

# Research on Dynamic Response Characteristics and Reliability of Power Battery Packs under Random Vibration Environments

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**Abstract.** With the rapid development of new energy vehicles (NEVs), the power battery pack, as a core component, has seen its structural safety become a critical factor in enhancing overall vehicle performance. This paper takes a specific power battery pack as the research subject and conducts comprehensive simulation studies on its dynamic characteristics and vibration environment adaptability using finite element simulation technology, thereby validating its structural reliability. Through the construction of a finite element model for the power battery pack, modal analysis, inertia force analysis, and random vibration analysis were systematically performed to evaluate structural stability and reliability under various vibration conditions. The findings indicate that the power battery pack demonstrates excellent dynamic response characteristics and vibration resistance under designed vibration loads, providing robust assurance for the safe operation of NEVs. The methodology and results presented in this study offer significant guidance for the optimized design of power battery packs.

**Keywords:** Power battery pack; Dynamic characteristics; Vibration environment; Simulation study

## 1. Introduction

With the global transition in energy infrastructure and heightened environmental awareness, the new energy vehicle (NEV) industry has entered an era of unprecedented development opportunities [1-2]. As the "heart" of NEVs, power battery packs have seen their performance optimization and reliability enhancement become pivotal drivers for sustainable industrial advancement [3]. The operational capabilities of power battery packs not only determine critical vehicle parameters including driving range and acceleration performance but also fundamentally govern safety stability during operation. Under real-world working conditions, these battery systems endure not only sustained complex mechanical loads but also confront dynamic stress environments formed by multi-physics coupled interactions. These interactions arise from random road excitations, harmonic vibrations in drive systems, and extreme thermal cycling. Particularly noteworthy are random vibration loads, characterized by wide frequency bands and abrupt amplitude variations, which may induce progressive damage mechanisms such as inter-module connection failures, micro-crack propagation in electrodes, and electrolyte leakage [4]. Such phenomena have emerged as critical bottlenecks constraining the service life of power battery systems. Conducting in-depth research on the dynamic response

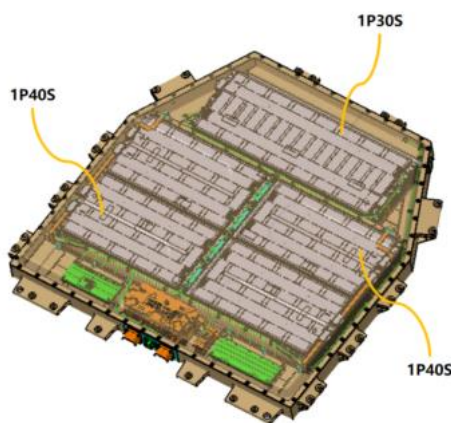
characteristics of power battery packs therefore holds substantial engineering significance for enhancing NEV operational reliability in complex vibration environments. Current research on the vibration characteristics of power battery systems predominantly focuses on static response analysis under deterministic loads, leaving insufficient exploration of dynamic adaptability in random vibration environments. Conventional approaches often employ equivalent static loads or simplified harmonic vibration loading patterns, which fail to accurately characterize the non-stationary, broadband vibration excitation spectra encountered during actual vehicle operation [5, 6]. This paper establishes a battery pack finite element model incorporating electro-mechanical-thermal coupling effects through the integration of random vibration theory and multi-body dynamics simulation. The study specifically investigates the impact mechanisms of vibration loads across different frequency domains on the structural dynamic response of battery packs. Given these considerations, the research employs advanced simulation technologies to systematically analyze dynamic response behaviors and endurance limits of power battery packs under various vibration conditions. Through in-depth exploration of reliability in dynamic response characteristics within random vibration environments, this work delivers urgent practical significance and substantial academic value for guiding battery pack

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design optimization, extending service life, and enhancing comprehensive vehicle performance.

## 2. Overall Design Scheme of the Power Battery System

The structural design and parameter configuration of the power battery system are pivotal factors ensuring the efficient operation and safety of new energy vehicles (NEVs). Based on the requirements of a specific NEV model platform, this paper adopts lithium-ion battery cells of model IFP52148102-87Ah as the basic units. These cells possess a capacity of 87Ah each, a nominal voltage of 3.2V, and exhibit high energy density and stable electrochemical properties. To meet the system's voltage and capacity demands, a hybrid grouping topology of 1P40S2+1P30S1 (i.e., two sets of 40-series parallel modules and one set of 30-series parallel modules) is employed. Through series-parallel combinations, the system achieves a rated voltage of 341V (at 1C discharge rate) with a nominal energy capacity of 29.67kWh and an energy density of 127.5Wh/kg (under 1/3C discharge conditions). This design not only guarantees energy output but also optimizes the internal space utilization within the pack through a modular layout. Furthermore, a lightweight aluminum alloy frame and high-strength insulating partitions are utilized for mechanical support and electrical isolation, effectively reducing the risk of internal short circuits caused by vibrations. The specific arrangement scheme of this power battery system is illustrated in Figure 1.



