Stress-Strain Monitoring of Li-Ion Battery Through Single-Frequency Ultrasonic Testing

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***Abstract*—The safety, performance, and lifespan of lithium-ion (Li-ion) batteries heavily depend on understanding their internal chemo-mechanical state. Conventional battery management systems, which depend on terminal electrical measurements, offer limited insight into the dynamic stress and strain that develop during operation. This paper introduces a non-destructive, in-situ method for monitoring the internal stress state of a commercial Li-ion pouch cell using single-frequency ultrasonic testing. Initially, a relation between stress-strain buildup within the battery and the amplitude of the transmitted ultrasonic signal is established. Then, a 120 kHz ultrasonic signal is transmitted through the cell in a through-transmission setup, and the amplitude of the received signal is analyzed as the main indicator for stress-strain and degradation monitoring. Experimental results over four charge-discharge cycles show a strong correlation between signal amplitudes and the State of Charge, with amplitude generally increasing during charging due to intercalation-induced compressive stress. The technique demonstrates high sensitivity, capturing non-monotonic behaviors attributed to electrode phase transitions. Additionally, a gradual, cycle-by-cycle decrease in overall signal amplitude is observed, providing a direct measure for tracking cumulative mechanical degradation and State of Health. These results demonstrate that ultrasonic signal amplitude is a comprehensive, versatile feature capable of offering real-time insights into the complex acousto-mechanical behavior of Li-ion batteries, offering a promising enhancement for next-generation battery diagnostics.**

Keywords—ultrasonic signal, lithium battery, stress-strain sensing.

I. Introduction

Growing interest in efficient energy storage has spurred significant advances in lithium-ion battery technology. Since lithium-ion batteries are crucial for applications such as electric vehicles and renewable energy systems, understanding their internal behavior and health is vital for improving performance and ensuring safety. However, conventional Battery Management System (BMS) architecture primarily depends on terminal measurements of voltage, current, and temperature, which are often lagging indicators of the complex and dynamic chemo-mechanical processes occurring inside the cell [1]. These methods offer an incomplete view of the battery's internal state, limiting the accuracy of State of Charge (SoC) and State of Health (SoH) estimates and potentially failing to foresee early failures.

To overcome these limitations, ultrasonic non-destructive testing has emerged as a powerful diagnostic tool capable of directly probing the internal mechanical properties of a battery in-situ and in-operando. This technique is based on the fact that acoustic wave propagation is highly sensitive to the physical characteristics of the medium through which it travels. As battery cycles, its internal components change density, porosity, and elastic moduli, which in turn alter the velocity and attenuation of an ultrasonic wave. By analyzing features of the transmitted or reflected signal, such as the Time-of-Flight (ToF) and signal amplitude, it is possible to track these internal changes in real-time [2].

The focus on ultrasonic testing is trending and researchers are trying to utilize the signal's different parameters as a probing tool. For instance, Hseih et. al. [3] employed a 2.25 MHz high-frequency ultrasonic wave in echo mode to track the SoC in both lithium-ion and alkaline batteries. It was further enhanced by using only a 200 kHz wave and observing the ToF and amplitude of the ultrasound [4]. Sewunet et al. also utilized the ToF feature of ultrasound to monitor battery SoC, stating that ToF decreases during the charging cycle and increases as the battery discharges [5]. Results were further verified through the use of Pearson correlation coefficients, polynomial fitting, and signal-to-noise ratio. Xia et al. tested the behaviour of ultrasonic waves under low temperature and found that with a drop in temperature, the transmitted ultrasonic waves are attenuated [6]. Sun et al. used multiple frequencies of ultrasonic waves to monitor SoC [7]. It shows that the longitudinal wave velocity of ultrasonic waves has a linear relationship with SoC and is influenced by temperature.

Various studies [8], [9], [10], [11] focused on SoC estimation with ultrasonic waves, and most of them utilized the ToF feature, while the signal amplitude can be an interesting parameter. During charging, the intercalation of Li-ions into the anode (typically graphite) causes a significant volumetric expansion of the electrode particles, while the cathode contracts, a process that reverses during discharge. Within the constrained environment of a battery pack or pouch cell, this swelling at the microscopic level adds up, creating large-scale mechanical stresses and strains. This internal stress directly impacts the quality of the interfaces between layers (e.g., electrode-separator) and the bulk mechanical properties of the cell stack, thereby establishing a direct, measurable link between the battery's electrochemical state and its acoustic response.

