



Capacity and impedance characteristics of the lithium-ion battery and mechanical properties of the battery pack under coupled temperature-vibration conditions: an experimental approach

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HIGHLIGHTS

- Li-ion cells and 3D-printed cases were tested under thermo-mechanical loading.
- SOC and internal resistance were tested from -20°C to 60°C across all SOC levels.
- Vibration slightly raised resistance and reduced SOC, especially at low SOC.
- PLA failed at 60°C , while ABS enclosures remained structurally stable.

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ABSTRACT

Since electric vehicles are subject to constant vibration and temperature fluctuations during operation, it is critical to understand the impact of these factors on the performance of batteries and battery enclosures. This study investigates the impact of vibration (random frequencies from 8 Hz to 200 Hz) and temperature (ranging from -20°C to 60°C in 10°C increments) on lithium-ion batteries at varying states of charge (SOC, from 0 % to 100 % in 10 % intervals). A 3D-printed plastic enclosure was used for the battery pack to assess its mechanical performance under operational vibration. Analysis of the experimental data reveals that battery internal resistance shows an upward trend, with increases ranging from $0.1\text{ m}\Omega$ to $0.5\text{ m}\Omega$ under standard conditions and up to $1\text{ m}\Omega$ at low temperatures after vibration. Battery capacity exhibited a slight decline after vibration, typically around 0.5 %, across most conditions. Temperature did not significantly impact the SOC response, with similar resistance and capacity trends observed across the temperature spectrum after vibration. For the battery pack, structural integrity was maintained under thermal and vibrational stress, as indicated by minimal changes in natural frequency (within 0.5 Hz). These results confirm the feasibility and potential of using 3D-printed battery enclosures in practical applications.

1. Introduction

The rapid development of hybrid electric vehicles and electric vehicles increases the popularity of lithium-ion batteries [1]. As a key component of these vehicles, the lithium-ion battery largely determines the vehicle's price, lifespan, safety, and performance [2]. If a battery in an electric vehicle fails, it can potentially lead to fires, explosions, and the release of toxic gases [3,4], posing significant risks to the vehicle itself and its occupants. Therefore, there has been a growing focus on research [5,6] and standardised safety testing efforts [7] for EV

batteries.

Several metrics, such as the maximum capacity, the resistance, the rate capability, and the degradation mechanism, are used to characterise the battery's performance [8]. They are affected by the actual environmental conditions (such as high temperatures, low temperatures, and road vibrations), which will affect the mileage and the life expectancy of the EVs [9,10]. Therefore, it is important to investigate battery performance with the consideration of environmental factors such as vibration and temperature under the actual working conditions of EVs.

Vehicles are subjected to various types of vibrations during

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operation. Hooper and Marco [11,12] examined the typical vibration levels experienced by a range of battery packs of EV batteries while driving on customer-representative road surfaces. They found that the typical vibration frequencies for battery durability were below 7 Hz. However, they also found vibration frequencies above 300 Hz, which were potentially induced by electric devices, the transmission system, or the cooling mechanism. Lang and Kjell [13] also observed similar wide vibration ranges with frequencies above 200 Hz.

Several publications have investigated the effects of vibration in electric buses [14], electric cars [15], and electric heavy-duty vehicles [16] through experimental testing with different standards. Maeda et al. [17] verified ISO 12405 for a pure electric car and a plug-in hybrid vehicle. Test results showed that vibrating for 6 h in the X-axis direction and 4 h in the Y-axis direction can more accurately reflect the actual operating vibration. On the contrary, Hooper and Marco [12] found that battery packs can experience vibration frequencies beyond the frequency range defined by current standards. Existing studies measured the battery performance, such as the internal resistance, impedance and capacity under vibration, using different standards. Awan et al. [18] used the IEC 62660-2 standard and tested lithium-ion on lithium-polymer batteries. Vibration affects both batteries, showing up as decreased capacity and increased impedance, and lithium-ion batteries are more sensitive to vibration than lithium-polymer batteries. In the other study [19], test data from Li-ion batteries using the SAE J2380 standard was analysed statistically. Results showed that the capacity mean of samples exhibited a reduction of 68.8 mAh, and the standard variation increased by 5.1463 mAh after vibration. At the same time, the internal resistance of the battery increased with a probability of 95 %.

Similarly, Hooper et al. [20] tested the Samsung ICR18650-22F lithium-ion batteries using the same standard (SAE J2380) and found a very significant performance degradation due to vibration. The internal resistance increased by 257.82 % after the vibration. This degradation is universal and does not depend on the test standard and cell type, such as 18650 cells [21]. Three commercial Li-ion cells from different chemistries, Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Cobalt Oxide (LCO) and Lithium Iron Phosphate (LFP), were subjected to sinusoidal vibration based on the United States Advance the Battery Consortium (USABC) standard in Ojas et al.'s research [22]. It was found that the resistance inside the battery increased and the capacitance value decreased.

Somerville et al. [23] investigated the mechanisms causing the battery performance deterioration after vibrations. They found that in the case of vibration, the selectively formed surface film was removed, and then the surface film was formed due to the breakdown of the electrolyte. This new surface film leads to the degradation of the battery, the loss of capacity, and a significant increase in the internal resistance. On the other hand, Berg et al. [24] investigated the effect of the battery's internal structure on the battery's vibration durability. They found that the negative pole of some batteries can be mechanically damaged after random vibrations.

Temperature is another significant parameter affecting the battery performance. The temperature of the battery surface is different from the ambient temperature during normal operation, and the electrical characteristics of batteries are affected [25–27]. The thermal generation behaviour increased the internal resistance of 18650 ternary LiNi0.5Co0.2Mn0.3O2 batteries in a working environment at 30 °C and 50 °C [25]. The instantaneous internal temperature detected in a commercial 18650 LiCoO2 lithium-ion battery can even reach 95 °C in the event of a failure [26]. Meanwhile, the discharge performance of batteries is worse in low-temperature environments, affecting the mileage of the EVs [28]. It was reviewed in Ref. [28] that the reduced capacity of lithium-ion batteries indicates poor battery performance in low-temperature conditions. The discharge capacity was reduced by 12.5 %, and the voltage platform was reduced by 0.52 V when the ambient temperature was –20 °C [29]. However, the battery heat generation at a low temperature causes the surface temperature of the battery to rise, which makes the

actual temperature to be higher than the ambient temperature. The minimum temperature of the battery packs can reach 8.8 °C while the ambient temperature is –20 °C when the EV runs for 1 h at a speed of 89 km/h [27].

Environmental factors may also influence the battery pack's performance. Most of the existing studies focused on the structural analysis of the battery pack's vibration performance. Choi et al. [30] proposed a single-axis acceleration test method for battery fixing brackets to convert the measured vibrational acceleration signals into a power spectrum diagram and developed a formula for the driving distance according to the testing time. Shui et al. [31] optimised the battery pack shape through ANSYS simulation to reduce the structural deformation under dynamic load and random vibration. Similarly, Zhou et al. [32] developed a simulation program for fatigue analysis of bus battery brackets under dynamic loads. However, there are rare publications about the battery looseness and pack's integrity under long-term vibration conditions.

According to the existing research, the review noticed that there were many studies on the impact of a single vibration or temperature on batteries and battery packs. However, academia lacks a battery performance investigation that considers the effects of the coupled temperature and vibration at the same time. In addition, research on the impact of battery pack vibration usually applies simulation methods to investigate the mechanical damage or the looseness of pack holders/fasteners due to vibration. No research has been conducted on the mechanical integrity of individual battery cells under coupled thermo-mechanical loading conditions. To address the research gaps, this paper tested the 18650 battery cell's electrical performance and investigated the pack's internal integrity under coupled temperature-vibration conditions.

2. Methodology

The presented work applied the experimental methodology to investigate battery cell electrochemical properties and battery pack integrity, considering both temperature and vibration influences. An overall methodology flow diagram is illustrated in Fig. 1.

2.1. Battery pack assembly

2.1.1. Lithium battery type selection

There are various shapes and sizes for commercial Li-ion batteries [33]. Among them, the most common one is the 18650 cell, referred to as a cylindrical shape with a diameter of 18 mm and a length of 65 mm [34]. Due to its economic scale, it is widely used in electric vehicles. Therefore, the 18650 battery was selected in the presented works.

Samsung NCR 18650 20R battery cells were used in the experiments. It has a rated discharge capacity of 2000 mAh, with a voltage range from 2.5 to 4.5 V. It is worth noting that all batteries in the tests were brand new. The specifications of the cell can be found in Table 1.

