

Dynamic behavior of a battery pack based on single reference impact testing of a secondary cell

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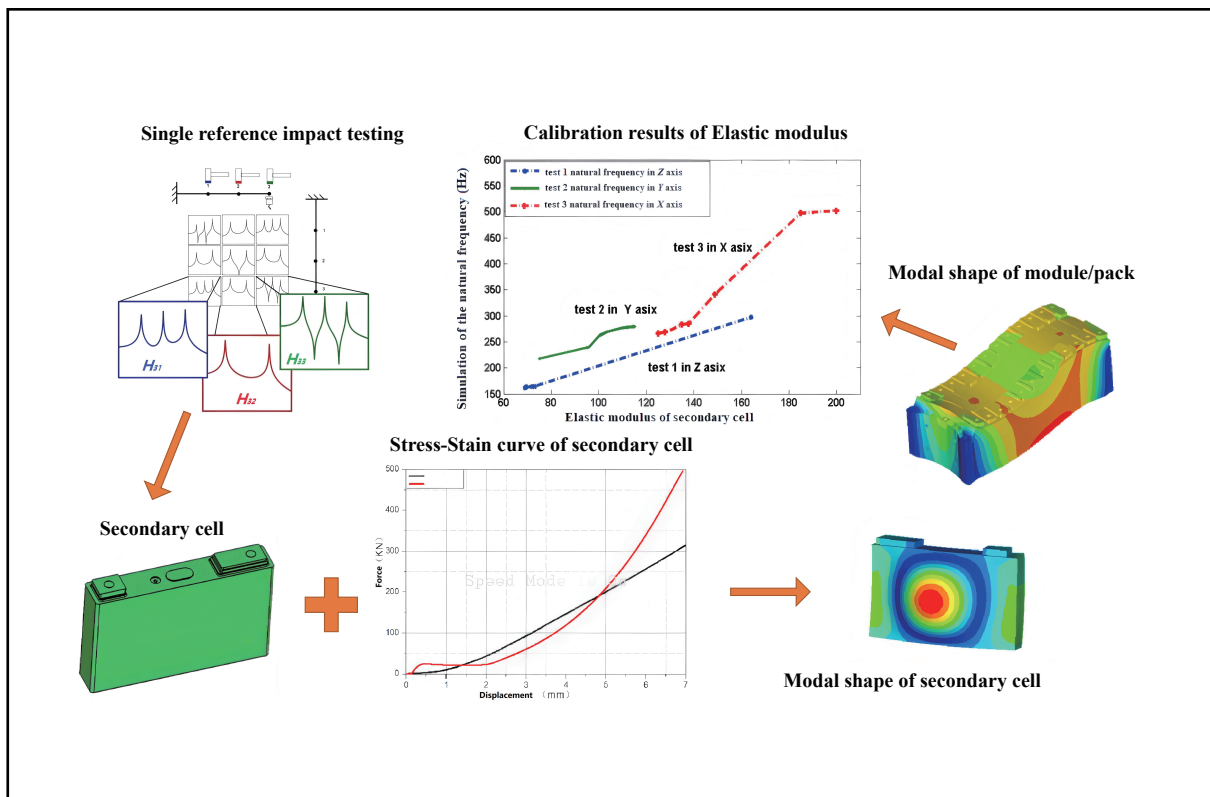
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Graphical abstract



Natural frequency analysis of a battery pack based on single reference impact testing of a secondary cell.

Public summary

- An equivalent constitutive relationship of secondary cells was proposed to reveal the dynamic properties of battery pack.
- The structure response of batteries was studied based on the single reference impact testing.
- The finite element model of battery modules was corrected based on the experiments and the equivalent constitutive relationship of secondary cells.
- The modal shapes and natural frequencies of battery module/pack systems have been studied since the elastic modulus of secondary cells were calibrated.

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Abstract: The mechanical properties of secondary cells are crucial to the safety and reliability of battery packs, which can fail due to extrusion and vibration in a vehicle crash. To analyze the structural response of the secondary cell and its other dynamic behaviors, the experiment and some numerical simulations were carried out based on single reference impact testing. Then, an equivalent constitutive relationship of the secondary cell was proposed to reveal the dynamic properties and used to guide the safety estimation of the battery pack. As the input parameter to the finite element model, the equivalent constitutive relationship, including but not limited to the elastic modulus and stain-stress curve, determines the simulation precision of the battery packs. Compared to the experimental results of the natural frequency of the battery pack, the simulation error is below 2% when the elastic modulus of the secondary cell in the battery pack has been verified.