This paper investigates the efficacy of using the amplitude of a single-frequency ultrasonic signal as a sensitive indicator for monitoring the stress, strain, and degradation within a commercial Li-ion pouch cell. This research provides the following key insights: a direct correlation between the received signal amplitude and SoC-induced stress variation is established, the amplitude variations over several cycles can be used to monitor the battery's mechanical degradation, and certain features of amplitude change, such as dips, can be linked with certain electrochemical phenomena like electrode phase transitions. The novelty of this study focuses on the signal amplitude of a single, low-frequency wave as the primary, multi-faceted indicator for monitoring both transient SoC-induced stress and permanent, cycle-over-cycle mechanical degradation (SoH). This simplifies the experimental setup and data analysis while demonstrating that a rich set of diagnostic information is contained within the

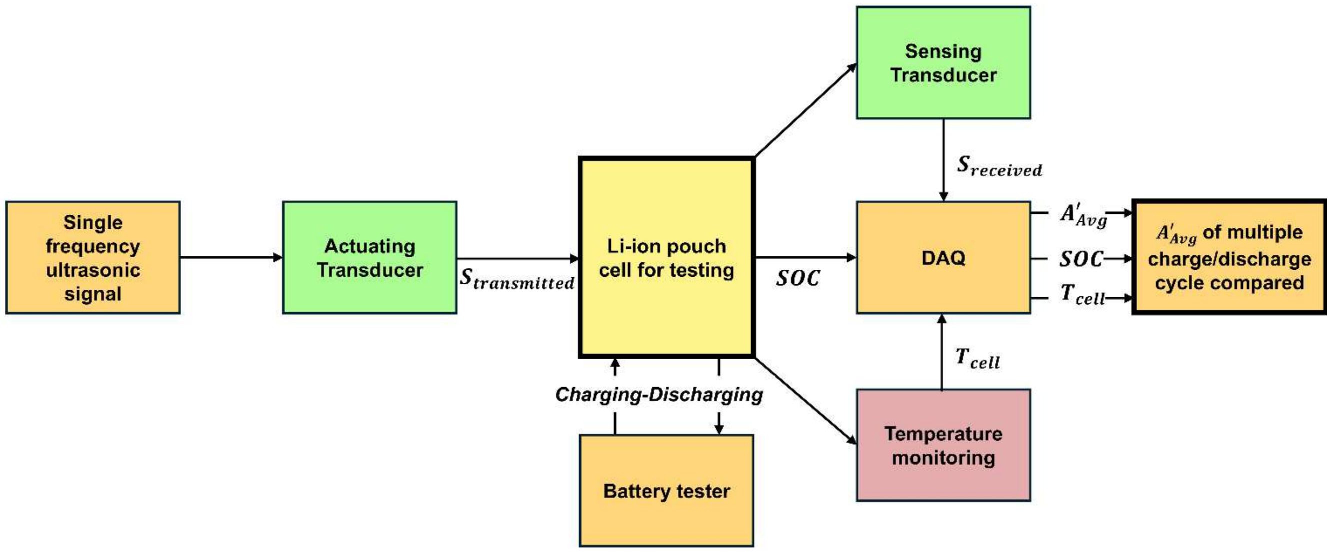

Fig. 1 Proposed strategy for stress/strain analysis in Li-ion battery.

amplitude alone. Unlike the other methods that use guided waves propagating in-plane along the battery's surface, the proposed through-transmission approach directly interrogates the bulk properties through the cell's thickness, making it highly sensitive to changes in stack pressure. This study provides a detailed interpretation of non-monotonic features within the amplitude signal, linking them directly to specific electrochemical phenomena such as electrode phase transitions, thereby offering a deeper diagnostic insight than a simple linear correlation.

II. Methodology

The methodology is designed to non-destructively monitor the internal chemo-mechanical state of a lithium-ion pouch cell in-situ. Fig.1 illustrates the experimental setup that includes two transducers, one for transmitting the ultrasonic signal through the battery and the other for collecting it. The internal mechanical changes experienced by the battery during charging and discharging cycles are studied by collecting a few parameters: SoC, received signal amplitude, and temperature. It is important to establish the relationship between the average amplitude change of a single-frequency ultrasonic signal to stress-strain and prove their correlation through real-life experiments.