2.1.2. Battery enclosure preparation

A 3D-printed plastic battery enclosure was used to house a battery pack of 11 cells. The choice of 3D printing technology was driven by its flexibility in prototyping complex designs and rapid iteration, which allowed us to efficiently produce a customised enclosure tailored to the specific dimensions and structural requirements of the battery pack [35].

The enclosure design was modelled in SolidWorks with features optimised to secure the battery cells tightly and prevent movement during operation, as shown in Fig. 2(1). The CAD design was saved as an STL file and sliced in Cura software for 3D printing. The 3D printing process was carried out using a Fused Deposition Modelling printer Ultimaker 2+ with the following key printing parameters: Nozzle size: 0.4 mm. Infill Density: 75 %. Layer thickness: 0.1 mm.

11 battery cells are placed in the pack by two brackets as shown in Fig. 2(2). The cells are not connected to each other, they are just

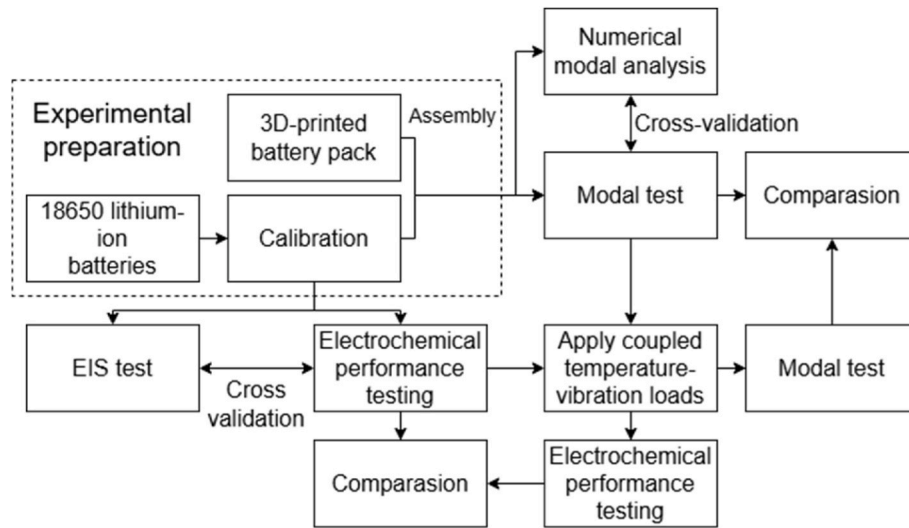


Fig. 1. Methodology flow diagram. The battery cell's electrical performance and assembled pack's modal response were measured before, during and after applying temperature-vibration loads. The results were cross validated using numerical and experimental methods.

Table 1
Battery specification.

Item Specification	Specification
Capacity	2,000mAh
Charge	1A, 4.20V, Constant-Current-Constant-Voltage (CCCV) 100 mA cut-off, 0.2C, 2.5V discharge cut-off
Discharge	3.6V
Nominal voltage	CCC, 1A, 4.20 ± 0.05 V, 100 mA cut-off
Standard charge	CCC, 4A, 4.20 ± 0.05 V, 100 mA cut-off
Rapid charge	CCC, 4A, 4.20 ± 0.05 V, 100 mA cut-off
Charging time, Standard charge	180min/100 mA cut-off
Charging time, rapid charge	50min (at 25 °C)/100 mA cut-off
Max. continuous discharge (continuous)	22A (at 25 °C), 60 % at 250 cycles
Discharge cut-off voltage (end of discharge)	2.5V
Cell weight	Cell weight 45.0g max
Height	64.85 ± 0.15 mm
Diameter	18.33 ± 0.07 mm
Charge operating temperature (surface)	Charge: 0–50 °C
Recommended recharge release (surface)	Recharge <45 °C
Discharge operating temperature (surface)	Discharge: –20 to 75 °C
recommended re-discharge release (surface)	Re-discharge <60 °C

physically secured inside the battery pack. The studs on the pack are interlocked with the tubes in the cell brackets so the batteries can be securely seated. There's an empty slot in the corner since there are only 11 cells.

2.2. Design of experiment

The experimental scheme considered both the temperature and vibration loads. Referring to ISO 16750-4, it lists the applicable operating temperature ranges from –40 °C to 180 °C. The temperature range in the test was set from –20 °C to 60 °C considering the location of the battery pack, with nine different temperature gradients at 10 °C intervals.

ISO 12405 was selected as the reference standard for the vibration tests [36]. It was a random vibration of 8–200 Hz conducted on the z-axis for 21 h since the z-direction has the most significant impact on the battery performance. Meanwhile, it is worth noting that the vibration energy was reduced from 1.44g RMS regulated by the standard to

0.9g RMS, considering the coupled temperature effect.

The batteries tested had varying states of charge (SOC), ranging from 0 % to 100 %, increased by 10 % steps. Therefore, given the nine different temperature conditions, there were 99 combinations, as shown in Table 2.

2.3. Experimental setup

2.3.1. Electrical tests

The ZKE EBC-20A battery tester was used to calibrate the battery cells to specific states of charge (SOCs). The HIOKI 3554 Battery Tester was employed to measure the internal resistance and voltage of the cells, with measurement accuracies of 1/10,000 Ω for resistance and 1/1000 V for voltage, respectively.

2.3.2. Vibration tests

Vibration testing was performed under controlled temperature conditions. Therefore, a thermostat (model: ECO MT135, accuracy: 1 °C) was used to achieve the required constant temperatures. Its temperature range is between –40 °C and 100 °C and hence can accommodate tasks in the range of –20 °C–60 °C.

Vibration Research 9500 controller was used as the vibration signal source. It was connected to the computer via the ethernet cable. VibrationVIEW software reads the random vibration profile and triggers the controller to output the signals. The signals were transferred to an amplifier to drive a shaker (Model: v55) manufactured by Data Physics to perform the corresponding random vibration. A bracket was used to fix the battery enclosure and fit it into the chamber. An additional counterweight was also fitted to ensure balance during vibration.

The excitation vibration data was measured by an accelerometer from PCB (Model: 352A21, Nominal sensitivity: 10 mV/g) fixed on the shaker platform with a 25600 Hz sample rate. It was connected to the Vibration Research 9500 controller to capture the acceleration data in real-time. By adjusting the gain in the software, the required root-mean-squared acceleration value can be set. Meanwhile, another accelerometer was fixed on the top surface of the battery enclosure to measure the structural modal performance. It was connected to the DAQ card (Model: NI9234) and chassis (Model: NI9174) from the National Instrument. The chassis was connected to the computer, so the captured acceleration data can be recorded and visualised in the DAQ Express software. The whole setup is shown in Fig. 3.

