Journal of Power Sources 384 (2018) 342–354

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Estimating state of charge and health of lithium-ion batteries with guided waves using built-in piezoelectric sensors/actuators

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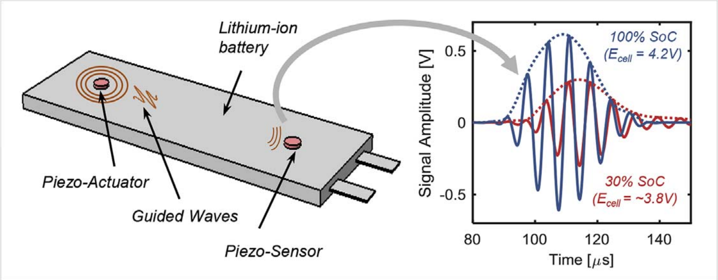
HIGHLIGHTS

- Guided waves precisely estimate a lithium-ion battery's state of charge and health.
- A simple implementation involves low-profile, built-in piezoelectric transducers.
- Time of flight and signal amplitude are indicative of state of charge and health.
- Signals from multiple propagation paths simplify computation and enhance accuracy.
- Analytical results relate acoustic signature with changes in modulus and density.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Lithium-ion battery
Ultrasonic guided waves
State of charge
State of health

ABSTRACT

This work presents the feasibility of monitoring state of charge (SoC) and state of health (SoH) of lithium-ion pouch batteries with acousto-ultrasonic guided waves. The guided waves are propagated and sensed using low-profile, built-in piezoelectric disc transducers that can be retrofitted onto off-the-shelf batteries. Both experimental and analytical studies are performed to understand the relationship between guided waves generated in a pitch-catch mode and battery SoC/SoH. The preliminary experiments on representative pouch cells show that the changes in time of flight (ToF) and signal amplitude (SA) resulting from shifts in the guided wave signals correlate strongly with the electrochemical charge-discharge cycling and aging. An analytical acoustic model is developed to simulate the variations in electrode moduli and densities during cycling, which correctly validates the absolute values and range of experimental ToF. It is further illustrated via a statistical study that ToF and SA can be used in a prediction model to accurately estimate SoC/SoH. Additionally, by using multiple sensors in a network configuration on the same battery, a significantly more reliable and accurate SoC/SoH prediction is achieved. The indicative results from this study can be extended to develop a unified guided-wave-based framework for SoC/SoH monitoring of many lithium-ion battery applications.

1. Introduction

In response to the ever-growing demand for electrical systems, recent extensive battery research, particularly research involving lithium-ion (Li-ion) batteries, is trying to push the envelope of high-energy battery packs from electric automotive applications to renewable energy storage [1,2]. However, Li-ion batteries are extremely complex systems with a very narrow operating range and are prone to premature

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https://doi.org/10.1016/j.jpowsour.2018.02.056
Received 24 October 2017; Received in revised form 9 February 2018; Accepted 19 February 2018

unexpected failure [3–5]. To optimize battery performance, lifespan, and most importantly, safety, a battery management system (BMS) is required to perform battery condition monitoring, charge/discharge control, thermal management, cell balancing, and fault mitigation [4–10]. To facilitate the foregoing functions, the BMS must first and foremost be able to accurately monitor the batteries' critical internal states, which primarily include state of charge (SoC) (the charge remaining in the battery with respect to the fully charged capacity, or the equivalent of a fuel gauge) and state of health (SoH) (a degree of degradation in battery health which usually manifests as a reduction in capacity retention) [4–11]. It is a true detriment to the field that the practical implementation of high-energy battery systems is still extremely challenging owing to the lack of a field-deployable, yet affordable battery management system (BMS) that can reliably and accurately monitor SoC/SoH [4–10].

In a laboratory setting, in-situ techniques (e.g., X-ray diffraction [12–14], neutron imaging [15,16], and electrochemical impedance spectroscopy (EIS) [17,18]) can be used to directly probe the physical states of the battery. However, such techniques cannot be practically implemented and, in most cases, can only be performed on small-scale, non-standard cells. In addition, the benefits of having these elaborate electrochemical tools on-board do not justify the significant additional cost and complexity. As it stands, conventional on-board BMSs are therefore limited to the measurement of extrinsic parameters, including voltage, current, and temperature. From these, SoC/SoH are merely approximated using a combination of time-series techniques, battery modelling, parameter identification, and state estimation algorithms [4–10]. In its most rudimentary form, interpolation and time-history integration of on-board collected data are utilized in the form of SoC-OCV lookup and coulomb counting [19]. Other strategies rely on mathematical models of battery dynamics (electrochemical models) [20] or an approximate form of which, commonly referred to as equivalent circuit models [21]. State estimation algorithms, parameter observer, and more advanced signal processing techniques (e.g. Kalman filtering [22], partial differential equation observer [20,23], etc.) are then used in conjunction with these models to estimate SoC/SoH. More recent machine learning and statistical methods (e.g. neural networks [24], support vector machines [23], etc.) have also been incorporated into the model-based methods. Alternately, these are formulated into a model-free, data-driven scheme, which directly exploits the voltage and current measurements or their extracted features (e.g. sample entropy [6,11], incremental capacity analysis [25–28], etc.).