A. Principle of single-frequency ultrasonic interrogation

Generally, ultrasonic testing for materials is done by the pulse-echo mode and the transmissive mode [12]. Pulse-echo mode utilizes one transducer to both emit and detect the ultrasonic waves. In transmissive mode, two transducers are positioned on opposite sides of the test sample—one for transmitting and the other for receiving the signal. In this study, the transmissive mode is employed for measuring battery stress, as it enables real-time monitoring of variation in the transmitted ultrasound across the battery layers.

A single-frequency transmissive signal allows frequency to be eliminated as a variable in the measurement. This allows for the establishment of a direct and unambiguous correlation between an observed change in the material's stress state and the measured change in the transmitted signal's amplitude. Any variation in the received amplitude can be more confidently attributed to a change in the material's acousto-mechanical properties, rather than to complex frequency-dependent effects like dispersion or the constructive/destructive interference of multiple frequency components. The transmitted signal (1) and the signal (2) received from the PZT transducers are:

$$S_{transmitted}(t) = Asin(2\pi ft) \quad (1)$$

$$S_{received}(t) = A'sin(2\pi f(t-\Delta t)) + N(t) \quad (2)$$

where, A and A' is the amplitude of the corresponding signals, f is the frequency of the ultrasonic signal, t is the instantaneous time when the signal is recorded, Δt is the time of flight (ToF) or the delay between transmission and receiving and $N(t)$ is the noise added during signal transmission.

According to [13], the signal may travel along multiple paths or in different modes, resulting in the reception of more than one wave packet. Because the different layers (anodes, cathodes, separators and current collectors) have different acoustic impedance, which results in reflection and refractions of the signal. In this more complex scenario, the received signal would be a superposition of all the arriving waves. The expression would look like:

$$S_{received}(t) = [A'_1 sin\big(2\pi f(t-\Delta t_1)\big) + A'_2 sin\big(2\pi f(t-\Delta t_2)\big) + \cdots] + N(t) \quad (3)$$

Here, each component ($A'_1, \Delta t_1, A'_2, \Delta t_2$) corresponds to a different path the wave took through the battery, arriving with a different amplitude and at a slightly different time.

The signal can be denoised using a denoising filter and if the entire battery is modelled as a single body, then the average amplitude of all the signals can be used as a probing tool for structural changes inside the battery. The final amplitude is thus inspected for n the number of signals through:

$$A'_{Avg} = \frac{A'_1 + A'_2 + \cdots + A'_n}{n} \quad (4)$$

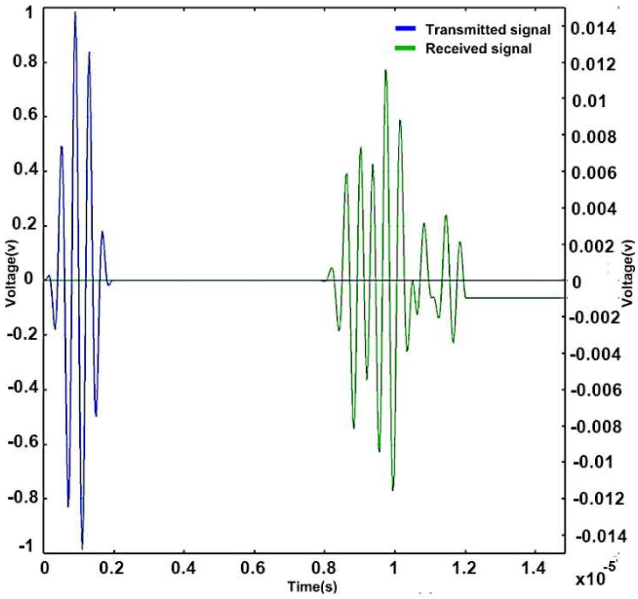

Fig. 2 Amplitude variation of transmitted and received ultrasound.

