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Preliminary Design and Modal Analysis of a 9S4P Lithium-Ion Battery Pack for Small Satellite Applications

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ABSTRACT

Ensuring robust energy systems is essential for satellite missions. Within the on-board power subsystem, lithium-ion batteries act as secondary power sources when solar arrays are unavailable. This study presents the preliminary design and modal analysis of a 9S4P lithium-ion battery pack based on NCR18650B cells for small satellite applications. A finite element model (FEM) is developed to evaluate the dynamic behavior of the structure under launch-relevant mechanical conditions. The modeling assumptions, including material properties, contact conditions, and boundary constraints representative of the launch configuration, are defined to accurately simulate the mechanical environment. Natural frequencies and mode shapes are extracted to assess compliance with structural requirements. The results demonstrate that the battery structure exhibits adequate stiffness, with natural frequencies significantly higher than the typical excitation range of launch vehicles. This indicates a reduced risk of resonance and dynamic coupling. These results confirm the structural integrity, dynamic robustness, and suitability of the proposed battery preliminary design for small satellite applications under the adopted modeling assumptions.

KEYWORDS

On-Board
Power Subsystem
Li-ion Battery
Satellite
Modal Analysis

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1 Introduction

The On-Board Power Subsystem (EPS) is one of the most critical subsystems in a spacecraft, as it ensures the continuous supply of electrical energy to all onboard components. It typically consists of solar panels as the primary energy source, power conditioning and regulation units, and an energy storage system [1].

Among available storage technologies, lithium-ion (Li-ion) batteries have become the preferred solution for small satellite applications due to their high energy density, low mass, and long cycle life. The increasing use of Commercial Off-The-Shelf (COTS) components has enabled rapid and cost-effective development of microsatellites [2, 3].

Battery technologies used in space missions can be classified into two main types: primary and secondary. Primary batteries are non-rechargeable and typically used for short-duration missions, while secondary batteries are rechargeable and widely used in long-duration missions [4–6].

Small satellites must withstand severe mechanical loads during launch, including sinusoidal and random vibrations. These dynamic conditions can induce resonance if the natural frequencies of onboard structures coincide with launcher excitation frequencies. Therefore, ensuring sufficient frequency separation is essential for satellite reliability.

Several recent studies have investigated the design, qualification, and structural behavior of lithium-ion battery packs for space applications. Akbulut and Erol [7] developed and experimentally validated different lithium-ion battery pack topologies for space equipment under resonance, harmonic, and random vibration environments. Asensio et al. [8] presented the mechanical design and finite element analysis of a Li-ion battery based on commercial off-the-shelf (COTS) cells for small spacecraft missions. Knap et al. [9] reviewed battery technologies used in CubeSats and small satellites, highlighting the increasing adoption of lithium-ion batteries due to their high energy density and reliability. Hua and Thomas [10] discussed the influence of dynamic loads and vibrations on lithium-ion battery structures and emphasized the importance of vibration-resistant designs. Furthermore, Cook et al. [11] analyzed the performance and failure mechanisms of lithium-ion batteries for Low Earth Orbit (LEO) CubeSat applications.

The remainder of this paper is organized as follows: Section 2 describes the battery configuration and finite element methodology. Section 3 presents and discusses the modal analysis results. Finally, Section 4 summarizes the conclusions and future work.

The Objective of this study is to design and evaluate the dynamic behavior of a 9S4P Li-ion battery pack based on ION cells for small satellite applications. The main contribution lies in developing a finite element model to extract natural frequencies and mode shapes, ensuring compliance with launcher requirements and minimizing resonance risks.

2 Methodology

2.1 Battery Configuration (9S4P ION)

The battery pack follows a 9S4P configuration, consisting of 36 cylindrical Li-ion cells (NCR18650B type). The structural components include:

Top and bottom plates manufactured from Al 6061-T6; Six X-shaped aluminum frames; Two connector supports; Two cell holders; Two 15-pin connectors; Heating system.

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This configuration provides mechanical support and thermal stability for space applications [3, 5]. Figures 1 and 2 illustrate the assembled and exploded views of the battery pack.

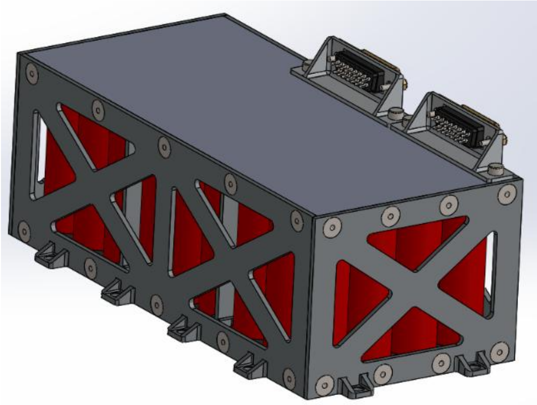

Fig. 1. The battery used in this study (lithium-ion battery).