**Figure 1.** Overall Schematic Diagram of the Power Battery System

In terms of safety protection and thermal management, the system meets the dual protection rating requirements of IP68 (dust and water protection) and IPX9K (high-pressure, high-temperature spray protection) through a sealed casing and multi-layer protective structure, enabling it to adapt to complex and variable driving environments. To address thermal stability requirements, the system employs a composite thermal management strategy combining active heating membranes with passive natural cooling: in low-temperature environments, the PTC heating membrane rapidly raises the cell temperature to the optimal operating range (10~35°C),

while in high-temperature conditions, the high thermal conductivity of the aluminum alloy housing and internal airflow ventilation design facilitate natural heat dissipation. This solution balances cost and energy efficiency while avoiding the additional weight and complexity associated with liquid cooling systems. The specific parameters of the power battery system are shown in Table 1.

**Table 1.** Battery System Parameters Table

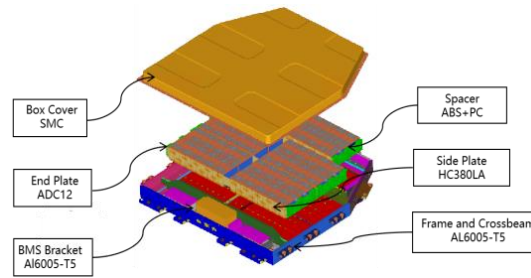
System Parameters	Value
Grouping Method	1P40S2+1P30S1
Rated Capacity (Ah)	87@1C
Rated Voltage (V)	341@1C
Nominal Energy (kWh)	29.67@1C
Voltage Range (V)	275~401.5
Usable SOC Range	0%~100%
Pack Weight (kg)	243
Energy Density (Wh/kg)	127.5@1/3C
Protection Rating	IP68, IPX9K
Thermal Management Method	Heating Membrane + Natural Cooling
BMS Layout	One Master, One Slave
Pack Dimensions (mm)	1378×1354×155

## 3. Reliability Simulation Analysis

### 3.1 Establishment of Finite Element Model

#### 3.1.1 Model Information

The finite element modeling of power battery packs needs to balance computational efficiency and mechanical representation accuracy, with its geometric topology fully reflecting the dynamic response characteristics of the actual structure[7]. Based on the design scheme, this paper employs finite element analysis software to establish a refined CAE model of the battery pack, as shown in Figure 2. During the modeling process, the interior of the battery pack was simplified, with the total mass of the model being 238.5 kg, which is basically consistent with the CAD model, ensuring the authenticity of the mass distribution and inertial properties. The main structure of the model includes key components such as the box body, battery module array, lifting lug mounting bracket, and protective support. The box body material is Al6005-T5 aluminum alloy, and the box cover is made of sheet molding compound (SMC) composite material. The optimization balance between structural stiffness and weight is achieved through material lightweighting and high specific strength characteristics. The performance parameters of the materials for each component inside the battery system are shown in Table 2.



**Figure 2.** CAE Modeling Diagram of the Battery Pack

**Table 2.** Performance Parameters of Various Components Inside the Battery System

Component	Material	Density (t/mm <sup>3</sup> )	Elastic Modulus (Mpa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (Mpa)	Elongation (%)
Frame and Crossbeam	AL6005-T5	2.7e-9	70000	0.33	240	262	11
End Plate	ADC12	2.7e-9	71000	0.33	170	232	5
Side Plate	HC380LA	7.85e-9	210000	0.3	439	531	26
Box Cover	SMC	1.9e-9	1290	0.4	/	133	1.5
Spacer	ABS+PC	1.2e-9	1200	0.38	/	54	50
BMS Bracket	AL6005-T5	2.7e-9	70000	0.33	241	262	11

To enhance computational efficiency, the battery cell module was equivalently simplified during the modeling process: the individual battery cells were reduced to homogeneous solid elements, with their equivalent density and stiffness defined through material properties, while retaining the true geometric characteristics of the connecting brackets and insulating separators between modules [8, 9]. Bolt connections were simulated using RBE2 rigid elements to represent multi-degree-of-freedom constraints under preload forces, and weld points were implemented through CWELD elements to achieve local flexible connections. The shear stiffness and tensile strength parameters for these connections were set according to the JIS Z3140 standard. The model was discretized into a mixed tetrahedral and hexahedral mesh comprising approximately  $1.2 \times 10^6$  elements. Local mesh refinement (with element sizes  $\leq 2$  mm) was applied to critical stress concentration areas, such as the root of lifting lugs and box welds. The global element Jacobian coefficient exceeded 0.7, meeting the convergence requirements of the explicit dynamics solver.