As shown in Fig. 2, which illustrates the signal obtained from simulating a battery in the COMSOL environment with ultrasound transmitted through it, there is a notable variation in amplitude between the transmitted and received signals. The received signal shows different peaks at certain time intervals and averaging it will form the overall structural model of the battery. It is worth mentioning that there is a significant drop in the overall amplitude of the signal due to the acoustic attenuation of the signal as it passes through the different layers inside the battery. The magnitude of this phenomenon is directly influenced by the quality of the internal interfaces, which is governed by the evolving stress and accumulated damage within the cell.

B. Principles of stress & strain monitoring

The mechanical state of a Li-ion battery is not static, it evolves dynamically with its electrochemical state. The primary mechanism driving this chemo-mechanical coupling is the insertion and extraction of lithium ions into the host electrode materials during charging and discharging cycles. As Li-ions intercalate into the crystal lattice of the anode during charging, they cause the lattice to expand. Conversely, the cathode material contracts as lithium is removed. This process reversed during discharge. Also, there is a formation of surface electrolyte interphase (SEI) on the electrode layer and its expansion through battery ageing or cycling. The expansion and contraction of electrode particles induce mechanical stresses and strains that alter the thickness, density, porosity, and elastic moduli (i.e., Young's Modulus, Shear Modulus, Bulk Modulus) of the entire cell [13].

Two main underlying factors alter the ultrasonic impedance (Z):

$$Z = \rho * V \tag{5}$$

Here, ρ represents the density of the material through which the signal travels and V denotes the signal's velocity within that medium.

As shown in Eq. (2), for a single-frequency ultrasonic wave, the received signal may exhibit changes in amplitude and ToF due to structural variations in the medium, since the frequency remains constant. For practical battery applications, the impedance is related to signal amplitude (A') and ToF to the velocity [13]. In Li-ion batteries, reduction in amplitude is primarily due to attenuation of the signal by absorption and scattering. For instance, an increase in external compressive stress or internal intercalation-induced stress can improve the mechanical contact between layers and particles. This improved contact reduces the acoustic impedance mismatch at the interfaces, leading to less energy being scattered and more energy being transmitted. The outcome is lower attenuation and an enhanced received signal amplitude [14]. Conversely, degradation mechanisms such as delamination, micro-cracking of electrode particles, SEI formation, or the generation of gas create new, highly reflective interfaces within the cell structure. These degradation-induced changes lead to a sharp increase in attenuation and a dramatic drop in the transmitted signal amplitude. For further investigation, the factors affecting the wave velocity can be examined. In an infinite solid medium, the wave velocities are expressed as:

$$V_L = \sqrt{\frac{E}{\rho}\frac{1-\upsilon}{(1+\upsilon)(1-2\upsilon)}} \tag{6}$$

$$V_T = \sqrt{\frac{E}{2\rho(1+\upsilon)}} \tag{7}$$

where V_L and V_T are the longitudinal and transverse wave velocities, respectively, E is the elastic modulus and υ is the Poisson's ratio.

Eqs. (6) and (7) establish that wave velocity is fundamentally dependent on the elastic modulus and density of the medium. Therefore, the Time-of-Flight (ToF), which directly measures this velocity, serves as a primary indicator of the cell stack's bulk material properties, making it an excellent candidate for tracking changes related to SoC. In contrast, signal amplitude, being a measure of attenuation, primarily reports on the quality and integrity of the interfaces within the cell. This makes amplitude an exceptionally sensitive indicator of mechanical stress, contact pressure, delamination, and gas evolution.

C. Proposed strategy for stress and strain analysis

Fig. 1 illustrates the proposed technical strategy for single-frequency ultrasonic sensing, which monitors stress and strain within the Li-ion battery. A single-frequency ultrasonic signal is transmitted through the battery by exciting the actuating PZT transducer (actuator). As the battery charges and discharges through multiple cycles, the received signal from the opposite end of the second PZT transducer (sensor) is captured and subsequently processed by the data acquisition system (DAQ). During each cycle, the battery's SoC and temperature are also monitored.

Savitzky-Golay filter [15] is applied to the received ultrasonic signal for denoising the noisy portion from Eq. (3). Then, as per Eq. (4), a period of the average received signal amplitude is collected for a particular SoC. As the battery's SoC varies with charging and discharging, there is development of stress and strain internally due to lithiation and delithiation at the electrodes. This can be reflected by a change in the average amplitude of the signal received.