Keywords: equivalent constitutive relationship; secondary cell; dynamic property

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1 Introduction

As the most important components of electric vehicles (EVs), battery packs are designed and manufactured based on a principle of long cycle life and performance at a high discharge rate to meet the demand of new electric equipment. Hence, the battery energy density should be enhanced over shape- and size-limited conditions in EVs, and then a high energy capacity can be achieved. However, a rapid growth in battery energy density may bring safety concerns; in most cases, failure and thermal runaway are caused by mechanical loading and intrusion in crash events. In this case, the mechanical properties of battery packs should be studied to evaluate the failure and thermal runaway of batteries, especially for secondary cells that may be damaged due to internal short circuits caused by the intrusion of foreign objects.

Research on the electrochemistry of batteries and thermal management has been conducted for a long time, while few people have considered the response and failure of secondary cells due to mechanical loading, which is the key to the safety of battery packs^[1]. In addition, the difficulty of estimating the rigidity of battery packs lies in the ambiguous mechanical properties of secondary cells, which probably vary from one manufacturer to another, although penetration and small overlap crash tests were studied to estimate the damage of battery packs during a collision, and the damage and failure of individual cell due to mechanical loading can also be discovered by the law of mechanics^[2]. Furthermore, a secondary cell is a complex multilayered structure consisting of a cathode, an anode, and two layers of separator, and all these components

are immersed in electrolytes and covered by a pouch or a steel shell casing. While the mechanical behavior of a secondary cell is not simply the sum total of the contributions of each component, the main factors that influence the possibility of electrical short circuits should be explained based on tests to discover the mechanical properties of battery packs^[3] and the constitutive relationship between different secondary cells^[4].

Considering the absence of a complete set of mechanics-based criteria for internal short circuits at the battery component material level, it is necessary to calibrate the mechanical behaviors of the battery component materials individually under representative mechanical loading conditions^[5]. Some approaches were proposed to provide data for the development of an advanced constitutive model for strength/weight optimization and safety assessments of commercial lithium-ion batteries^[6]. In Sahraei et al.'s research^[7], mechanical tests were performed on pouches and bare lithium-ion cells under five loading conditions. According to the measured load-displacement data, three compression stress-strain curves were calculated for the separator, the active anode, and cathode materials. It was also demonstrated that a thin pouch enclosure could provide considerable reinforcement and could change the deformation and failure mechanism in some cases.

Furthermore, the mechanical failure of battery-pack systems under crush and vibration conditions is a crucial research topic in automotive engineering^[8,9]. Some multiobjective optimization algorithms can be used to evaluate and optimize the mechanical response of battery pack systems under various loading conditions to achieve a reliable and robust design^[10–12]. For example, a method for optimizing the

crushing stress of modules and the vibration fatigue life of battery pack systems was developed based on a nondominated sorting genetic algorithm II (NSGA-II) algorithm and the linear weighting method^[13]. Meanwhile, Marano et al.^[14] proposed a multiobjective optimization criterion for linear viscous-elastic devices utilized for decreasing vibrations induced in mechanical and structural systems by random loads, and the NSGA-II algorithm was adopted to obtain the Pareto sets and the corresponding optima for different characterizations of the system and input.

As is well known, some mechanical characteristics of secondary cell components could be obtained if the materials were defined; for example, the distribution of plastic strain in an 18650 cylindrical secondary cell was exposed by Zhu et al.^[15]. Nonetheless, in regard to pouch cells, the greatest challenge is how to align the cell without causing buckling, edge fracture, and wrinkling, which are very common for thin films (large length/thickness ratio)^[16]. One of the strategies to overcome this difficulty is single reference impact testing (SRIT), especially for anisotropic objects that are difficult to measure by traditional equipment^[17]. The purpose of this paper is to analyze the dynamic properties of the battery pack system, battery module, and secondary cell (taking the punch cell as an example). Then, the main factors that influence the strength and rigidity of the battery can be studied. In this paper, a new approach is proposed to analyze the mechanical properties of battery packs based on the SRIT, while a finite element (FE) model of commercial lithium-ion batteries is constructed to simulate the collision and oscillation of battery packs. Furthermore, by comparing the results of the impact test and the numerical analysis, the mechanical properties of the battery pack can be estimated based on the modified model, which is corrected partly from the constitutive relationship of the secondary cell.