### 3.1.2 Boundary Conditions and Joint Modeling

The mounting boundary of the battery pack in the vehicle is rigidly connected to the chassis through lifting lugs. In the model, the mounting holes of the lifting lugs are simulated with SPC (Single Point Constraint) to mimic bolt fixation, restraining all six degrees of freedom to represent actual assembly conditions. To characterize the interaction forces between the modules and the casing under random vibration environments, a surface-to-surface contact pair (CONTACT\_ AUTOMATIC\_ SURFACE\_TO\_SURFACE) with a friction coefficient of

0.15 is defined at the interface between the module bottom and the casing, and a normal stiffness scaling factor of 0.1 is set to avoid penetration phenomena.

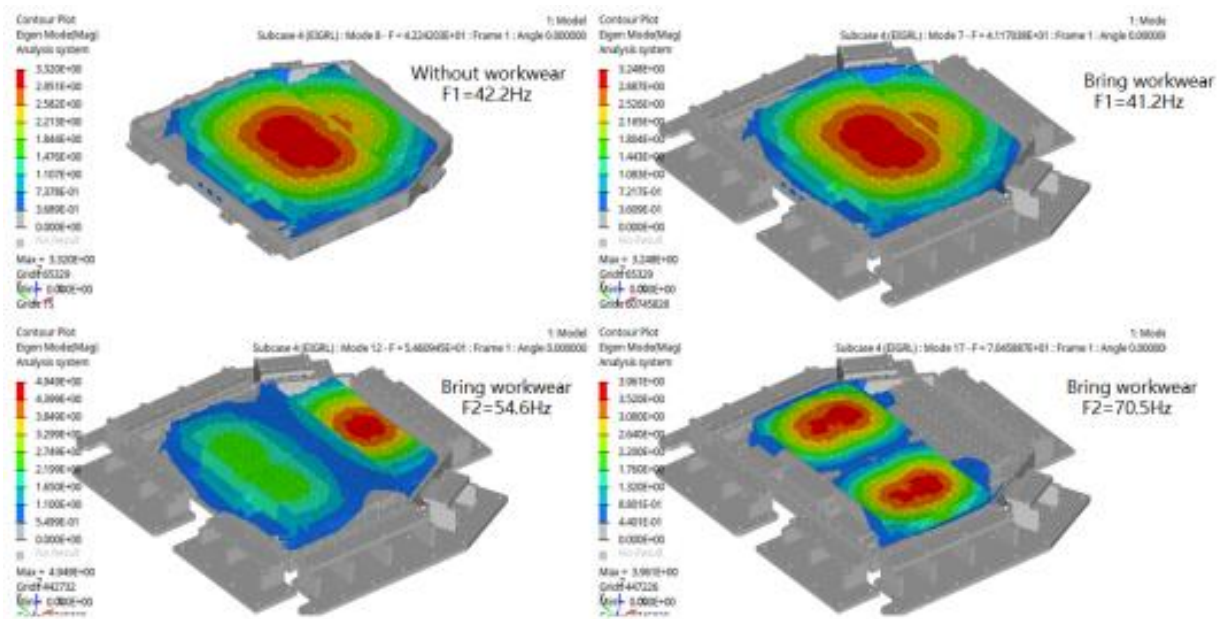
For the complex internal connections within the battery pack, a multi-scale modeling strategy is adopted: the bending stiffness of the high-voltage copper bars between modules is simulated using BEAM elements, while the torsional resistance of the busbar insulating supports is modeled using SHELL elements. The joint surface between the box cover and the casing is simulated using ADHESIVE elements to represent the viscoelastic behavior of the sealing glue layer. The shear modulus (1.2 MPa) and failure strain (80%) parameters of the ADHESIVE elements are calibrated through DMA (Dynamic Mechanical Analysis) tests. The establishment of this finite element model lays a theoretical foundation for subsequent dynamic response simulations.

### 3.2 Modal Analysis

Modal analysis is a crucial method in structural dynamics research, aiming to reveal the natural vibration characteristics (including natural frequencies, mode shapes, and damping ratios) of power battery packs in free or constrained states. Its core value lies in avoiding resonance between the system's natural frequencies and external excitation frequencies, thereby suppressing structural fatigue failure caused by dynamic stress concentration [10]. In the case of power battery systems for new energy vehicles, they operate in an environment with broadband random vibration loads. If the natural frequencies of the battery pack overlap with the excitation frequency range, the vibration energy will be significantly amplified, leading to accelerated loosening of module connectors, cracking of casing welds, and delamination of

internal interfaces within the battery cells [11]. Therefore, conducting modal analysis is a key prerequisite for

assessing the dynamic stability of battery packs and optimizing vibration-resistant designs.