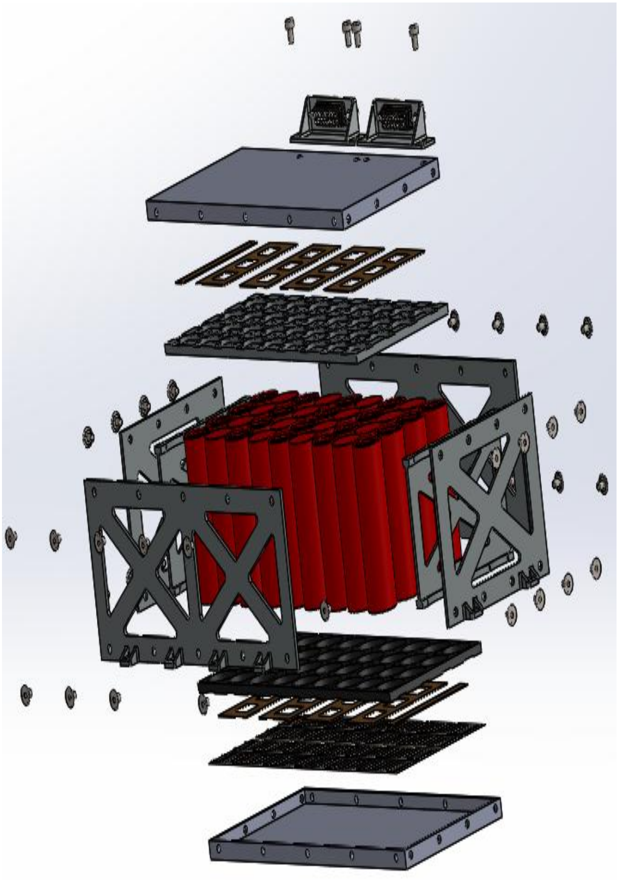

Fig. 2. Exploded view of the battery used in this study (lithium-ion battery).

Table 1. Mechanical properties of the materials used in the finite element model.

Material	Al 6061	ABS	Equivalent NCR18650B Cell	Nickel
Density (kg/m^3)	2700	1100	2707	8908
Young's modulus (GPa)	68.9	2.9	5.0	210.0
Poisson's Ratio (-)	0.33	0.422	0.35	0.31

2.2 Material Properties

The main materials used in the battery pack and their mechanical properties are summarized in Table 1.

These properties were used in the FEM model.

2.3 Finite Element Model (FEM)

A three-dimensional finite element model of the 9S4P battery was developed in ANSYS. Hexahedral solid elements were used for structural components, while bonded contacts were applied between interfaces to simulate rigid connections.

The simplify model of the 9S4P battery pack is shown in Figure 3.

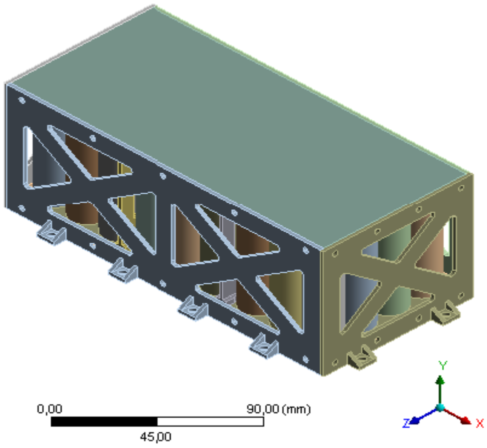

Fig. 3. Finite element model of the 9S4P battery.

Modeling assumptions: Materials are linear, homogeneous, and isotropic [2, 6]. Small deformation theory is applied. Thermal and nonlinear effects are neglected. Contacts are modeled as bonded interfaces to ensure structural continuity during the preliminary design phase.

The finite element model employs bonded contact conditions between all interfacing components, including the aluminum plates, X-frames, cell holders, and battery cells. This supposition was adopted to ensure structural continuity and to simplify the numerical representation of the assembly during the preliminary design phase. It is acknowledged that bonded contacts generally increase the global stiffness of the structure and may therefore lead to higher predicted natural frequencies compared to a physical assembly.

In practical spacecraft hardware, several factors reduce structural stiffness, including bolted-joint compliance, interface micro-slippage, manufacturing tolerances, preload variations, and local contact nonlinearities. These effects are omitted by fully bonded contact formulations, potentially resulting in lower natural frequencies during experimental testing.