2 Dynamic properties of secondary cells

As a basic element of commercial lithium-ion batteries, a pouch secondary cell (see Fig. 1) was studied to determine the mechanical properties.

2.1 Theoretical basis of the impact test

As a typical dynamic test method, the impact test is convenient and practical for obtaining the dynamic stiffness of secondary cells. During the test, an impact hammer was used to give an excitation force to the test surface of the specimen in a free state (supported by the flexible foam with a low damping, as shown in Fig. 2), and the dynamic response of the specimen was recorded by a vibration sensor.

In regard to the vibration response, the frequency response function (FRF) must be analyzed. The FRF is derived from the structure response labeled as X and excitation force labeled as F . The former is monitored by the dynamic analyzer based on the fast Fourier transform (FFT) algorithm, and the latter is recorded by the force sensor. With the help of FRF and parametric feature recognition, the structure mode shapes and other modal parameters can be obtained from the

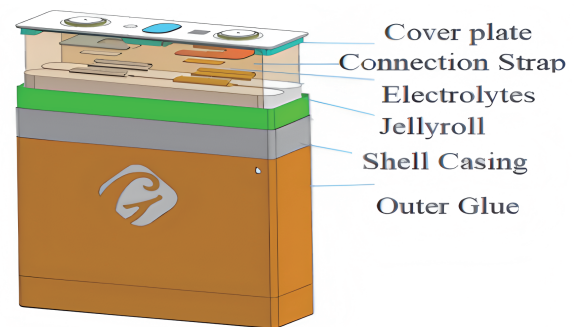


Fig. 1. A pouch secondary cell.

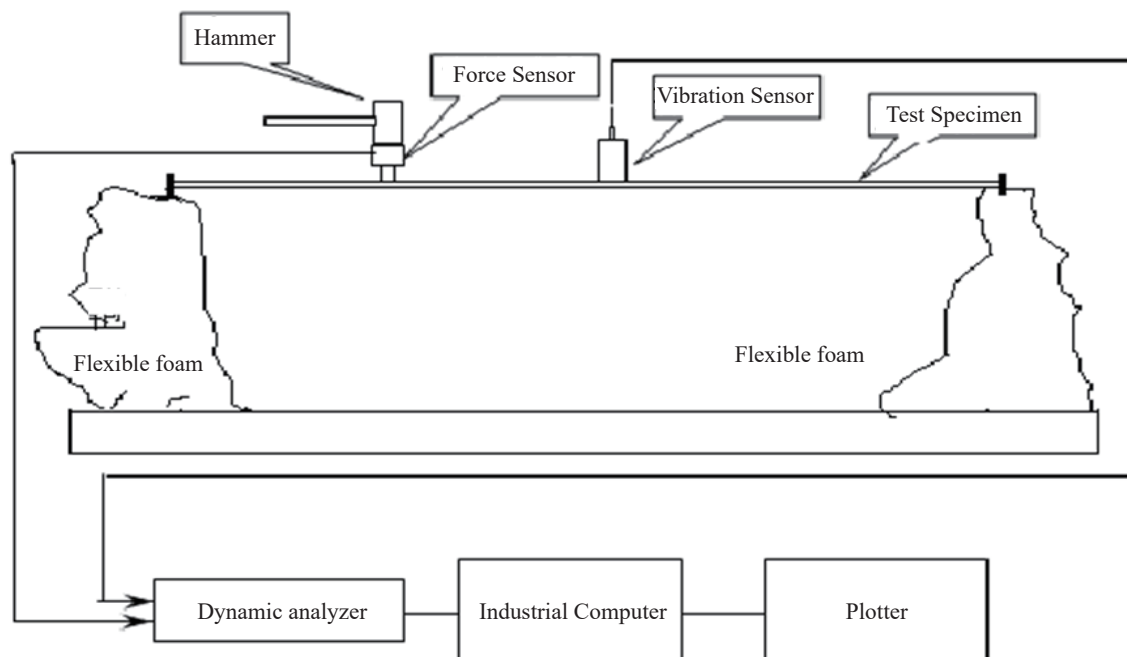


Fig. 2. The single reference impact testing system.

time-domain signals and then used to estimate the dynamic stiffness of the secondary cell.