**Figure 3.** Modal Analysis Diagram

In this paper, modal parameters of the finite element model were extracted using the Lanczos algorithm based on boundary conditions with fixture constraints (simulating the actual installation state of the battery pack on the vehicle frame). The simulation results indicate that the first-order natural frequency of the system under fixture-constrained modal conditions is 41.2 Hz, meeting the customer's design requirement (first-order frequency > 40 Hz). The primary mode shape exhibits bending deformation of the casing along the longitudinal direction, which has a significant correlation with the direction of low-frequency vertical vibration excitation during vehicle travel, as shown in Figure 3. Further comparative analysis reveals that fixture constraints have a high sensitivity to modal frequencies. When fixtures are considered, the modal frequency F1 decreases slightly, while the modal frequency F3 increases significantly. This indicates that the introduction of fixtures significantly enhances the vibration characteristics of the battery system. However, regardless of whether fixtures are present, the modal frequencies of the system meet the design requirements, suggesting that the battery pack can effectively avoid the main frequency domain of common road excitations (typically concentrated between 5 and 30 Hz) in both free and installed states. This characteristic verifies the rationality of the structural stiffness design of the battery pack and provides theoretical support and methodological references for the dynamic reliability design of power battery systems by quantifying the coupling effect between modal characteristics and fixture constraints.

### 3.3 Inertia Force Analysis

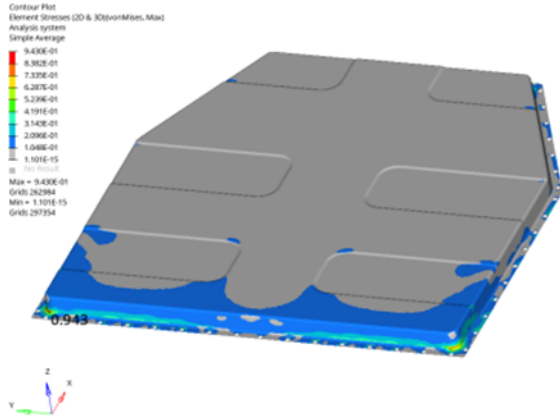
Inertia force analysis is a critical aspect of the structural reliability design of power battery packs, focusing on evaluating the mechanical response characteristics of the

battery system induced by mass inertia effects under dynamic vehicle conditions such as rapid acceleration, emergency braking, high-speed steering, and road impacts [12]. According to D'Alembert's principle, inertia forces can be equivalently treated as virtual forces acting on the center of mass of an object in the opposite direction to acceleration, with a value linearly related to the system's mass and the magnitude of acceleration ( $F=ma$ ) [13]. For power battery packs, the distribution of inertia forces within their internal cell modules, high-voltage connectors, and casing structures directly affects the degree of structural stress concentration and the stability of connection interfaces. Poor design can lead to excessive module displacement, preload failure of lifting lug bolts, or plastic deformation of the casing, potentially causing serious safety hazards such as electrolyte leakage and thermal runaway. Therefore, multi-axial inertia force loading simulations based on national standards are essential technical means for verifying the impact resistance of battery packs and optimizing material selection and structural design.

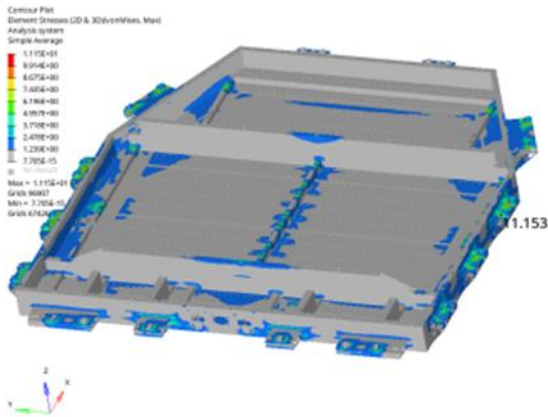
In this paper, multi-axial inertia force loading analysis of the battery pack was conducted in accordance with GB/T 31467.3-2015 "Testing Specifications for Lithium-ion Traction Battery Packs and Systems for Electric Vehicles - Part 3: Safety Requirements and Testing Methods"[14]. X and Y-direction Loading: A 3g acceleration load was applied (corresponding to longitudinal rapid acceleration and deceleration and lateral centrifugal force in vehicles), simulating the mechanical environment of frequent start-stops and curved driving in urban conditions.