Consequently, the frequencies obtained in the present study should be interpreted as an upper-bound estimate of the battery pack's dynamic response.

2.3.1 Equivalent Cell Representation

The detailed internal geometry of the NCR18650B cell, including the casing, electrodes, separator, electrolyte, and current collectors, was not explicitly modeled in this preliminary study. Instead, each cell was represented as a simplified cylindrical solid having the same external dimensions as the actual cell. This simplification was adopted to reduce the computational cost of the finite element model while preserving the overall mass distribution of the battery pack.

The NCR18650B cells were represented as equivalent homogeneous cylindrical solids having the same external dimensions as the actual cells. The equivalent density was calculated from the manufacturer's specified cell mass (47.5 g) and cell geometry, resulting in a density of approximately 2707 kg/m^3. This approach preserves the overall mass distribution of the battery pack while maintaining a computationally efficient finite element model.

2.3.2 Cell Characteristics

The 9S4P battery pack consists of 36 NCR18650B lithium-ion cells arranged in nine series-connected groups and four parallel strings. These cells were selected because of their high energy density and suitability for small satellite power systems.

The main electrical and physical characteristics provided by the manufacturer are summarized in Table 2 [12]. The cell dimensions and mass were also used to define the equivalent cell representation adopted in the finite element model.

Table 2. Characteristics of NCR18650B cells [12].

NCR-18650 B	
Nominal voltage	3.6 V
Minimum nominal capacity (20°C)	Min 3.200 mAh
Nominal capacity (25°C)	Min 3.250 mAh
	Typical 3350 mAh
Diameter	18.5 mm
Height	65.3 mm
Weight	47.5 g
Volumetric energy density	676 Wh/L
Gravimetric energy density	243Wh/kg

2.4 Boundary Conditions

To replicate the satellite environment during launch, the battery is fixed at all attachment points, with translational degrees of freedom fully constrained and rotational degrees restricted [13]. Figure 4 illustrates the boundary conditions.

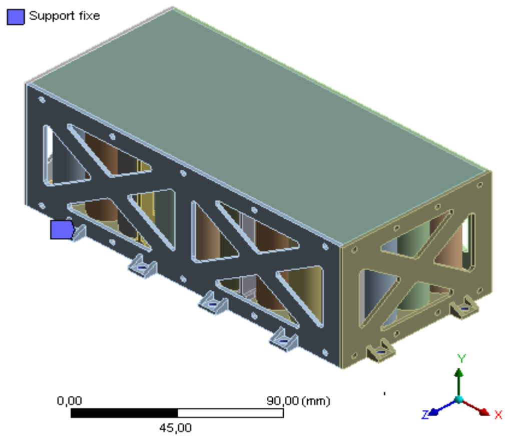

Fig. 4. Boundary condition of the model 9S4P battery.

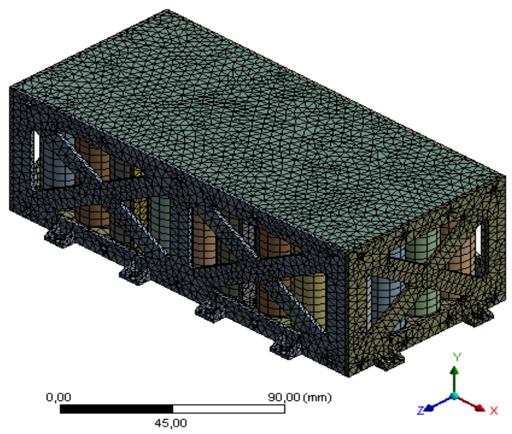

Fig. 5. Mesh model of the 9S4P battery.

2.5 Mesh Configuration

Mesh convergence was verified to guarantee the stability of the computed natural frequencies.

The elements employed in the finite element (FE) model are tetra-3 element topology for cover and (quad- 4 element topology) for cellules. To perform the numerical simulation, a tetrahedral 3D element is used to model the battery Li ion frame with average element size of 4 mm whereas the internal components has been modeled with quadrilateral 3D element with average size of 5 mm. The mesh was optimized to ensure accuracy without excessive computational cost [6].as shown in the Figure 5.

2.6 Modal Analysis

Modal analysis was conducted using the FEM model to evaluate the dynamic behavior of the battery pack. Natural frequencies represent the vibration frequencies at which resonance may occur, and mode shapes illustrate the deformation patterns corresponding to each frequency [6, 7]. The ST-001 requirement was adopted as the design criterion. The battery configuration consists of nine cells in series and four parallel rows (36 cells total) [3, 5].