The current techniques have not come to exploit the fact that a Li-ion battery is fundamentally a composite material system. A battery undergoes mechanical evolution, most notably modulus and density distribution, during electrical cycling and aging [3]. Thus, the mechano-electrochemical coupling presents an opportunity for mechanical characterization and inspection techniques to be used to monitor the electrochemical processes. Ultrasonic inspection is one of the most elegant and widely-used solutions in the context of ultrasonic non-destructive evaluation (NDE) [29] and structural health monitoring (SHM) [30,31]. Mechanical stress waves are excited, propagated, and received in a structure, allowing the mechanical properties, structural integrity, and internal damage to be accurately and continuously monitored almost in real time. Ultrasonic inspection can therefore potentially be used to monitor the battery modulus and density activities, and ultimately to estimate the SoC/SoH.

Recent research has utilized ultrasound to probe Li-ion batteries. The work by Sood et al. is one of the pioneering studies to adopt an ultrasonic NDE technique for battery monitoring [32]. In this work, an ultrasonic pulser and a receiver are used to generate through-thickness compressional waves to detect local degradation at the interfaces between electrode layers. The information is then used to qualitatively determine any detrimental delamination of the electrode. Hsieh and Bhadra et al. perform a very comprehensive study using a similar experimental setup on numerous types of commercial batteries [33,34]. Through-thickness bulk-wave transmission and reflection data show correlations with the charge, discharge, and aging processes. The authors also attempt to validate the experimental findings analytically; however, owing to limitations of their model, only the relative changes in wave propagation times are presented. A follow-up work by Davies et al. shows that the propagation time and intensity of the through-thickness bulk waves can be used as predictors for SoC/SoH estimation [35].

Gold et al. introduce the use of a piezoelectric disc transducer pair mounted on the surface of a Li-ion battery using an adhesive, instead of a temporary gel couplant, which provides significantly cleaner signals and prevents baseline variability [36]. Ultrasonic waves are propagated in the form of a modulated sinusoid, as an alternative to a rudimentary ping. The study is limited to discontinuous, incomplete trends of signal parameters at several points during the charge and discharge processes. Gold et al. validate the experimental results analytically with a novel approach that considers the variation in electrode porosities during cycling, despite the numerous assumptions involved.

Most importantly, however, all these previous studies rely on the propagation of through-thickness compressional waves, which usually need external bulky ultrasonic probes and equipment, require extensive operator intervention, and suffer from inaccurate baseline collection [37,38]. In stark contrast, acousto-ultrasonic guided waves take advantage of the geometric boundaries of the structure to ‘guide’ the wave propagation [31,39]. This allows the stress waves to propagate a long distance in structures of various dimensions and complexities with minimal loss in energy. The complete process can be achieved using an onboard, built-in network of sensors and actuators. Unlike other stress wave counterparts, the properties of guided wave propagation enable a single actuator-sensor pair to have a large coverage area, hence resulting in simultaneous global and local inspection with a minimal footprint [31]. The literature so far has not explored the concept of SoC/SoH estimation with guided waves using a built-in network of piezoelectric transducers, despite its immense potential.

Therefore, the objective of this investigation is to develop a built-in acousto-ultrasonic guided wave technique to monitor SoC/SoH of Li-ion batteries. Building upon our previous companion work [40,41], the cornerstone of this method is the field-deployable use of small-footprint, built-in piezoelectric transducers to propagate windowed tone-burst guided waves. Since guided waves perform best in elongated, plate-like structures [31,39], they are well-suited for the form factor of pouch and prismatic batteries, which are commonly used in electrical systems, from stationary grids to electric vehicles and satellites.

Following is an outline of the rest of the article. Section 2 briefly describes the problem formulation, scope, and constraints. The overall approach to the problem is summarized in Section 3. Sections 4 and 5 present the experimental setup and details of the analytical wave propagation model, respectively. The results from the experiments are fully discussed in Section 6 and compared with findings from the analytical model. Section 7 constitutes a statistical framework that predicts battery SoC/SoH using guided wave features, followed by conclusions in Section 8.

2. Problem statement

Consider a Li-ion pouch cell, as shown in Fig. 1, which is equipped with permanently mounted piezoelectric disc transducers which can serve as actuators and sensors. One of the piezoelectric discs can be chosen as an actuator to generate acousto-ultrasonic guided waves. The other piezoelectric disc then serves as a receiver to record the transmitted guided wave signals. It is desired to correlate the guided wave signals from piezoelectric sensors with battery SoC/SoH through both experiments and analysis. The obtained results are imperative for evaluating the efficacy of SoC/SoH prediction using guided waves with built-in sensors/actuators. The proposed technique is to be evaluated on indicative commercial Li-ion pouch cells (graphite/NMC chemistry;