Temperature is also monitored, as a high shift in temperature will also affect the internal structures of batteries. Furthermore, the degradation of the battery due to the intercalation of SEI is also monitored by observing the overall shift in average amplitude of the received signal over several charge and discharge cycles.

III. Results and Discussions

Experiments were conducted to characterize the acousto-mechanical response of the lithium-ion pouch cell during electrochemical cycling. The ultrasonic testing setup is shown in Fig.3, a 120 kHz ultrasonic signal was propagated through the cell's thickness, and the root mean square amplitude of the received signal was recorded as a function of the SoC over four consecutive charge-discharge cycles. The results of amplitude change provide significant insight into the evolution of internal stress, strain, and mechanical degradation within the cell.

An ultrasonic signal is applied to one side of the battery by using a function generator to excite the PZT actuator. The PZT sensor, used for receiving the transmitted signal, is placed on the rear side of the battery. The thermocouple, which rests on the battery surface, is connected to an amplifier (Max6675). The battery is charged at a 2C rate and discharged at a 1C rate using a battery tester (EBC-A20) by the standard CC-CV method. All the data collected from the PZT sensor and thermocouple are fed to the microcontroller (Arduino) acting as a DAQ. Finally, all data is post-processed in the MATLAB software on a PC.

A. *Acousto-Mechanical Response*

The relationship between the transmitted ultrasonic amplitude and the battery's SoC during the charging phase is shown in Fig. 4(a). Across all four cycles, the RMS amplitude is increased as the cell charges from 0% to 100% SoC. This occurs because lithium ions intercalate into the graphite anode, causing volumetric expansion of the electrode particles during charging. Inside the confined pouch cell, the expansion of countless individual particles generates a collective force. This results in a significant increase in internal compression, or 'stack pressure,' across the entire battery [16]. This rise in internal stress improves the mechanical contact at the interfaces between the cell's layers (e.g., electrode-to-separator). Better interfacial contact reduces acoustic impedance mismatch, minimizing energy loss from scattering and reflection [17]. As a result, the overall attenuation of the ultrasonic wave decreases, leading to an increase in the transmitted signal amplitude. This strong correlation between charging and signal amplitude indicates that the ultrasonic signal effectively probes the evolution of intercalation-induced stress.

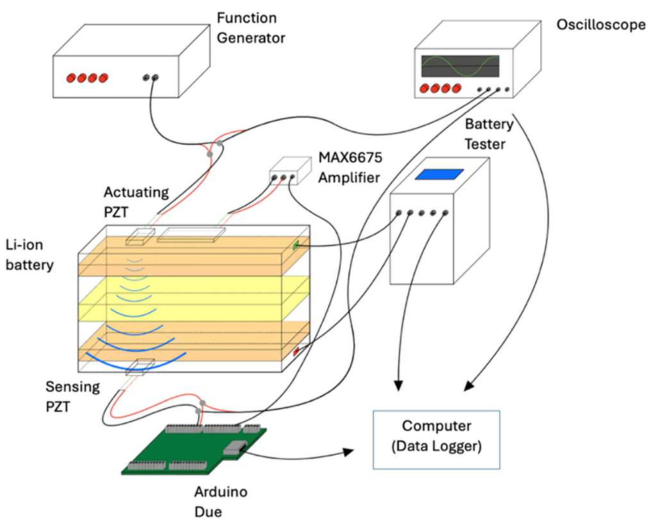

Fig. 4 Experimental components and connection.

However, the relationship isn't purely linear. During charging, a clear and consistent dip in amplitude appears in the mid-SoC range (about 50% to 70% SoC). This non-linearity suggests the acoustic response is affected by more than just a simple stress increase. Electrode materials like graphite undergo distinct phase transitions at specific lithium concentrations, which cause sudden changes in elastic moduli and density. These changes directly affect the ultrasonic wave's velocity and attenuation. The observed dip in amplitude is an acoustic signature of this phase transformation. The complex interaction of changing modulus and density temporarily increases attenuation, overriding the general trend of increasing compressive stress. During discharge, as shown in Fig. 4(b), a similar complex, non-monotonic shift occurs. As lithium ions leave the anode, the