Z-direction Loading: Acceleration loads of 5g (for conventional vertical impacts) and 7g (for extreme bumpy roads or collision conditions) were applied separately,

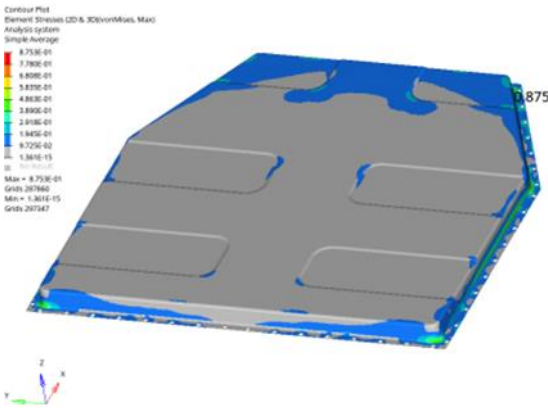
covering the frequency bands where high-frequency impact energy is concentrated in the road spectrum. Through finite element explicit dynamics analysis, the inertia force distribution and stress response contours of key components of the battery pack, including the cover and lower casing, in different directions were obtained, as shown in Figure 4-11 below. The detailed analysis results are presented in Table 3.



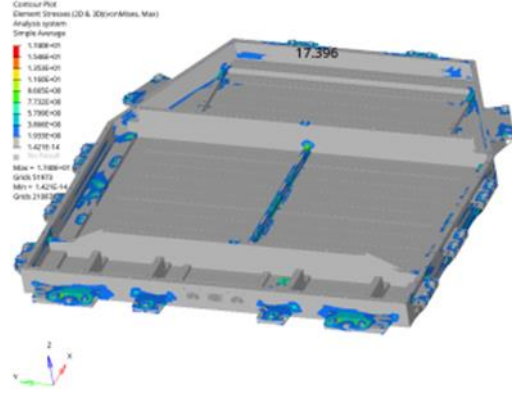
**Figure 4.** Simulated Stress Contour of the Box Cover in the X-Direction



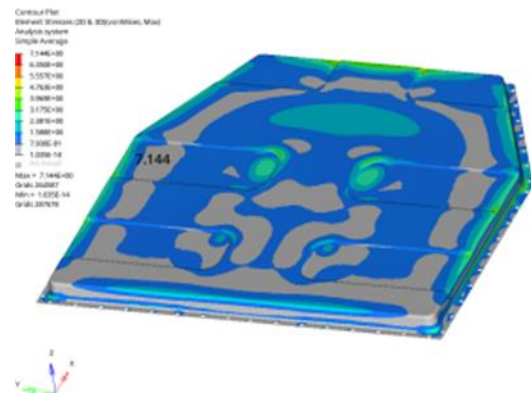
**Figure 5.** Simulated Stress Contour of the Lower Box Assembly in the X-Direction



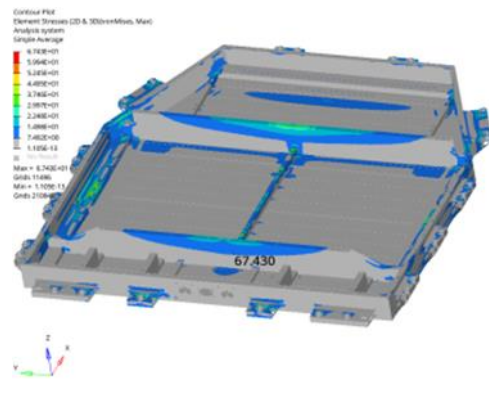
**Figure 6.** Simulated Stress Contour of the Box Cover in the Y-Direction



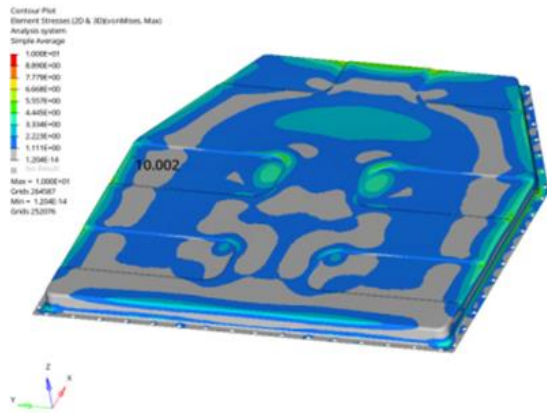
**Figure 7.** Simulated Stress Contour of the Lower Box Assembly in the Y-Direction