The FRF matrix can be described as:

$$\begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} & \cdots & H_{1j} \\ H_{21} & H_{22} & H_{23} & H_{24} & \cdots & H_{2j} \\ H_{31} & H_{32} & H_{33} & H_{34} & \cdots & H_{3j} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ H_{i1} & H_{i2} & H_{i3} & H_{i4} & \cdots & H_{ij} \end{bmatrix}. \quad (1)$$

In particular, the element of the FRF matrix, which is used to describe the response at point i excited by the force F at point j , is also a complex number including the amplitude labeled as a and the phase ω calculated by the following equations:

$$H_{ij}(\omega) = \frac{X_i(\omega)}{F_j(\omega)}. \quad (2)$$

Taking the amplitude and phase into consideration, the element is

$$[H(j\omega)] = \sum_{k=1}^N \left(\frac{[A_k]}{(j\omega - p_k)} + \frac{[A_k^*]}{(j\omega - p_k^*)} \right), \quad (3)$$

$$H_{ij}(j\omega) = \sum_{k=1}^N \left(\frac{a_{ijk}}{(j\omega - p_k)} + \frac{a_{ijk}^*}{(j\omega - p_k^*)} \right), \quad (4)$$

where k is the mode order and p is the pole of the measuring system, including the natural frequency f_n and damping, which is shown as the extremum in the time-domain signals. a_{ijk} is the residue and describes the modal shape that is derived from the signals, calculated from the following equation:

$$H_{ij}(j\omega) = \sum_{k=1}^N \left(\frac{q_k u_{ik} u_{jk}}{(j\omega - p_k)} + \frac{q_k^* u_{ik}^* u_{jk}^*}{(j\omega - p_k^*)} \right), \quad (5)$$

in the formula above, q is the scale factor of the modal shape. When the structure vibrates at one modal, u_{ik} is the vibration peak value at the response output point i , while u_{jk} is the response data at the input excitation point j . Moreover, the asterisking parameters, such as u_{ik}^* and u_{jk}^* , are the conjugate complex numbers of u_{ik} and u_{jk} , which are measured by referring to the single reference point, which is the location of the vibration sensor.

Fig. 3 gives the measurement process of the specimen based on the SRIT. When the hammer moved along the planned trajectory, a row of FRF matrices could be obtained from a series of modal response signals collected by the vibration sensor. At the same time, the FFT algorithm was used to transform the time-domain signals to the frequency response, and the modal parameters at the measuring point could be analyzed if the response data, such as amplitude and phase, were derived from the signals.

To decrease the noise in the time-domain signals, the cross power G_{XF} and autopower G_{XX} and G_{FF} were used to obtain the structure response of the test specimen. In this way, the response spectrum of the structure can be derived from the frequency signals with the help of feature recognition.

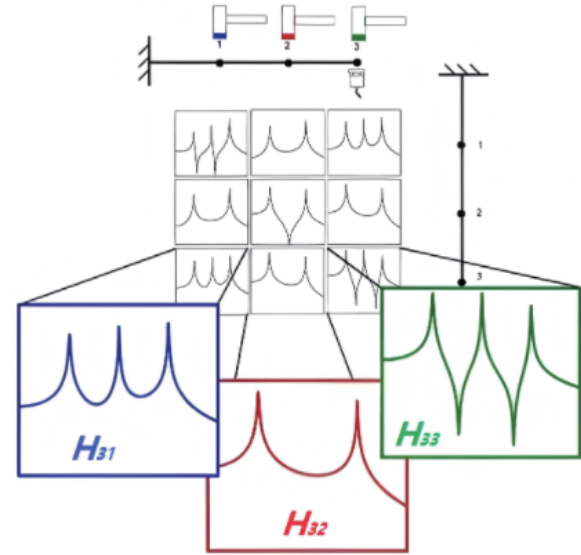


Fig. 3. Structural response at each measuring position.