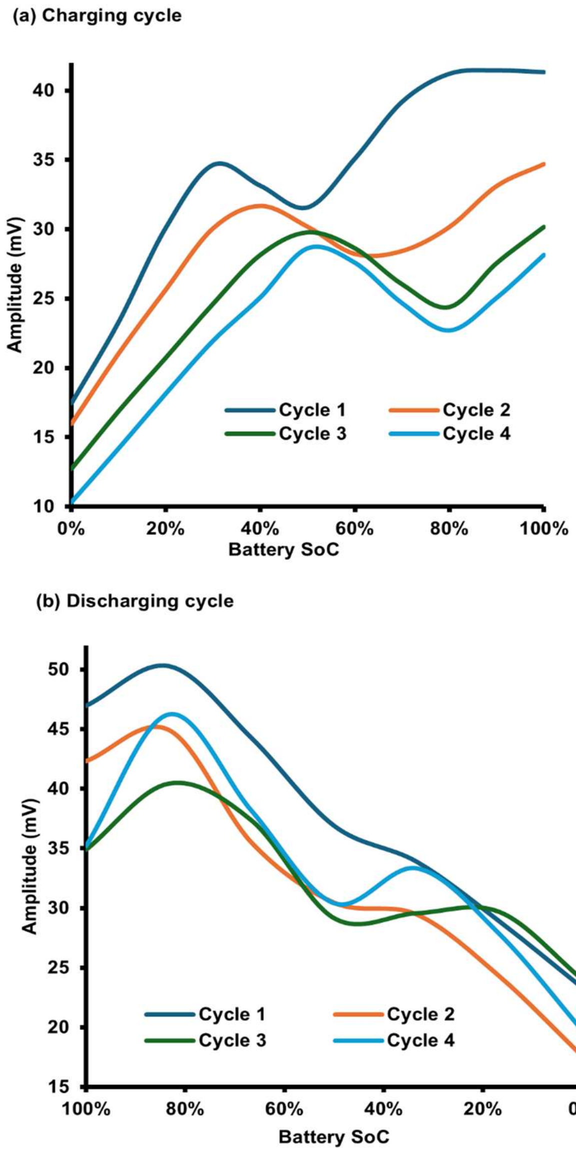

Fig. 3 Ultrasonic amplitude response for: (a) Battery charging cycle from 0% SoC to 100% SoC for four consecutive cycles; (b) Battery discharging cycle from 100% SoC to 0% under four consecutive cycles.

cell contracts, decreasing internal stack pressure. This leads to increased attenuation and lower signal amplitude, as expected. The fluctuating amplitude during discharge confirms that the cell's acoustic properties are influenced by stress relaxation and the non-linear evolution of material properties related to specific de-intercalation stages.

B. Cyclic Degradation

A critical observation from both the charging and discharging plots shown in Fig.4 is the progressive, cycle-over-cycle decline in the overall RMS amplitude. For any given SoC, the amplitude measured in Cycle 4 is consistently lower than in Cycle 1. This consistent decrease in signal strength indicates cumulative, irreversible degradation and offers a direct way of monitoring the battery's SoH.

With each charge-discharge cycle, various degradation mechanisms can occur, including growth of the SEI layer, micro-cracking of electrode particles, loss of electrical contact, or partial delamination between layers. These physical changes create new interfaces (e.g., cracks or gas pockets) or modify the nature of existing ones, increasing the number of sites for acoustic scattering and absorption. This results in a permanent rise in the cell's baseline acoustic attenuation. The downward trend in amplitude across the four cycles directly reflects this accumulated mechanical damage. This highlights the ultrasonic amplitude's sensitivity not only to the transient stress state related to SoC but also to the permanent evolution of the cell's mechanical integrity, which underpins SoH.

C. Influence of Temperature

Temperature, among other confounding factors, must be considered when evaluating the acousto-mechanical behavior. As illustrated in Fig.5, the temperature of the battery cell steadily increases during operation, rising by approximately 3-5°C over a cycle. Temperature fluctuations have a significant influence on the physical properties of battery materials, including the density, viscosity, and elastic moduli of the electrolyte and polymer separator. These changes, in turn, affect the propagation velocity and attenuation of the ultrasonic wave, regardless of stress or SoC effects.