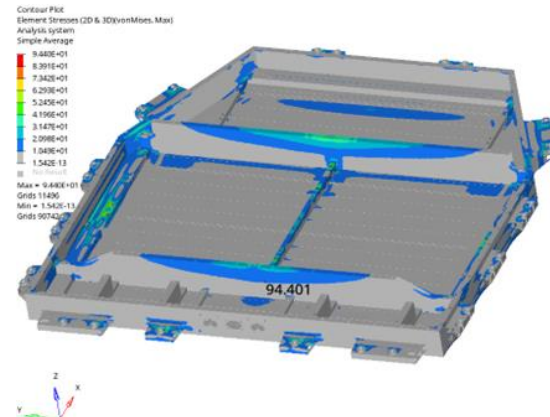
**Figure 8.** Simulated Stress Contour of the Box Cover in the Z-Direction (5g)



**Figure 9.** Simulated Stress Contour of the Lower Box Assembly in the Z-Direction (5g)



**Figure 10.** Simulated Stress Contour of the Box Cover in the Z-Direction (7g)



**Figure 11.** Simulated Stress Contour of the Lower Box Assembly in the Z-Direction (7g)

**Table 3.** Inertia Force Analysis in X, Y, and Z Directions for Components

Component	Direction	X-direction (3g)	Y-direction (3g)	Z-direction (5g)	Reinforcement in the Z-direction (7g)
Box Cover	Evaluation Criterion (MPa)	53.2	53.2	53.2	133
	Maximum Simulated Stress Values (MPa)	0.9	0.9	7.1	10.0
Lower Box	Evaluation Criterion (MPa)	104.8	104.8	104.8	241
	Evaluation Criterion (MPa)	11.2	17.4	67.4	94.4

Based on the simulation results presented above, it can be concluded that under a 3g load in the X and Y directions, the maximum equivalent stresses in the box are 11.2 MPa and 17.4 MPa, respectively. These stresses are concentrated at the intersections of the lifting lug mounts and the reinforcing ribs on the sidewalls of the box (as shown in Figures 5 and 7). These values are significantly lower than the evaluation criterion of 104.8 MPa, indicating that the structural stiffness and restraint design in the X and Y directions effectively suppress the deformation caused by inertial forces. In the Z direction under a 5g load, the peak stress in the support beams at the bottom of the box is 67.4 MPa. Under extreme conditions of a 7g load, the stress value increases to 94.4 MPa (as shown in Figures 9 and 11). Although the maximum inertial forces on various components increase slightly under 7g conditions, they remain within a reasonable range. This demonstrates that the battery pack exhibits good structural strength in the Z direction and meets the design requirements. These findings also provide mechanical boundary conditions for subsequent research on structural reliability under dynamic loads and for fatigue life studies related to random vibrations in power battery packs.

### 3.4 Random Vibration Analysis

As a core component of new energy vehicles, the reliability and stability of the power battery system are crucial. Random vibration analysis, as an effective evaluation method, can simulate vibration conditions in actual working environments, thereby ensuring the safety

performance of the battery system under various vibration conditions [9].

Random vibration analysis simulates vibration conditions in actual working environments to assess the impact of vibrations on battery performance, including changes in battery capacity, internal resistance, cycle life, and other aspects. Vibrations in the battery case can potentially lead to issues such as damage to the internal battery structure, loose connections, or short circuits, which may pose safety hazards. Therefore, random vibration analysis can identify and rectify these issues promptly, ensuring the safety of the battery system. Consequently, this analysis can optimize the structural design of the battery system, enhance product reliability and stability, and thus strengthen market competitiveness.

Based on the practical application scenarios of the power battery system and relevant standards (Q/JL J166002-2022), conditions such as the test frequency range, acceleration amplitude, and duration are determined for random vibration analysis in the X, Y, and Z directions. The specific loading conditions are as follows: random vibration at 0.64g for 12 hours and fixed-frequency vibration at 24Hz and 1.5g for 1 hour along the Z-axis. This indicates that in the Z-axis direction, the power battery system is subjected to a random vibration acceleration of 0.64g (times the acceleration of gravity) in the simulation for a duration of 12 hours, and it is also subjected to fixed-frequency vibration at 24Hz and an acceleration of 1.5g for 1 hour. For the X and Y axes, the power battery system is loaded with random vibration accelerations of 0.45g and 0.5g, respectively, in the simulation for a duration of 12 hours, and it is also

subjected to fixed-frequency vibration at 24Hz and an acceleration of 1.5g for 1 hour. Random vibration analysis of the power battery system is conducted based on the above conditions, with stress contour plots shown in Figures 12-17 and specific analysis results presented in Table 4.