Furthermore, the modal parameters, such as eigenvalues and eigenvectors, can be solved. The modal features, including natural frequency and mode shapes, were described by those modal parameters, including but not limited to $H_{ij}(j\omega)$, G_{XF} , G_{XX} , and G_{FF} .

$$G_{FF} = \frac{1}{N} \sum_{i=1}^N F_i F_i^*, \quad (6)$$

$$G_{XX} = \frac{1}{N} \sum_{i=1}^N X_i X_i^*, \quad (7)$$

$$G_{XF} = \frac{1}{N} \sum_{i=1}^N X_i F_i^*. \quad (8)$$

Taking the excitation force and input energy into consideration, enhancing the dynamic stiffness and resonant frequency of the test specimen can avoid the possibility of failure since the high structure response may cause failure when a stochastic resonance occurs.

2.2 Experiment setups

A measuring system including a dynamic analyzer, an impact hammer, and vibration sensors was constructed based on the SRIT. We collect the frequency response signals to obtain the FRF matrix during the test.

Fig. 4 gives the natural frequency of the specimen based on the results of the SRIT. The dynamic analyzer gives the stabilization chart based on the frequency response, and a stabilization chart is exported to select poles accurately by adopting the global curve fitting method. Because the frequency response is a steady-state, the natural frequency of the test specimen can be observed from the stabilization chart since the poles were defined according to the signals.

2.3 Experimental analyses

While the secondary cell is composed of several materials, such as copper foil, aluminum foil, and separator, the stiffness of the battery cannot be concluded from the



Fig. 4. Frequency response signals based on the results of SRIT.

constitutive relationship of metals; meanwhile, some factors, such as the state of charge (SOC), will affect the strength and stiffness of the battery^[18]. In this case, we estimate the dynamic stiffness of the battery with the help of the equivalent constitutive relationship. As the input parameter to the commercial FE model of a battery, the equivalent elastic modulus and strain–stress curve are usually obtained from the quasistatic test of the secondary cell. However, due to the anisotropy of the secondary cells, it is time-consuming to properly design a quasistatic test by a traditional hydraulic machine and drop tower system^[19]. We propose a new approach to calculate the equivalent elastic modulus from the numerical analysis and dynamic test and give the dynamic property and characteristic parameters to guide the structure response estimation of secondary cells, which are necessary to correct the FE model.

Fig. 5 gives each natural frequency of the secondary cell caused by the different exciting energies in the Z axis and Y axis; for example, the experimental result is 1087 Hz, corresponding to the modal shapes in the Z axis, which is measured based on the structure response of the secondary cell, and 1095 Hz, corresponding to the modal shapes on the Y axis. Compared to the simulation value and experimental results of

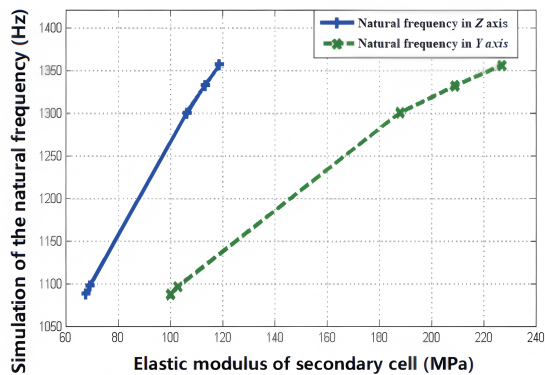


Fig. 5. The natural frequency of the secondary cell.

the SRIT, the optimal equivalent elastic modulus in the Z axis is 67.9 MPa and 103 MPa in the Y axis.

Henceforth, the results of the SRIT provide some information about the structural response of the secondary cell at each measuring point. Several dynamic characteristics, such as the elastic modulus, were recorded and analyzed from the monitoring signals.

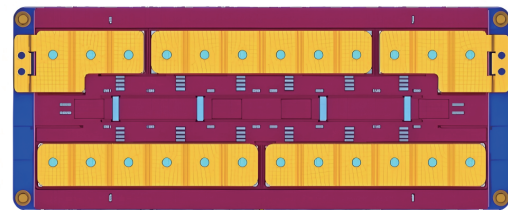
3 Numerical analysis—verification of the experimental analyses

To verify the experimental results, a series of numerical simulations are carried out.