Therefore, the measured amplitude trends are a complex signal reflecting the combined effect of SoC-induced stress changes, progressive mechanical degradation (i.e., SoH), and operational temperature changes. The steady temperature increase during each cycle contributes to the observed amplitude profile. For the development of a fully quantitative stress-monitoring model, it would be imperative to separate these effects, either by performing calibration under strictly isothermal conditions or by developing a temperature compensation algorithm to correct the acoustic data. Nonetheless, these results qualitatively demonstrate the immense potential of ultrasonic amplitude as a multi-faceted indicator for the comprehensive in-situ assessment of a battery's chemo-mechanical behavior state.

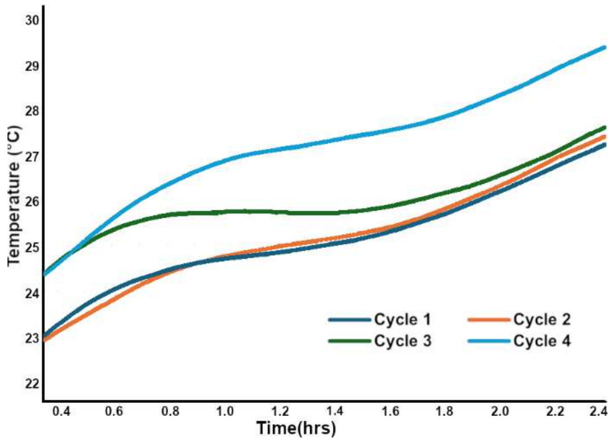

Fig. 5 Temperature variation during battery discharging.

D. Comparative analysis

Table 1 provides a comparative study of the proposed method with the ultrasonic battery monitoring techniques. As the previous studies have successfully utilized ultrasonic signals for state estimation, they have predominantly focused on the ToF as the primary feature for tracking the SoC. Other studies have employed high-frequency or multi-frequency approaches, which can introduce complexity in signal processing and interpretation.

IV. CONCLUSION

This paper presents a framework for monitoring the internal stress state and mechanical degradation of a commercial Li-ion cell using in-situ ultrasonic analysis. By applying a 120 kHz single-frequency signal in a through-transmission mode to the cell, a consistent correlation between the received signal amplitude and the battery's dynamic chemo-mechanical condition is established. The study reveals three key findings: (1) the amplitude of the ultrasonic signal strongly correlates with the SoC during charging, indicating increased internal compressive stress; (2) subtle changes within the electrodes are detected by non-monotonic "dips" in the amplitude profile, interpreted as acoustic signatures of graphite phase transitions; and (3) a gradual decrease in

TABLE I. COMPARISON OF DIFFERENT ULTRASONIC BATTERY TESTING METHODS WITH THE PROPOSED METHOD

Study	***Ultrasonic Mode***	***Frequency***	***Primary Acoustic Feature(s)***	***Application***
Hsieh et al. [3]	Pulse-echo	High-frequency (2.25 MHz)	ToF & Amplitude	SoC estimation.
Gold et al. [4]	Through-transmission	Single, low-frequency (200 kHz	ToF & Amplitude	SoC estimation via porosity changes.
Sun et al. [7]	Through-transmission	Multiple frequencies	Wave Velocity (from ToF) & Attenuation	SoC estimation, exploring temperature influence and optimal frequency.
Ladpli et al. [18]	In-plane Guided Wave	100-200 kHz	ToF & Amplitude	SoC and SoH estimation using waves traveling along the cell plane.
General Trend [5], [8], [9], [10], [11]	Various (Primarily Through-transmission)	Multiple frequencies	Primarily ToF	Primarily SoC estimation.
This Study	Through-transmission	Single, low frequency (120 kHz)	Amplitude only	Correlating amplitude with SoC-induced stress and SoH degradation. Interpreting non-monotonic features as phase transitions

overall signal amplitude is observed cycle-over-cycle, providing a direct measure for monitoring irreversible mechanical damage and assessing battery health. This method offers a robust, non-destructive diagnostic tool that exceeds conventional battery management system monitoring. However, temperature significantly influences the measurements, acting as a confounding variable. Future research should aim to decouple these thermal effects by developing effective temperature compensation models. Integrating multiple acoustic features with traditional battery management system data within advanced multisensor machine learning frameworks could lead to a more comprehensive assessment of the battery's internal state.

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