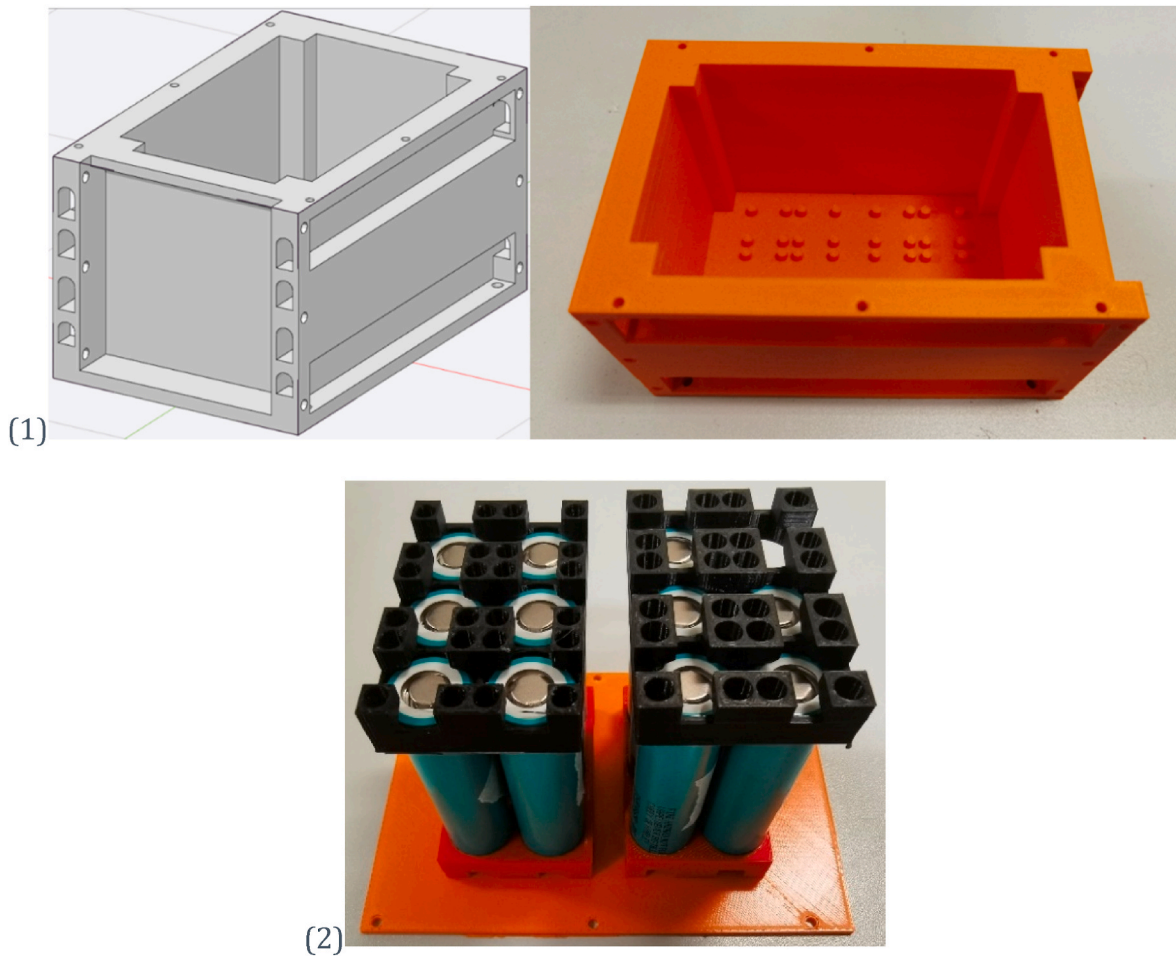


Fig. 2. (1) Battery enclosure design and finished product. The internal bottom studs are designed to hold the cell bracket. (2) Battery cells are fixed on the brackets inside the pack. Black brackets are fixed on the bottom of the battery pack. Red brackets are fixed with the top cover of the pack. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Test combinations of temperature and SOC.

Temperature (°C)	Batteries with different SOC
−20	S0T-20, S1T-20, S2T-20, S3T-20, S4T-20, S5T-20, S6T-20, S7T-20, S8T-20, S9T-20, S10T-20
−10	S0T-10, S1T-10, S2T-10, S3T-10, S4T-10, S5T-10, S6T-10, S7T-10, S8T-10, S9T-10, S10T-10
0	S0T0, S1T0, S2T0, S3T0, S4T0, S5T0, S6T0, S7T0, S8T0, S9T0, S10T0
10	S0T10, S1T10, S2T10, S3T10, S4T10, S5T10, S6T10, S7T10, S8T10, S9T10, S10T10
20	S0T20, S1T20, S2T20, S3T20, S4T20, S5T20, S6T20, S7T20, S8T20, S9T20, S10T20
30	S0T30, S1T30, S2T30, S3T30, S4T30, S5T30, S6T30, S7T30, S8T30, S9T30, S10T30
40	S0T40, S1T40, S2T40, S3T40, S4T40, S5T40, S6T40, S7T40, S8T40, S9T40, S10T40
50	S0T50, S1T50, S2T50, S3T50, S4T50, S5T50, S6T50, S7T50, S8T50, S9T50, S10T50
60	S0T60, S1T60, S2T60, S3T60, S4T60, S5T60, S6T60, S7T60, S8T60, S9T60, S10T60

2.4. Experimental procedures

2.4.1. Battery calibration

The batteries for testing were under different SOC levels, so the first step was to calibrate the batteries to the required SOC. Since the battery

had specific voltage values corresponding to each SOC from 0 % to 100 %, a ZKE EBC-20A battery tester was applied to charge or discharge the battery to certain voltage conditions with 0.1C rate.

2.4.2. Electrical performance measurement

Two electrical parameters, the voltage and the internal resistance, were measured before and after the test using the HIOKO 3554 battery tester. The data were recorded for further comparison and analysis.

2.4.3. Vibration test under the constant temperature environment

After the initial electric measurement, 11 batteries with a SOC range of 0 %–100 % were assembled into the battery pack. Nine same battery packs were assembled corresponding to nine temperature gradients. Each pack was fixed on the shaker and placed in the thermostat under different temperatures, from −20 °C to 60 °C, respectively, for 30 min to ensure temperature stability.

The experimental modal analysis was then performed through the impact test to measure the fundamental frequency of the battery pack since it provided a clue about the pack's structural integrity [37–39]. After the initial measurement, the pack was excited by the shaker and vibrated based on the vibration profile. The shaker was paused per hour during the 21-h test. The impact test was repeated during the paused period to obtain the structural modal data. The final impact test was carried out after the vibration. These dynamic responses were used to characterise the changes in the battery pack during vibration at a specific temperature. Meanwhile, the battery pack was disassembled from the shaker, and the potential deformations and damages were visually

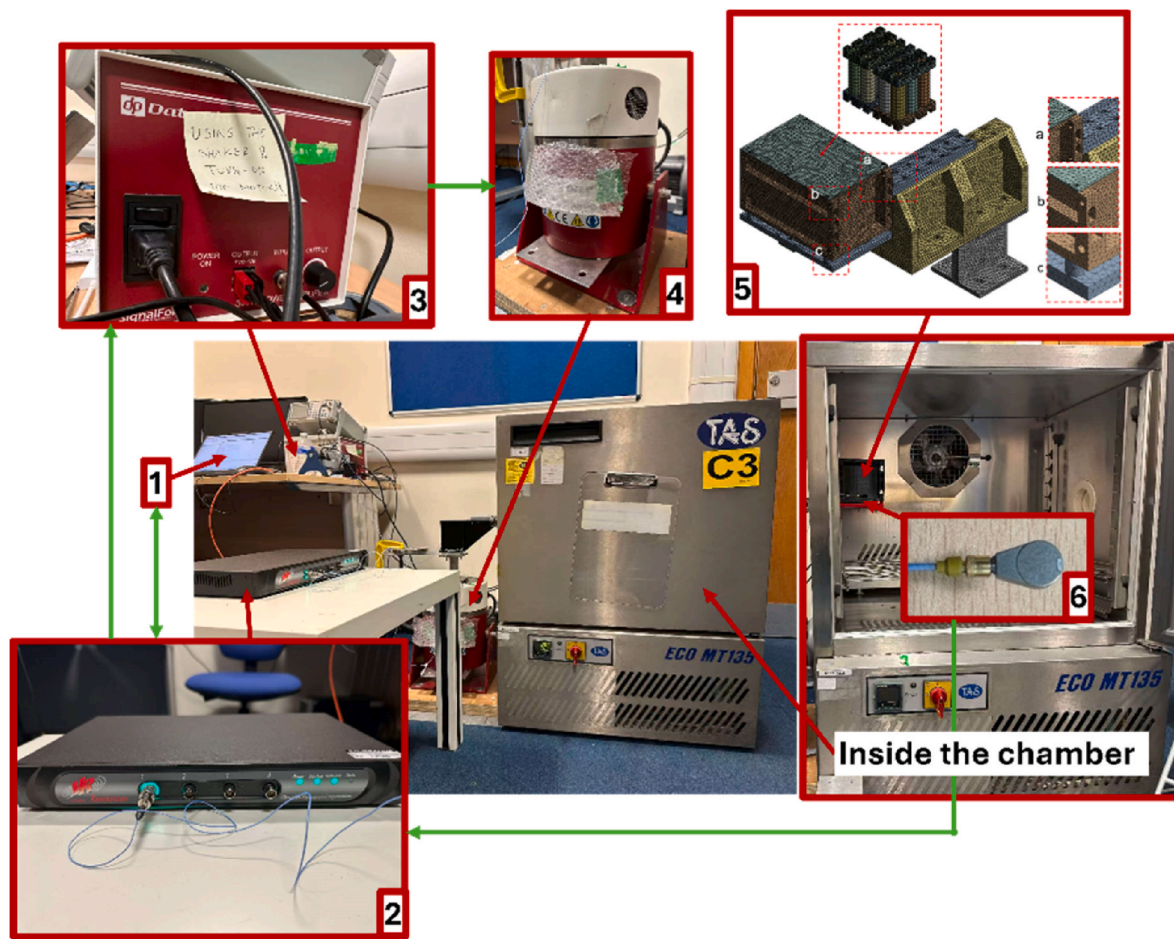


Fig. 3. Experimental Setup. 1: Computer with the control and data collection software. 2: Vibration generator. 3: Power amplifier. 4: Shaker. 5: Battery pack. 6: Accelerometer. Green arrow lines represent the wire connection and data communication between the instruments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

observed.