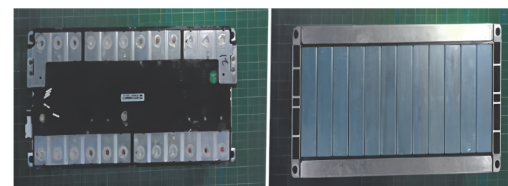
3.1 FE models of secondary cells and battery module

The FE model of the secondary cell and battery module were constructed based on the design scheme (Fig. 6).

Most materials were defined when the design scheme was proposed. The constitutive relationship of metals in the battery was acquired from the quasistatic test, as shown in Table 1.



(a) FE model of the battery module



(b) battery module in test

Fig. 6. FE model of the battery module.

Table 1. Constitutive relationship of metals in the battery.

Components	Materials	Density (kg/mm ³)	Elastic modulus (GPa)	Yield strength (MPa)
Shell casing	Aluminum	2.3E-6	70	165
Cathode	Cu	8.96E-6	110	200
Anode	Aluminum	2.3E-6	70	165
Cover board	Plastic	1.2E-6	1.2	70

However, the mechanical properties of secondary cells vary with the constrained boundary condition, SOC, and interior expansion force. The equivalent elastic modulus of the secondary cell should be obtained, which is crucial to the simulation accuracy of the secondary cell.

3.2 Analysis of the dynamic properties of the secondary cells and battery module

We give an initial value derived from Fig. 5 for the equivalent elastic modulus of the secondary cell, and then a vibration simulation result can be observed with the help of modal shapes. By the time, the natural frequency is recorded while the structure response of the test surface and natural frequency are explored by the numerical simulation, which describes the maximum displacement and amplitude of the node in the FE model referring to the test surface. Then, the input parameter of the FE model can be adjusted based on the differences between the experimental result and the simulation value, especially for the equivalent elastic modulus of the secondary cell.

Fig. 7 gives a series of modal shapes and natural frequencies of the battery module in a frequency band. Usually, its

relatively weaker parts are pointed out when the principal mode of vibration is obtained, and the first-order natural frequency is of greater concern due to the resonance. In the simulation results, the places marked with red states are the maximum displacement during the vibration.

When the natural frequency of the secondary cell is verified from the experimental tests, the equivalent elastic modulus of the secondary cell can be defined based on the corrected FE model.

It is obvious in Fig. 8 that the elastic modulus in the Z axis is 69 MPa according to the modal shape and natural frequency of the battery module (164 Hz), 105 MPa in the Y axis (corresponding to 273 Hz) and 180 MPa in the X axis (corresponding to 473 Hz). They are close to the real elastic modulus of secondary cells and verify the correction of the characteristic parameters of the FE model.

3.3 Estimation of the dynamic property of the battery pack

Fig. 9a gives the FE model of the battery pack, which is composed of battery modules and secondary cells. The constitutive relationship, such as the equivalent elastic modulus, has been verified by the results of SRIT; in this case, the modal shapes and natural frequency can be given by the simulation results.

Due to the external excitation, the resonance of the battery pack will be observed at each modal shape. Fig. 9b gives the modal shapes of the battery pack, which discloses the characteristics of vibration and oscillation during work. Because the safety of the battery pack is affected by the dynamic characteristics, we should choose an optimization structure with a higher natural frequency to avoid possible resonance of the battery pack.

