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Experimental modal analysis of lithium-ion pouch cells

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HIGHLIGHTS

- Experimental assessment of the frequency response of a Li-ion pouch cell.
- Assessment of the mode shapes for a Li-ion pouch cell using impulse excitation.
- Quantifying cell stiffness as a function of state of charge.
- Quantifying cell damping as a function of state of charge.
- Correlation of the cell's frequency response with road-induced vibration profiles.

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ABSTRACT

If future electric and hybrid electric vehicle batteries are to be designed such that the impact of vibration induced resonance is minimized, engineers tasked with the design of the vehicle's energy storage system must have a rigorous understanding of key system attributes such as the natural frequencies of the cell, the level of damping present and the mode shapes induced within the battery under mechanical load. This paper describes the underpinning theory and experimental method employed when using the impulse excitation technique to quantify the natural frequencies and mode shapes of a commercially available 25 Ah Nickel Manganese Cobalt Oxide (NMC) Laminate Pouch Cell. Experimental results are presented for fifteen cells at five different values of state of charge (SOC). The results indicate that irrespective of the energy content within the cell, the same four modes of vibration (torsion and bending) exist within a frequency range of 191 Hz–360 Hz. This is above the frequency range (0–150 Hz) typically associated with road-induced vibration. The results also indicate that the cell's natural frequencies of vibration and damping do not vary with changing values of SOC.

1. Introduction

Within the automotive and road transport sector, one of the main drivers for technological development and innovation is the need to reduce the vehicle's fuel consumption and the emissions of carbon dioxide (CO_2). Legislative requirements are motivating vehicle manufacturers and subsystem suppliers to develop new and innovative electric vehicle (EV) and hybrid electric vehicle (HEV) concepts. Within this field, a key enabling technology is the design and integration of the high voltage (HV) battery system.

The impact of mechanical vibration on the vehicle's electrical and electronic components and subsystems is known to be a major cause of in-market durability failure [1]. If excessive warranty claims are to be avoided, it is important that engineers tasked with the design of the HV battery system, properly understand the magnitude and frequency of the vibration inputs that the energy storage system will be exposed too during the vehicle's predicted life. If future vehicle battery systems are to be designed such that the impact of vibration induced resonance is minimized, engineers must have a rigorous understanding of key system attributes such as the natural frequencies of the cell, the level of damping for each natural frequency and the mode shapes induced within the cell when it is under mechanical load (e.g. the presence of bending, torsional or panting modes).

Experimental modal analysis measures the natural vibration response of a system. To ensure vehicle durability it is necessary to determine, at the design stage, the natural vibration characteristics of components, both in isolation and when they are aggregated into larger vehicle sub-systems. Recent studies [2] have highlighted that if a system was allowed to vibrate at one of its modal frequencies

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Nomenclature

Terms and abbreviations

BMS	battery management system
dB	decibels
EMS	electromagnetic shaker
EV	electric vehicle
FRF	frequency response function
HEV	hybrid electric vehicle
HV	high voltage
Li-ion	lithium ion
NMC	nickel manganese cobalt
NVH	noise vibration and harshness
PSD	power spectral density
SISO	single input single output
SOC	state of charge

Mathematical notation – symbols and units

f_{max}	maximum frequency Hz
k_p	tip stiffness Nm^{-1}
k_c	cell stiffness Nm^{-1}
m_H	hammer mass kg
m_c	cell mass kg
Q	quality-factor -
T	time s
ω	frequency $rads^{-1}$
ω_n	natural frequency $rads^{-1}$
ς	damping ratio -
$G_{xy}(f)$	cross-spectral density
$G_{xx}(f)$	auto-spectral density (x)
$G_{yy}(f)$	auto-spectral density (y)
$x(t)$	system input (time domain)
$y(t)$	system output (time domain)
$X(s)$	system input (laplace domain)
$Y(s)$	system output (laplace domain)
$H(s)$	system transfer function (laplace domain)
$H(j\omega)$	system transfer function (frequency domain)

with excessive, sustained, oscillatory motion permanent deformation or structural damage may occur. One example of an automotive component that failed through sustained excitation at one of its natural frequencies is presented within [1]. The research discusses the complete mechanical failure of the component after only 7000 km of driving [1]. The failure mode was identified using modal analysis techniques. The study found that the first natural frequency of the component occurred at 52.2 Hz and the road-load profile induced an accelerated fatigue condition within the device. Modal analysis is not limited to small components or systems. The methodology is also widely employed within the civil engineering domain, for example when assessing the structural integrity of bridges [3]. A recent study from the UK [3] highlights the application of modal analysis for understanding the undesirable swaying motion experienced when the Millennium Bridge was opened in London during the year 2000. It was identified that the 1st and 2nd natural modes of vibration for the bridge occurred between 0.5 and 1 Hz respectively and pedestrians excited these modes when they traversed the bridge [3]. Due to excessive motion of the structure and the subsequent fears for public safety, the bridge was closed until 2002, while engineer's integrated additional dampers within the bridge to reduce the amplification associated with the natural frequencies.

This paper describes the underpinning theory and experimental method employed when using the impulse excitation technique to quantify the natural frequencies and mode shapes of a commercially available 25 Ah Nickel Manganese Cobalt Oxide (NMC) Laminate Pouch Cell. From the experimental results obtained, values for cell damping and stiffness are estimated. Through the evaluation of different cells at the same SOC and at different values of state of charge (SOC), this research has been able to quantify the variability in the mechanical frequency response of the cells due to cell-to-cell manufacturing variations and stored energy.

This paper is structured as follows; Section 2 discusses the concept of mechanical testing for Li-ion cells and Section 3 introduces the experimental theory that underpins modal analysis. Section 4 describes the experimental set-up and method employed when undertaking modal analysis with a Li-ion pouch cell. Key results and discussions are presented in Section 5, with conclusions and further work presented in Sections 6 and 7 respectively.

2. Related research

Research undertaken into the mechanical testing and characterization of Li-ion cells, particularly within the context of designing and testing the vehicle's HV battery system can broadly be classified as being based on either static or dynamic test methods [2]. Irrespective of the exact methodology employed, the primary motivation for performing such experiments is often the generation of data to either parameterize or validate high fidelity finite element models of the battery system to better understand the impact of mechanical loading [2]. Research that aims to quantify pertinent material properties under a combination of different environmental conditions with varying mechanical and electrical loads includes, but is not constrained too: assessments of mechanical stress and strain within the numerous different components that comprise the cell (outer casing, electrodes, separators and current collector) [2,4–6], quantifying the creep within a representative sample of conductive material at different temperatures [6] and measuring the volume expansion of a pouch-cell during charge–discharge conditions [8].

In addition to the performance evaluation of different cell chemistries and formats, there is also a significant body of research that attempts to quantify the mechanical robustness (crashworthiness) of the cell or complete battery system. Examples of recent publications include the mechanical crushing of the cell [4,7,9], the effect of cell penetration [2,10], assessing the durability of the cell against impact [4,9] and mechanical shock [4] and understanding the fatigue conditions and possible failure modes of the battery system due to extreme variations in temperature and pressure [11,12]. The need to conduct such tests is often driven by the requirement to satisfy whole vehicle crash homologation Standards [13,14] and legislation, such as UN38.3, that governs the transportation of dangerous goods [15–17].

In recent years, there has been comparatively less research addressing the mechanical durability and vibration response of individual cells or the complete battery system. Research has been published [18] that correlates mechanical fatigue within the cell to the use of repetitive deep-discharge cycles. However, as discussed within Section 1, another of source of mechanical fatigue within the battery may well be the vibration-induced resonance resulting