During the experimental procedures, several challenges were encountered that required careful mitigation to ensure the reliability of the results. Maintaining stable temperature environments, particularly during low-temperature vibration tests, was critical. To address this, for all vibration tests at sub-ambient temperatures, extended pre-conditioning times were adopted to ensure thermal equilibrium before data acquisition.

Furthermore, ensuring the mechanical stability of the battery pack prototype during vibration testing was critical, as even minor slippage or fixture loosening could alter the vibrational response. Therefore, an aluminium-stiffened holder and periodic inspection of fixation points were applied throughout the tests to maintain setup stability.

2.4.4. Data process

The measured voltage change can represent the actual battery SOC condition after the vibration in the thermostat. Therefore, the SOC value after the test was calculated using the interpolation method based on the calibrated open circuit voltage.

The accelerometer only captured the raw acceleration data in the time domain. Fast Fourier Transform (FFT) was thus applied in MATLAB to convert the data to the frequency domain and extract the fundamental frequency. Finally, there were two sets of voltage and internal resistance data and 22 fundamental frequency values for each combination.

2.5. Validation

To ensure the reliability of the experimental results, cross-validation was performed through electrochemical impedance spectroscopy (EIS) measurements and finite element analysis (FEA).

2.5.1. EIS measurements

EIS tests were conducted to validate the internal resistance measurements obtained by the HIOKI 3554 Battery Tester. The EIS measurements were performed at two representative temperatures, 20 °C and 40 °C, which correspond to typical ambient conditions during battery operation. In each test, a new cell was used to avoid the influence of prior thermal degradation on the results. The cells were first charged to 100 % SOC at a constant voltage of 4.2 V with a 1C rate (2 A charging current), and charging was terminated when the current dropped below 200 mA. After charging, the cells were allowed to rest for 1 h to stabilise before measurements.

After obtaining the EIS data at 100 % SOC, the cell was discharged to the next SOC level (90 %) at a 1C rate, followed by a 1-h relaxation period and subsequent EIS measurement. This process was repeated in 10 % SOC increments, down to 0 % SOC, resulting in a total of eleven EIS measurements per cell at each temperature. The EIS data were used to extract the ohmic resistance (R_0) and interfacial resistance (R_{int}) for each SOC level. The consistency between the ohmic resistance values obtained from EIS and those measured by the HIOKI 3554 Battery Tester provided validation for the accuracy of the electrical measurements used in this study.

2.5.2. Numerical modal analysis

FEA simulations were conducted using ANSYS Mechanical to validate the mechanical performance of the battery pack prototype under thermal, static, and dynamic loading conditions. The geometry of the test rig model, including the casing, brackets, holders, and cylindrical cells, was constructed using Ansys SpaceClaim based on a scaled prototype designed to resemble the structural configuration of electric vehicle (EV) batteries. The model incorporated the mass of all components, and temperature-dependent material properties were assigned to accurately capture the thermo-mechanical behaviour across a range of operating temperatures from -20°C to 30°C .

The mechanical boundary conditions were defined by fixing the bottom surfaces of the shaker bracket, corresponding to the mounting interface with the magnetic shaker. The random vibration profile as same as the experimental setting, was applied at this interface to simulate the vibrational loads experienced during real-world operation. Mesh discretization was performed with a combination of hexahedral and tetrahedral elements, optimised to balance computational efficiency and result accuracy. The final mesh consisted of approximately 595,098 nodes and 848,595 elements.

Modal analysis was first conducted to determine the natural frequencies of the battery structure over a frequency range of 0–200 Hz. The first natural frequencies obtained from the simulations were compared with those measured experimentally under different thermal

conditions.

3. Results and discussion

After the tests, all electrical parameters and modal frequencies were collated according to their temperature and SOC combinations. This section shows and discusses the test results regarding the influence of temperature and vibration on the battery performance and pack's integrity.

3.1. Battery enclosure failure under 60°C

It is worth discussing a particular case under 60°C test environmental temperature at first. 60°C was set as the upper limit of the test temperature. The 21-h random vibration test was carried out as per the experimental schedule at this temperature. However, the 3D-printed PLA battery enclosure underwent severe deformation after even 20 min of vibration at this temperature. Therefore, the changes in battery electrical parameters and pack's modal parameters could not be obtained.

3.1.1. PLA battery pack

After the initial 20-min vibration, the battery pack's deformation is shown in Fig. 4(1). One side wall of the battery underwent an

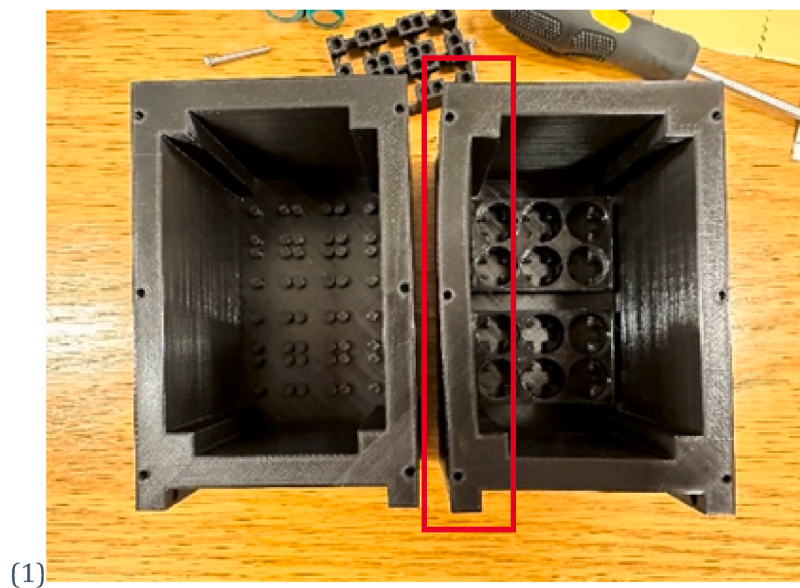
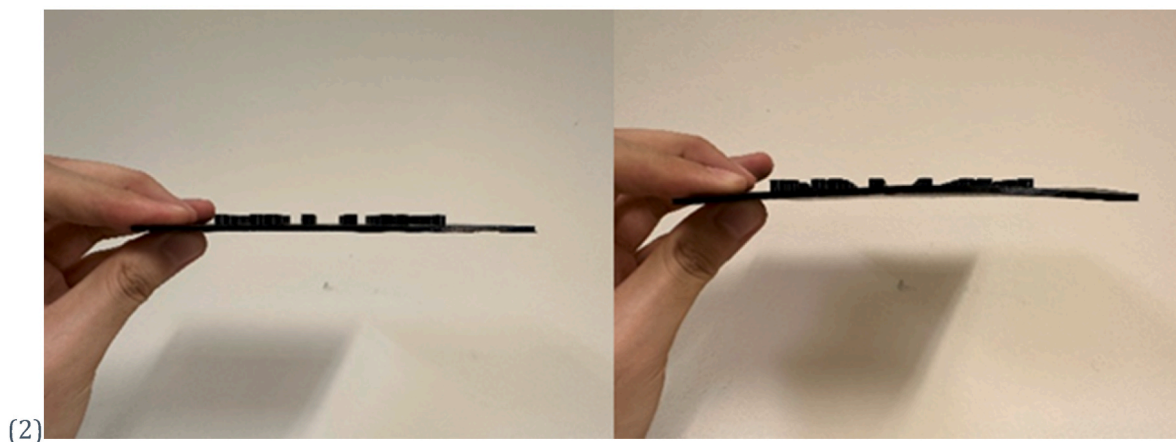


Fig. 4. (1). Top view of the battery pack (left): Normal state before the test. (right): Deformed state after the test. (2). Side view of the top lid of the battery pack. Left: A healthy lid. Right: The lid after the test with a slight warp.

approximate 5 mm deflection. Similarly, the top lid of the battery pack warped slightly, as shown in Fig. 4(2). The buckling visible to the naked eye occurred quickly and damaged the connection bolts and internal battery holders as well. Therefore, the bracket used to fix the battery inside the pack could not be removed.

Considering the PLA material's thermal properties, low glass transition temperature is the main reason for this immediate structural failure. The applied PLA material has a 59.1 °C glass transition temperature measured by the ISO 11357 test method. This indicates that the pack experienced softening at 60 °C in the thermostat. The coupled random vibration excitation applied extra force to the softened structures and promoted the deformation rapidly.