4 Experimental verification

Several vibration tests were carried out to verify the

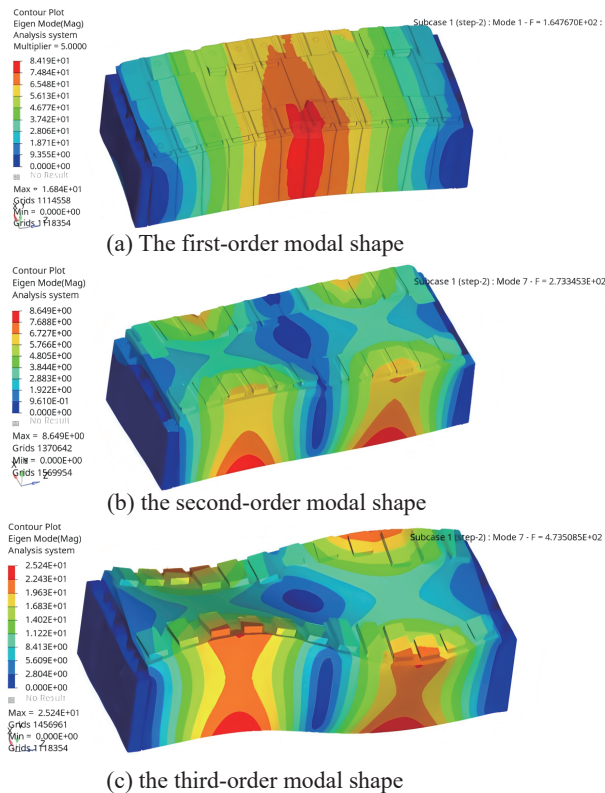


Fig. 7. Modal shapes of the battery module.

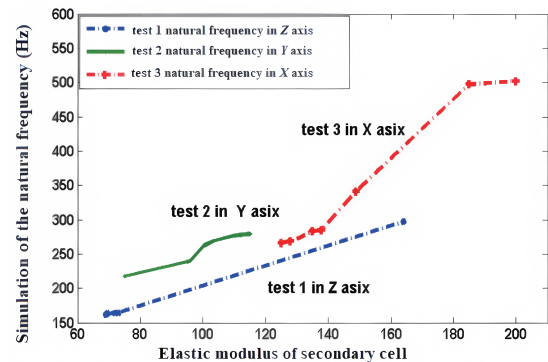


Fig. 8. The natural frequency of the battery module.

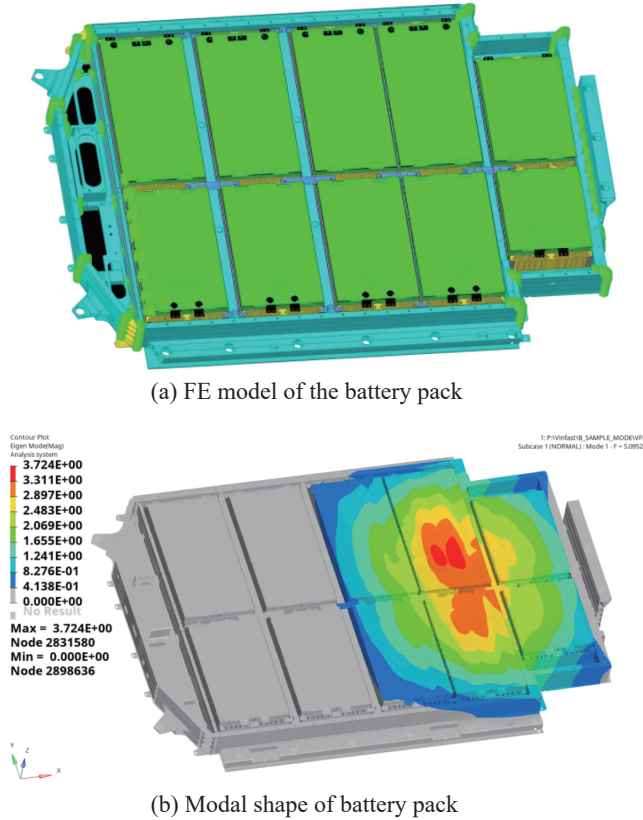


Fig. 9. FE model and modal shapes of the battery pack.

correction of the dynamic characteristics of the battery pack.

4.1 Dynamic test of the battery pack

To verify the equivalent constitutive relationship and construct the input parameter database for the FE model, a battery pack is placed on the electrical vibration table and excited with the acceleration spectrum according to the designed power spectral density (PSD), which is transformed from the road spectrum collected by the vehicle at work (Fig. 10).

The system resonance can be discovered based on the maximum amplitude of the monitoring signal (see Fig. 11). Based on a comparison between the simulation value of the modal shapes of the battery pack and the characteristic value of the dynamic property in the test, we can obtain an exact FE model so that the input parameters of the secondary cells can be corrected, as well as the battery pack.