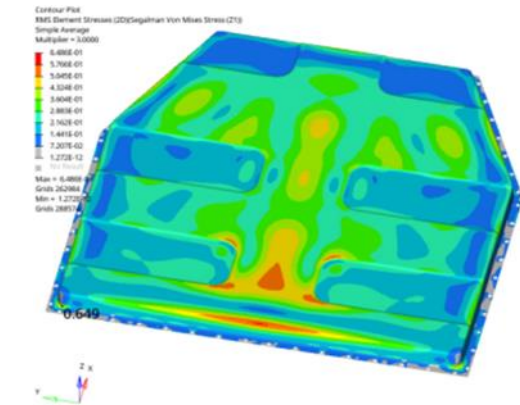


Figure 12. Simulation Stress Contour Plot of the Box Cover in the X-Direction

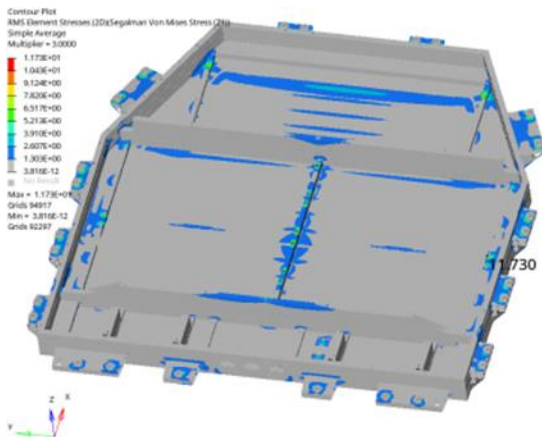


Figure 13. Simulation Stress Contour Plot of the Lower Box Section in the X-Direction

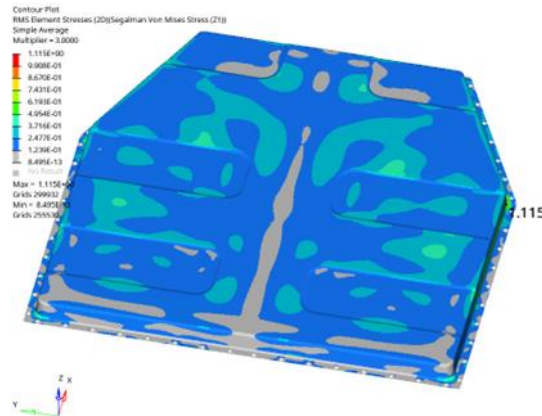


Figure 14. Simulation Stress Contour Plot of the Box Cover in the Y-Direction

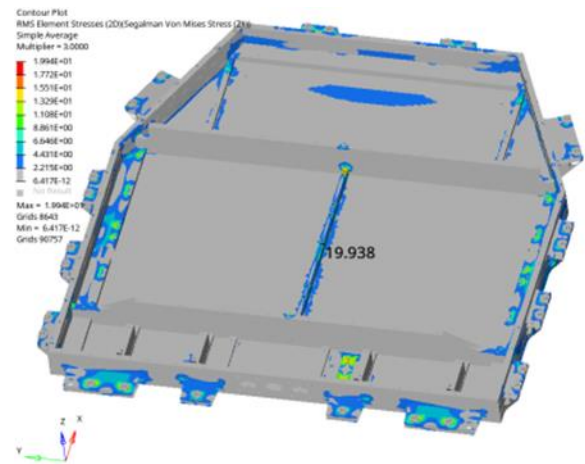


Figure 15. Simulation Stress Contour Plot of the Lower Box Section in the Y-Direction