3.1.2. ABS battery pack

To overcome the material limitation, another common-used polymer, ABS, was applied to manufacture a new battery pack and tested under 60 °C only. After 5 h of exposure and vibration in the thermostat, the battery pack made by ABS remained with good structural integrity. There is no visible deformation or damage. The observation proves that the ABS battery pack works well under random vibration at 60 °C.

Some typical thermal properties of PLA and ABS are listed in Table 3. Compared with the PLA, the glass transition temperature of ABS increased from around 60 °C to 100 °C. This significant difference yields that the ABS material can keep solid and structural integrity at higher temperatures. 60 °C environmental temperature is much lower than the glass transition of ABS. Therefore, the ABS battery pack performed better during the test.

It is important to point out that ABS has lower mechanical properties than PLA, as shown in Table 4. This means that the ABS battery pack may experience fatigue failure, which is more likely under vibration loads. However, its structural integrity was better than that of the PLA one when considering the coupled thermal loads, especially in relatively high-temperature environments. The additive manufacturing method also affected the mechanical performance of the pack. As some opposite results described by Lay et al. [42] in their research, FDM ABS has better mechanical properties than PLA. Therefore, the deformation damage and buckling failure of the PLA battery pack at 60 °C were caused by a number of the above reasons.

3.2. Battery electric performance analysis

The voltages and internal resistances measured before and after the tests are shown in Fig. 5 (1) and (2), respectively. Whether before or after testing, battery voltage decreased from around 4.2 V–2.6 V between 100 % and 0 % SOC range. The trend of the battery voltage change is the same as the nominal change during the calibration. Therefore, they can be used to calculate the actual SOC conditions after the tests. Meanwhile, the voltage difference under various temperatures is very small when the SOC is between the range of 10 %–100 %.

3.2.1. Battery SOC change after the test

The SOC changes after the vibration were calculated according to the measured battery voltage. The results are depicted in Fig. 6(a). Red markers represent the SOC increased after the vibration test, while blue

Table 4

Mechanical properties of PLA and ABS [40,41].

Properties	Test Method	PLA	ABS
Tensile (Young's) modulus	ASTM D3039 (1 mm/min)	3250 ± 119 MPa	1962 ± 31 MPa
Tensile stress at yield	ASTM D3039 (5 mm/min)	52.5 ± 0.9 MPa	38.1 ± 0.3 MPa
Tensile stress at break	ASTM D3039 (5 mm/min)	45.5 ± 1.1 MPa	33.9 ± 1.5 MPa

markers indicate where SOC decreased. Overall, the test has a relatively minor impact on SOC, with most changes falling within the narrow band of ±0.5 %. This suggests that the effect of vibration on the battery's SOC is extremely limited.

Notably, SOC decreases are more frequent than increases. Most batteries experienced SOC decrease after the vibration, even though the changes were extremely small. When an outlier at 20 % SOC under 0 °C was excluded, the average SOC change is −0.063 %, which is almost negligible. Even the most significant SOC drop occurs at 10 °C, and the 40 % SOC level is just −0.55 %. This decrease in SOC after vibration aligns with the existing research [19]. It can be attributed to the mechanical and electrochemical effects of the vibrations on the battery's internal structure. Vibrations may induce mechanical stress, causing micro-cracks or displacements within the electrodes, separators, and electrolytes, which reduces ion mobility and charge retention [24]. They have been observed in the previous study. A damaged current collector tab on the negative side for the Samsung INR18650-35E and the Samsung ICR18650-22FM was observed after the vibration [24]. However, the SOC drop in the presented work is much lower than in other studies. The possible reason is that the vibration energy is lower than the recommended value.

In terms of temperature effects, the overall pattern of SOC changes is consistent across the different temperature conditions. Fig. 6(a) shows more significant SOC fluctuations under lower temperatures from −20 to 10 °C. Conversely, at 20 °C, SOC changes become less significant after the vibration, representing a more stable environment for the battery's chemical processes, thereby reducing the impact of vibrations. This trend is further summarised in Fig. 6(b), where the mean SOC change at each temperature is presented. It can be observed that low temperatures, particularly between −20 °C and 10 °C, exhibit larger average SOC losses, whereas moderate temperatures around 20 °C show minimal SOC variation. Although a noticeable SOC decrease is also observed at 40 °C, the overall pattern indicates that lower temperatures have a more consistent and stronger effect on SOC degradation under vibration. This result suggests that low-temperature conditions may increase the battery's sensitivity to vibration. This could be due to increased electrolyte viscosity at lower temperatures, which affects ion transport, thereby making the battery more sensitive to the vibration loads. In addition, there are more apparent changes when SOC levels are relatively low, between 0 % and 50 %. In contrast, at higher SOC levels, the SOC changes are more minor and more stable, ranging around −0.25 %–0 %. This means that batteries with higher charges are less affected by vibration.

In summary, the observed minor decreases in SOC after vibration can be attributed to mechanical stresses induced by vibration, which may cause micro-cracks or displacements within electrodes, separators, and electrolytes. These microstructural changes could slightly hinder ion mobility and charge retention. Additionally, low-temperature conditions, which increase electrolyte viscosity, further increase the sensitivity of cells to vibrational impacts, leading to more SOC variations at lower temperatures and lower initial SOC levels.

3.2.2. Internal resistance changes after the test

Apart from the SOC, internal resistance is another electrical property that experiences changes after the vibration test. Fig. 7 illustrates the

Table 3

Thermal properties of PLA and ABS [40,41].

Properties	Test Method	PLA	ABS
Heat deflection (HDT) at 0.455 MPa	ISO 75-2/B	58.8 ± 0.4 °C	86.6 ± 0.4 °C
Vicat softening temperature	ISO 306/A120	64.5 ± 0.4 °C	93.8 ± 0.7 °C
Glass transition	ISO 11357 (DSC, 10 °C/min)	59.1 °C	100.5 °C
Melting temperature	ISO 11357 (DSC, 10 °C/min)	151.8 °C	- (amorphous)