4.2 Verification of the finite element model

We constructed a constitutive relationship database for secondary cells so that the safety and mechanical properties of battery packs can be estimated exactly. Fig. 12 gives the simulation results of the modified FE model of the battery pack, where the input parameters were corrected based on the experimental results. Compared to the FE model of the battery pack with the constitutive relationship of the aluminum cathode, anode, and steel shell casing, the simulation results of the corrected FE model have exact values for the natural frequency of the battery pack. The error at each dimension of the experimental result of the natural frequency is decreased

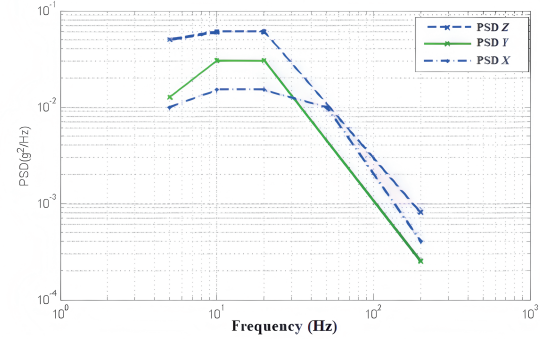


Fig. 10. PSD of battery pack.

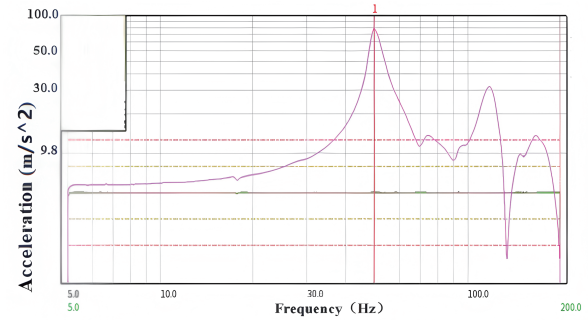


Fig. 11. Monitoring signal of the battery pack.

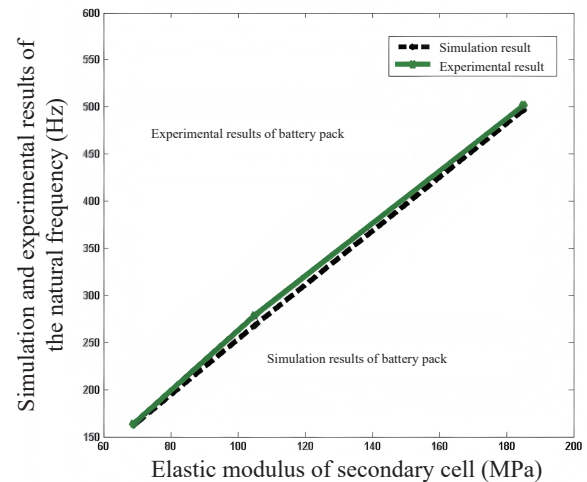


Fig. 12. Simulation and experimental results of the natural frequency of the battery pack.

below 2%, and then it is useful to estimate an equivalent constitutive relationship of the secondary cell to analyze the mechanical property of the battery pack.

5 Conclusions

The input parameters to the FE model are crucial to the accuracy of the simulation results, especially for the mechanical property estimation of the battery pack. Henceforth, the analysis of the constitutive relationship of secondary cells, as an input characteristic parameter that plays an important role in the FE model, is necessary for numerical analysis.

We obtain the key parameters to estimate the dynamic property of the secondary cell based on the SRIT results. The

vibration and oscillation were simulated to verify the constitutive relationship of secondary cells. The consequence indicates that the oscillation amplitude of the finite element model is close to the experimental structure response, also verifying the constitutive relationship of secondary cells. We give the chief factors to decide the mechanical property of the battery pack in an oscillation or crash, and the safety estimation of the battery pack would be improved based on the proposed constitutive relationship of the secondary cell.

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Conflict of interest

The authors declare that they have no conflict of interest.

Biography

Zhen Xiao was engaged in the postdoctoral research in Department of Modern Mechanics, University of Science and Technology of China, co-operated with Hefei Gotion High-tech Power Energy Co., Ltd. & Shanghai Gotion New Energy Co., Ltd. from 2018 to 2022. He received his Ph.D. degree in Mechanical Engineering from Beijing Institute of Technology in 2017. His research mainly focuses on the mechanical property of battery pack and the equivalent constitutive relationship of secondary cell.

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