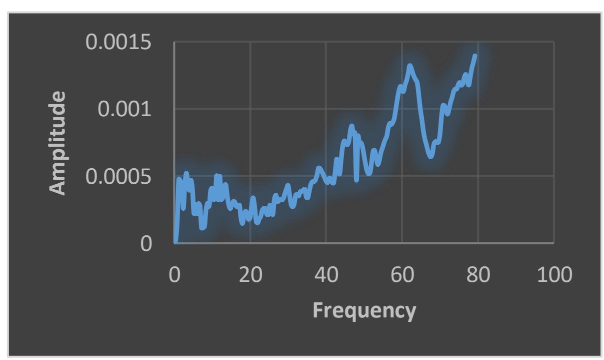

Figure 7: Frequency spectrum obtained from the experimental test

4. Conclusion and Summary

In the previous sections, the results of the experimental test and simulation for the two sub-modules under free–free conditions were presented. In this section, the first and second natural frequencies in the non-rigid modes—considered among the most important natural frequencies—are compared. The results of the experimental test and simulation are provided in Table 3.

As shown in Table 3, the difference between the natural frequencies obtained from the modal test and those obtained from the Abaqus simulation is acceptable. This discrepancy may be due to the fact that the experimental conditions did not fully match the theoretical assumptions. The results indicate that the simulation outcomes are reliable and can be confidently referenced.

Table 3: Comparison of Experimental Test and Simulation Results.

frequency	Experimental test result	Simulation result	Difference (%)
First natural frequency (Hz)	48	42.84	10
Second natural frequency (Hz)	63	58.83	6

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