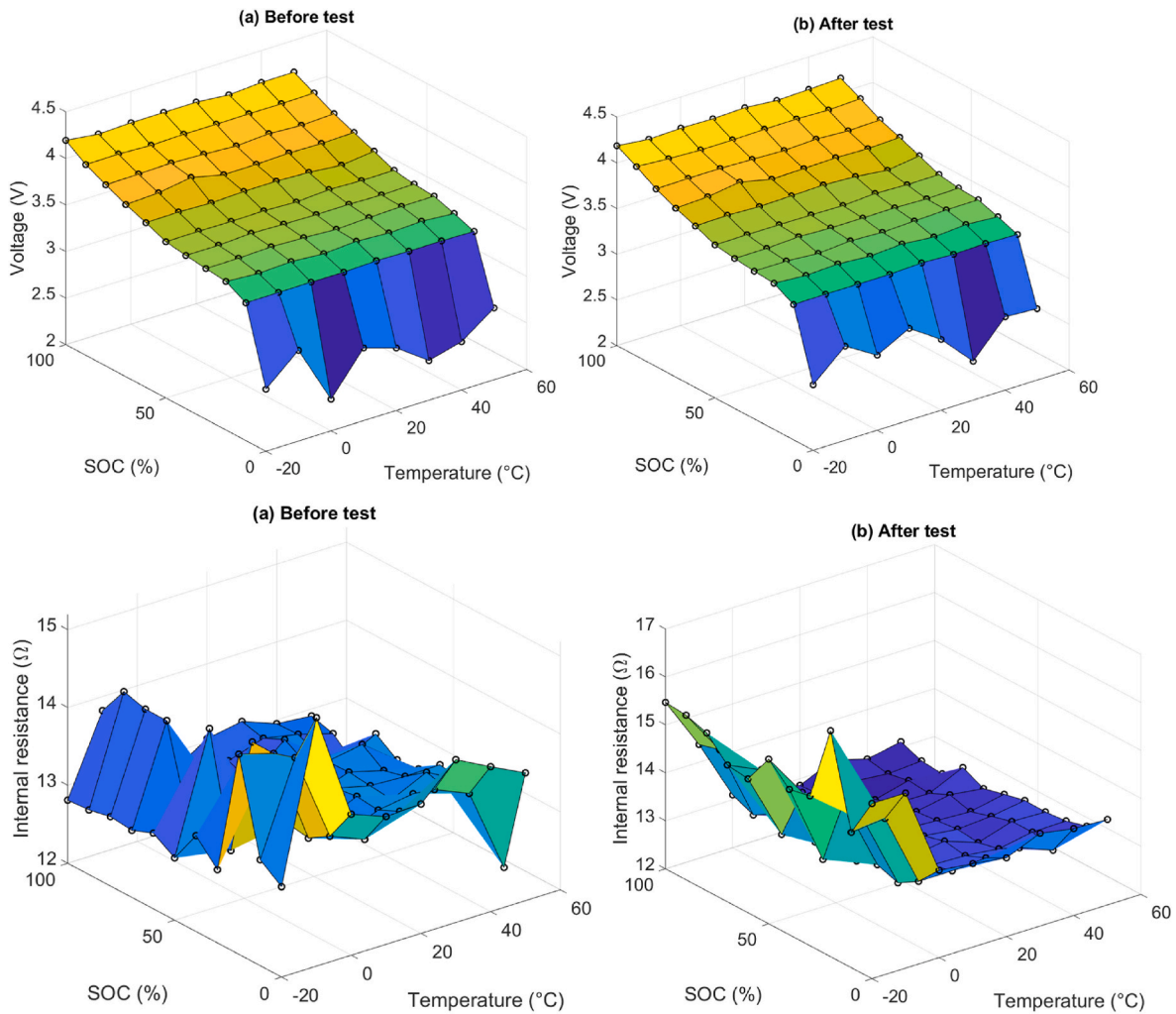


Fig. 5. (1) Battery voltage measurement under different temperatures and SOC levels. (a) Before the vibration test. (b) After the vibration test. (2) Battery internal resistance measurement under different temperatures and SOC levels. (a) Before test. (b) After test.

changes across various temperatures before and after vibration testing. Each subplot represents a distinct temperature, showing IR values before (solid blue line) and after (dashed blue line) vibration, along with the IR change (represented by red and blue dots).

It is evident from Fig. 7 that temperature significantly affects the internal resistance of the battery. Generally, IR is notably higher at lower temperatures and decreases as temperature increases. For example, at -20°C , IR values range between 13 and 17 mΩ, whereas at 50°C , IR drops to around 12.5–13.5 mΩ. This phenomenon aligns with the temperature characteristics of lithium-ion batteries. Lower temperatures reduce electrolyte conductivity, leading to increased IR, while higher temperatures enhance ionic mobility in the electrolyte, thereby reducing IR. This overall trend is further illustrated in Fig. 7(b) which compares the average internal resistance before and after vibration testing across different temperatures. It is clearly shown that the IR decreases progressively as the temperature increases from -20°C to 50°C .

The IR also varies across different SOC at a given temperature range of -10 to 40°C . IR tends to decrease as SOC increases since SOC affects the disassembly and embedding speed of lithium ions in the anode and cathode, as well as the viscosity of electrolyte [40,43,44]. When the SOC increases from 0 to 80 %, the IR value drops by approximately 1 mΩ. IR is generally higher at low SOC levels, which is attributed to the limited availability of active lithium ions and reduced conductivity.

The red and blue dots in each subplot represent the IR change before

and after vibration, with red indicating an increase in IR and blue indicating a decrease. Overall, in most cases, even though under different the value of the IR has increased slightly by less than 0.5 mΩ, which is almost negligible. Despite the very slight reduction in internal resistance, the decreased trend is similar to other studies [27–29]. Another study observed that the battery's inner mandrel was completely loose after vibration testing and fell to the lower tab [28]. This mechanical degradation causes the IR to decrease. One special case is when the temperature is -20°C , the IR change after the vibration reaches around 2 mΩ. The reason of it is due to the low temperature enhanced the mechanical degradation of battery inner.

Conversely, the minor change observed (less than 0.5 mΩ) in the presented work suggests that the battery's electrodes, separators, and electrolyte interfaces have maintained their integrity, absorbing the vibrational energy without causing structural disruptions that would significantly affect resistance. In other words, the vibration testing may cause minor rearrangements in electrode materials rather than substantial structural degradation. These minor shifts do not alter the electrochemical pathways significantly. At the same time, the effect of temperature on this IR change was not significantly observed. This resilience in IR indicates that the external battery enclosure is well-designed to resist such mechanical impacts under varying thermal conditions. It demonstrates the application of 3D-printed polymer materials in this context.

Additionally, the limited cycle count is likely a key factor

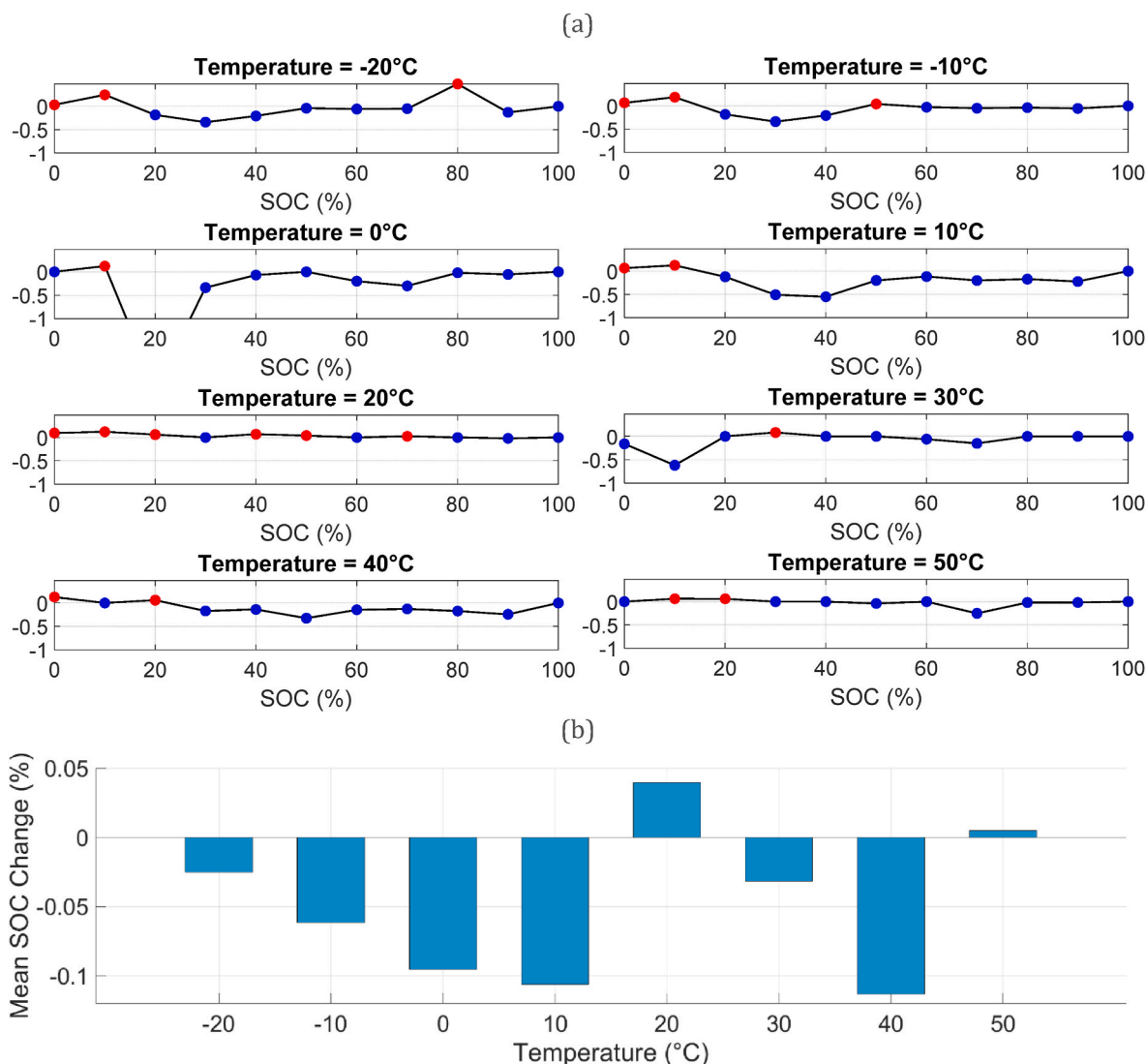


Fig. 6. (a) SOC change (%) after the vibration test under different temperatures. Red marks the increase. Blue marks the decrease. (b) Mean SOC change of the battery under different temperature conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

contributing to the minimal change observed in our results. All batteries used in this experiment are brand new and have only undergone their first cycle. Under these conditions, such slight changes are expected and can be considered normal, as the batteries are in excellent condition with optimal performance characteristics.

Overall, the slight increase in internal resistance following vibration is likely due to minor mechanical rearrangements of electrode materials rather than severe structural damage. This suggests that the batteries' internal electrochemical pathways remained largely intact, supported by the effective protection offered by the 3D-printed battery enclosure. The more significant IR increase observed at -20°C is attributed to the combined effects of low-temperature-induced electrolyte conductivity reduction and enhanced mechanical stress.