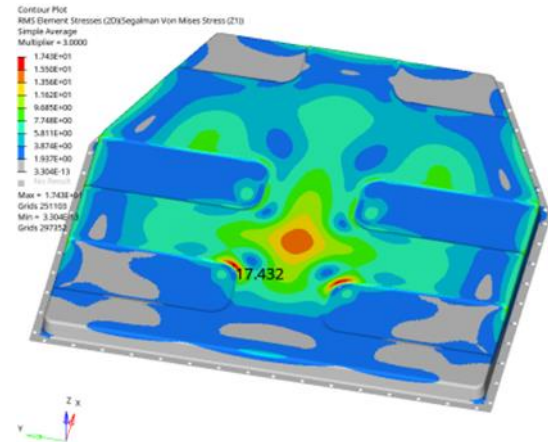


Figure 16. Simulation Stress Contour Plot of the Box Cover in the Z-Direction

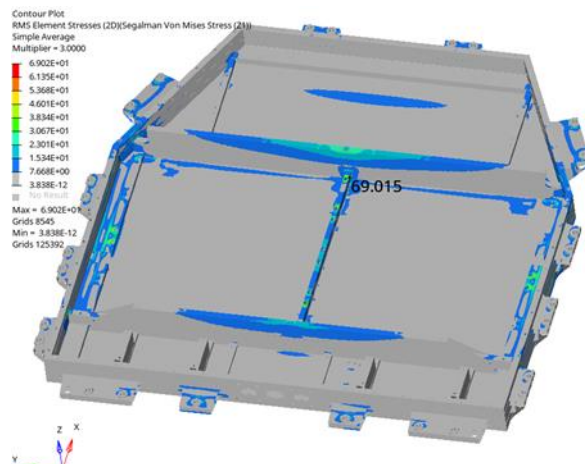


Figure 17. Simulation Stress Contour Plot of the Lower Box Section in the Z-Direction

**Table 4** Results of Random Vibration Analysis in X, Y, and Z Directions

Component	Direction	X-direction	Y-direction	Z-direction
Box Cover	Evaluation Criterion (MPa)	<b>79.8</b>	<b>79.8</b>	<b>79.8</b>
	Maximum Simulated Stress Values (MPa)	<b>0.6</b>	<b>1.1</b>	<b>17.4</b>
Lower Box	Evaluation Criterion (MPa)	<b>157.2</b>	<b>157.2</b>	<b>157.2</b>
	Evaluation Criterion (MPa)	<b>11.7</b>	<b>19.9</b>	<b>69.0</b>

From the above analysis, it can be concluded that the maximum stress values of both the box cover and the lower box section in the X and Y directions are far below the evaluation criteria of 79.8 MPa and 157.2 MPa, respectively, indicating that random vibrations in these directions have minimal impact on the box cover and the lower box section. The simulated maximum stress values of the box cover and the lower box section in the Z direction are 17.4 MPa and 69.0 MPa, respectively. Although these values are higher than those in the X and Y directions, they remain below the evaluation criteria of 79.8 MPa and 157.2 MPa. This suggests that although random vibrations in the Z direction have some impact on the box cover, they remain within the safe range. Therefore, based on the above analysis, the simulated results of random vibrations of the power battery system in the X, Y, and Z directions are all well below the evaluation criteria. This demonstrates that the stress distribution of the power battery system under random vibration loads is favorable, with no areas of stress concentration or exceeding the material's strength limit. Consequently, this indicates that the power battery system exhibits good tolerance to random vibrations and meets relevant standards and requirements, laying a solid theoretical foundation for further testing in the future.

#### 4. Conclusion

In this paper, the dynamic response characteristics and structural reliability of power battery packs under complex vibration environments have been systematically studied through a multi-physics field coupling finite element simulation method. The research adopts a technical approach combining modal analysis, inertial force analysis, and random vibration analysis to reveal the interaction mechanism between the structural dynamics of the battery pack and random vibration loads. The main conclusions are as follows:

(1) Modal analysis based on the Lanczos algorithm reveals that the first-order natural frequencies of the battery pack system under free and tooling-constrained conditions are 42.2 Hz and 41.2 Hz, respectively, both satisfying the customer's design requirements (first-order frequency > 40 Hz). Additionally, the first three natural frequencies under tooling-constrained conditions are distributed within the range of 41.2-70.5 Hz, effectively avoiding the common road excitation frequency band (5-30 Hz) of new energy vehicles. This characteristic verifies

the rationality of the structural stiffness design of the battery pack.

(2) The simulation results of inertial loads show that under 3g loads in the X and Y directions, the maximum equivalent stresses of the battery case are 11.2 MPa and 17.4 MPa, respectively. In the Z direction, under a 5g load, the peak stress of the supporting beam at the bottom of the battery case is 67.4 MPa, and in extreme conditions of 7g, the stress value rises to 94.4 MPa. All these values are within a reasonable range, indicating that the battery pack has good structural strength in the X, Y, and Z directions and meets the design requirements.

(3) Random vibration analysis indicates that the maximum stress values of the box cover and lower box section in the X and Y directions are far below their evaluation criteria. The simulated maximum stress values of the box cover and lower box section in the Z direction are 17.4 MPa and 69.0 MPa, respectively, still lower than the evaluation criteria of 79.8 MPa and 157.2 MPa. This demonstrates that the stress distribution of the power battery system under random vibration loads is favorable. Given the above research results, the power battery pack exhibits good dynamic response characteristics and vibration tolerance under the designed vibration loads. The results of modal analysis, inertial force analysis, and random vibration analysis all verify the structural stability and reliability of the battery system. The research methods and findings in this paper have important guiding significance for the optimal design of power battery packs and provide a strong guarantee for the safe operation of new energy vehicles.

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