3 Results and Discussion

An eigenvalue analysis was performed to determine the natural frequencies and corresponding mode shapes of the structure.

The first three natural frequencies were found to be 1221.9 Hz, 1454.4 Hz, and 1858.9 Hz, respectively. These values are significantly higher than the launcher excitation frequency ranges (45 Hz lateral and 90 Hz longitudinal), indicating a wide frequency separation between the structural response and the launch environment. Table 3 presents the three obtained natural frequencies.

Table 3. First three natural frequencies of the 9S4P battery pack.

Modes	Frequency (Hz)
1	1221.9
2	1454.4
3	1858.9

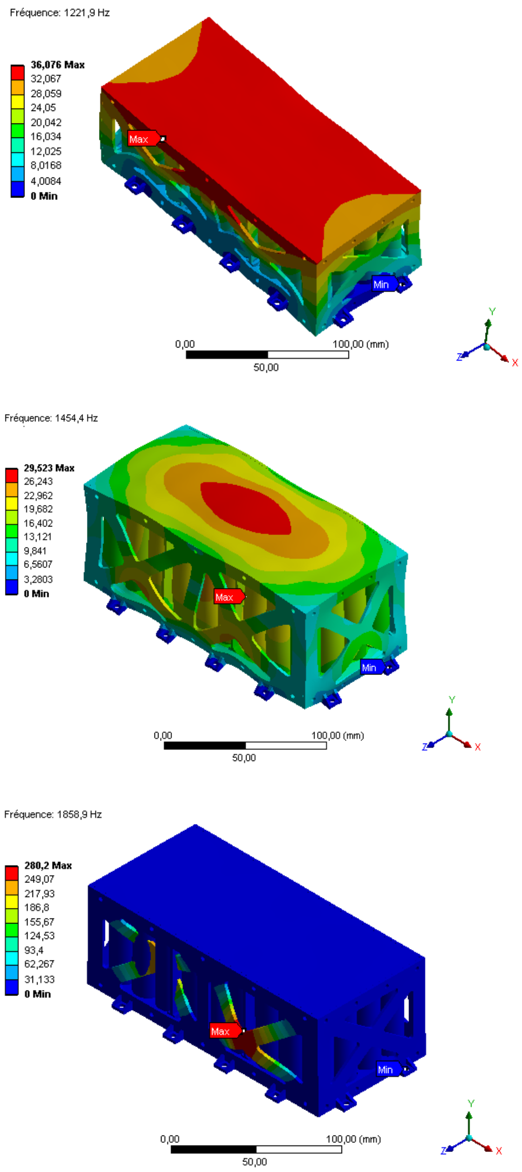

Fig. 6. First three mode shapes of the 9S4P battery pack. (a) Mode 1 (f_1 = 1221.9 Hz) ;(b) Mode 2 (f_2 = 1454.4 Hz) ; (c) Mode 3 (f_3 = 1858.9 Hz).

The first natural frequency (1221.9 Hz) is approximately 13.6 times higher than the longitudinal requirement and more than 27 times higher than the lateral requirement, demonstrating a substantial margin against potential resonance phenomena.

The obtained modal results show that the vibration modes are well separated in the frequency domain, which reduces the possibility of modal coupling under dynamic loading. This behavior suggests a globally stiff structural response of the battery pack under the adopted modeling assumptions.

Even when considering potential reductions in stiffness due to joint compliance, manufacturing tolerances, and interface effects, the system is expected to maintain adequate dynamic margins with respect to the launch environment.

Figure 6 illustrates the first three mode shapes of the battery assembly. These modes represent global deformation patterns of the structure and confirm that no low-frequency local instability is present in the model. Overall, the results indicate that the battery design provides sufficient dynamic stiffness to satisfy the launcher frequency separation requirements within the limitations of the finite element assumptions.

4 Conclusion

The results of this study demonstrate that the preliminary design of the proposed battery pack for small satellite applications exhibits sufficient structural robustness under the predicted launch environment, as confirmed by the modal analysis. The main conclusions of this work are summarized as follows:

1. A preliminary design of a 9S4P lithium-ion battery pack was developed for small satellite applications.
2. A three-dimensional finite element model (FEM) was established to evaluate the dynamic behaviour of the battery assembly.
3. The natural frequencies and corresponding mode shapes were determined through modal analysis using representative launch boundary conditions.
4. The obtained natural frequencies are significantly higher than the launcher frequency requirements, demonstrating high structural stiffness and providing a substantial safety margin against launch-induced resonance.
5. Future work will focus on static structural, quasi-static, random vibration, and thermo-mechanical analyses to further evaluate the structural performance of the battery pack under representative launch conditions.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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