3.3. Modal test results and the structural integrity analysis

After the analysis of the electrical performance of the batteries, examining parameters including SOC and internal resistance under varying temperature and vibration conditions, the following analysis focuses on the mechanical performance of the entire battery pack. Specifically, we investigate how prolonged vibration and temperature impact the natural frequency of the 3D-printed pack's structural

integrity.

Fig. 8 presents the natural frequency values of the battery pack subjected to continuous vibration over 21 h, measured at various temperatures and recorded hourly. Almost all natural frequencies are distributed in the 7–9 Hz. This means that the fundamental frequency of the whole battery pack structure with the test rig is around 8 Hz. Comparing the different subplots, the data suggests that temperature has a measurable influence on the natural frequency of the battery pack. Specifically, as temperature increases, there appears to be a slight decrease in the average natural frequency. At lower temperatures, such as -20°C , the natural frequency fluctuates around 8 Hz. However, at higher temperatures, such as 50°C , the natural frequency stabilises at a lower range of approximately 7.5 Hz–8 Hz, representing a decrease of roughly 0.5 Hz across the temperature range. This result aligns with other studies about 3D-printed polymers [45,46]. The fundamental frequency drop of about 5% is consistent with the expected effects of temperature on material stiffness, as higher temperatures typically decrease material stiffness due to increased molecular chain sliding and mobility in 3D-printed PLA, resulting in a lower natural frequency.

Furthermore, the natural frequency changes due to the effect of continuous vibration over the 21-h testing period represent the structural stability of the battery pack. Across all temperature conditions, the

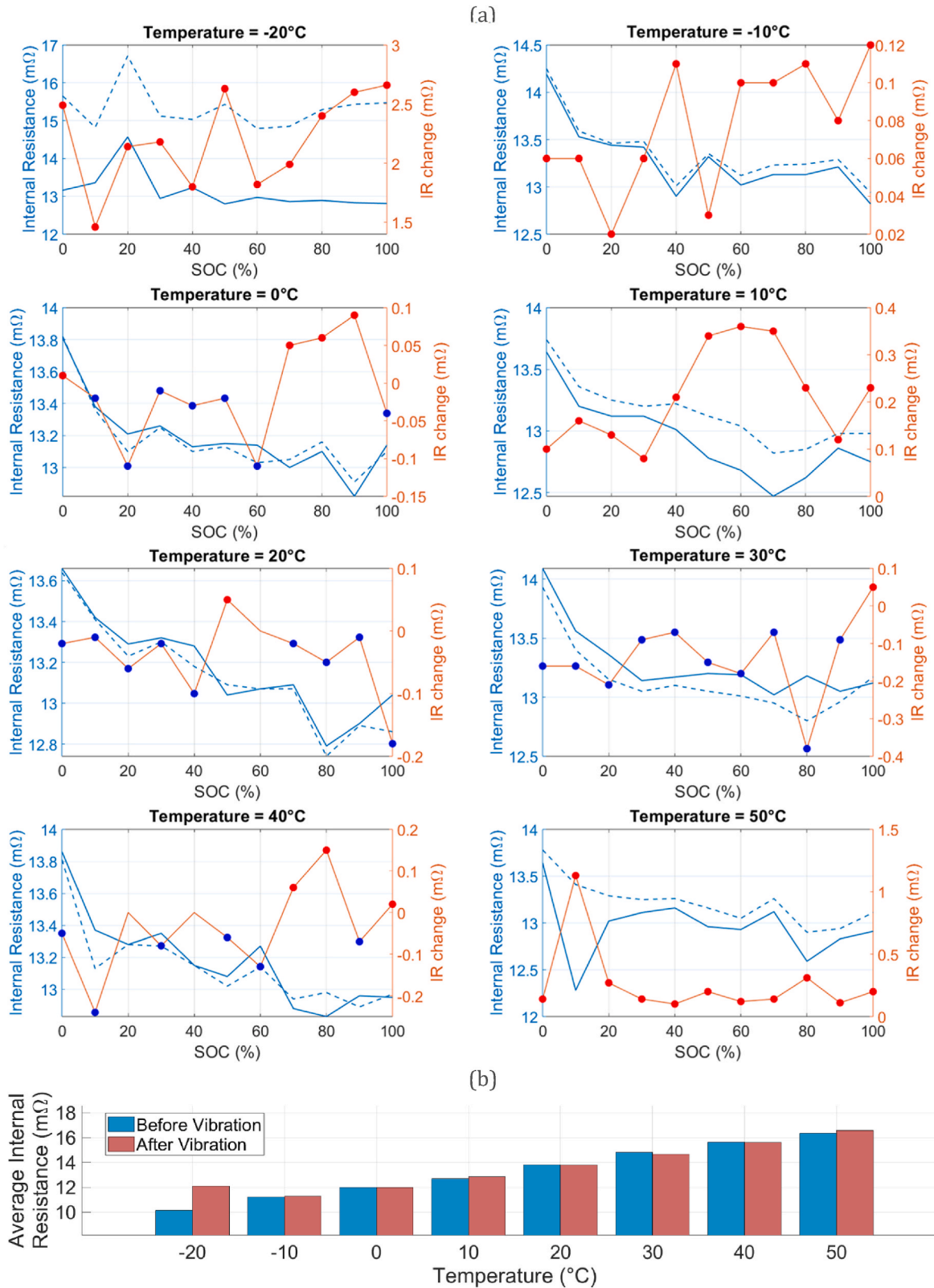


Fig. 7. (a) Internal resistance (IR) change after the vibration test under different temperatures. Solid blue line: IR before the vibration test. Blue dash line: IR after the vibration test. Red line: IR difference after the vibration test. (b) Comparison of average internal resistance before and after vibration testing at different temperatures. Blue bars represent the measurements before vibration, and red bars represent the measurements after vibration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

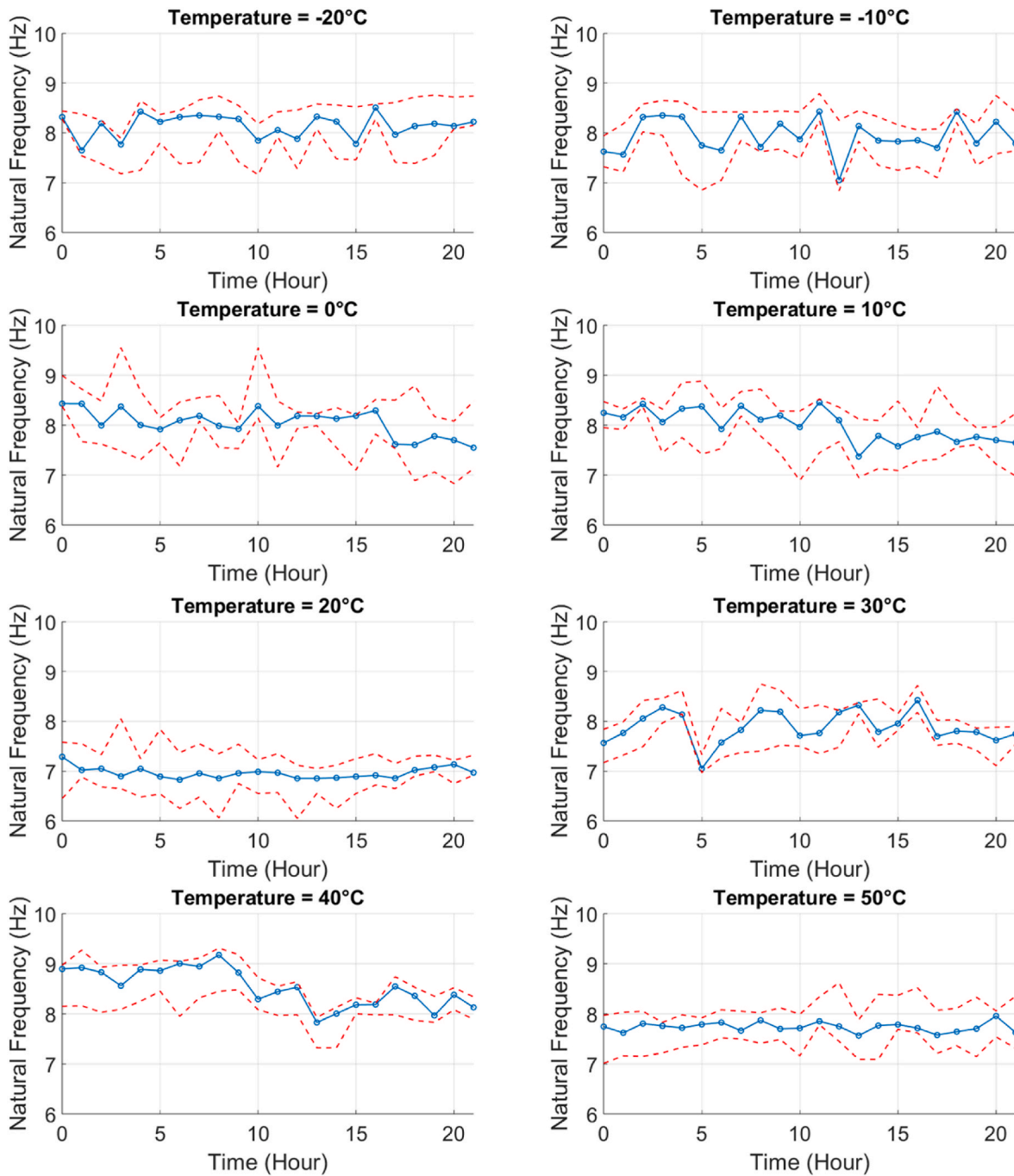


Fig. 8. Monitored fundamental frequency during the vibration testing. The blue curve represents the average value. Red dash lines represent the measured maximum and minimum fundamental frequency values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

natural frequency remains relatively stable, with no significant downward trend that would suggest structural degradation or damage due to vibration. The observed fluctuations in natural frequency are generally within ± 0.5 Hz, indicating that the structural integrity of the battery pack has been preserved throughout the test. This low standard deviation in frequency fluctuations further supports the notion that the 3D-printed polymeric battery pack's structural resilience is sufficient to withstand vibrational stress without significant changes in natural frequency.

This observed stability in natural frequency under vibration may be attributed to structural damping mechanisms within the 3D-printed materials that likely absorb vibrational energy, thus minimising its

impact on the frequency response. Additionally, minor thermal expansion effects at higher temperatures could slightly adjust the fit or dimensions of internal components. However, the stability in natural frequency suggests that such effects are minimal or are counterbalanced by increased material flexibility at elevated temperatures.

3.4. Experimental results validation

To validate the experimental results obtained in this study, both electrochemical and mechanical validations were conducted. EIS measurements were employed to cross-verify the internal resistance measurements, while FEA simulations were used to validate the mechanical

response of the battery structure under vibration loading.

3.4.1. Validation of internal resistance measurements via EIS

EIS tests were performed at 20 °C and 40 °C to independently determine the ohmic resistance (R_0) of the battery cells across different states of charge (SOC). The R_0 values obtained from the EIS measurements were compared with those measured by the HIOKI 3554 Battery Tester under the same SOC and temperature conditions.

As summarised in Table 5, the deviations between the two measurement methods ranged from 0.15 % to 8.47 % at 20 °C and from 2.34 % to 12.50 % at 40 °C. It was observed that the discrepancies were more significant at lower SOC levels (0–40 %), with the maximum deviation recorded at 0 % SOC. Conversely, at higher SOC levels (50–100 %), the differences significantly decreased, typically remaining below 5 %.

This SOC-dependent trend can be attributed to the underlying electrochemical behaviour of lithium-ion batteries. At low SOC levels, higher interfacial impedance and less stable ion transport mechanisms dominate, resulting in increased sensitivity in impedance measurements and greater variability between testing methods. In contrast, at higher SOC levels, the battery's internal resistance is largely governed by bulk ohmic resistance, leading to more stable and consistent measurements.

It should be noted that the EIS validation conducted in this study was performed prior to the vibration tests. Due to time and resource constraints, post-vibration EIS characterisation could not be completed within the current scope of work. Future studies will focus on conducting comprehensive post-vibration EIS measurements to further validate the findings. Nevertheless, the present validation results, obtained across a wide SOC and temperature range, are considered sufficient to confirm the reliability and accuracy of the internal resistance measurements employed in this study.

3.4.2. Validation of mechanical response via FEA

Modal analysis was performed to predict the natural frequencies of the battery structure across different temperatures ranging from −20 °C to 30 °C. The first natural frequencies obtained from the simulations were compared with the experimentally measured values, as summarised in Table 6.

The comparison showed that the FEA-predicted frequencies were generally higher than the experimental measurements, with deviations ranging from 8.83 % to 25.01 %. The largest deviations were observed at low temperatures (−20 °C and −10 °C), exceeding 20 %, while at moderate temperatures (0 °C–30 °C), the deviations decreased to within 9 %–13 %.

Several factors can account for these discrepancies. First, the material properties assigned in the simulation, particularly the Young's modulus and density of the PLA components, may not fully reflect the actual behaviour of the 3D-printed structures across different

Table 6

Comparison between the experimentally measured and numerically predicted first natural frequencies of the battery prototype at different temperatures. The relative differences between simulation and experimental results are also presented.

Temperature (Hz)	Experimental Frequency (Hz)	Numerical Frequency (Hz)	Difference (%)
−20	8.44	10.53	22.03
−10	7.94	10.21	25.01
0	8.99	9.82	8.83
10	8.47	9.33	9.66
20	7.58	8.67	13.42
30	7.84	6.93	12.32

temperatures. Second, the numerical model employed idealised boundary conditions, assuming perfectly rigid fixations, whereas in the experimental setup, minor flexibility, slippage, and assembly tolerances can reduce the overall stiffness, leading to lower natural frequencies. Furthermore, the simulations did not incorporate structural damping effects, which are present in physical systems and typically lower the observed resonant frequencies [47].

Despite these deviations, the numerical model successfully captured the overall trend of decreasing natural frequency with increasing temperature, consistent with the experimental observations. This indicates that the FEA model adequately represents the dynamic behaviour of the battery structure under thermal and vibrational loading for preliminary validation purposes.

4. Conclusions

This study recorded and evaluated the performance of lithium-ion batteries and 3D-printed PLA battery enclosures under combined vibration and temperature loads simulating electric vehicle operating conditions, an area with limited prior research.

Through comprehensive testing across temperature ranges from −20 °C to 60 °C, vibration frequencies from 8 Hz to 200 Hz, and states of charge (SOC) from 0 % to 100 %, the results indicate that lithium-ion batteries exhibit an increase in internal resistance, especially under low temperature −20 °C, consistent with findings in the existing literature. Notably, while battery capacity declines slightly under varying conditions, SOC response remains stable across the temperature spectrum.

Both PLA and ABS 3D-printed battery enclosures demonstrated structural stability, withstanding 21 h of random vibration without loosening or deformation. However, while ABS enclosures remained functional at 60 °C, PLA enclosures did not, indicating that ABS may be a more suitable material for battery packs subjected to high temperatures. These results prove the feasibility and potential of 3D-printed enclosures for practical applications in electric vehicles.

Future work should explore batteries with varying cycle counts, extend test durations, and apply increased vibrational energy to understand further impacts of combined thermal and vibrational loads on battery life and performance.

CRedit authorship contribution statement

Ran Li: Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Feiyang He:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation. **Oscar Rojas Vargas:** Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Muhammad Khan:** Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Table 5

Comparison of R_0 values measured by the HIOKI 3554 Battery Tester and EIS at different SOC under 20 °C and 40 °C. The relative differences between the two methods are also presented.

SOC (%)	20 °C			40 °C		
	Test result (mΩ)	EIS result (mΩ)	Difference (%)	Test result (mΩ)	EIS result (mΩ)	Difference (%)
0	13.66	12.55	8.47 %	13.86	12.23	12.50 %
10	13.42	12.56	6.62 %	13.37	12.24	8.82 %
20	13.29	12.57	5.57 %	13.28	12.26	7.99 %
30	13.32	12.58	5.71 %	13.35	12.25	8.59 %
40	13.28	12.57	5.49 %	13.15	12.26	7.01 %
50	13.04	12.57	3.67 %	13.08	12.36	5.66 %
60	13.07	12.63	3.42 %	13.27	12.37	7.02 %
70	13.09	12.68	3.18 %	12.88	12.41	3.72 %
80	12.79	12.72	0.55 %	12.83	12.44	3.09 %
90	12.9	12.86	0.31 %	12.96	12.5	3.61 %
100	13.04	13.02	0.15 %	12.95	12.65	2.34 %

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jpowsour.2025.237688>.

Data availability

I have shared the link to my data in the manuscript

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Capacity and impedance characteristics of the lithium-ion battery and mechanical properties of the battery pack under coupled temperature-vibration conditions: an experimental approach

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