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An Exhaustive Review On Hybrid Electrical Vehicular Designs Using Ergonomical Based Mechanical Designs

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Abstract

The advent of hybrid electric vehicles (HEVs) has spurred extensive research into optimizing their design and performance. This paper presents a comprehensive review of hybrid electrical vehicular designs, with a specific focus on incorporating ergonomical mechanical designs to enhance overall efficiency, comfort, and sustainability. The study encompasses a wide spectrum of HEV configurations, ranging from parallel and series hybrids to more advanced powertrain architectures. The review systematically evaluates the impact of ergonomical mechanical designs on various aspects of HEV performance, including energy efficiency, power management, and thermal control. Special attention is given to the integration of regenerative braking systems, energy storage technologies, and advanced transmission mechanisms. Additionally, the paper explores innovative approaches to enhance user experience and comfort through the incorporation of ergonomic principles in vehicle interiors and exteriors. In order to provide a holistic perspective, the review also discusses the challenges and opportunities associated with ergonomical mechanical designs in HEVs. This includes considerations related to manufacturing processes, materials selection, and the potential environmental implications of adopting these designs. Furthermore, emerging trends in the field, such as the application of artificial intelligence and smart technologies, are addressed to underscore their potential contributions to future advancements in hybrid electric vehicular design. Ultimately, this exhaustive review aims to serve as a valuable resource for researchers, engineers, and policymakers in the field of electric vehicles, providing insights into the current state of HEV technology and offering guidance for future research directions and innovations in the pursuit of sustainable and ergonomic transportation solutions.

Keywords : Electric, Mechanical, Hybrid, Vehicle

Introduction

Electric Vehicles (EVs) face increasing challenges attributed to various factors, such as cost reduction, environmental concerns, and climate awareness. Lithium-ion batteries are commonly employed in electric vehicles due to their cost-effectiveness and straightforward manufacturing processes. This discussion delves into the obstacles and choices surrounding dynamic models for the operation of lithium-ion batteries, presenting a comprehensive overview of models and dynamics while exploring further developments in this field. Understanding the intricacies of battery analysis and operation necessitates a thoughtful consideration of key procedures, their dynamics, limitations, and time-related aspects. This review encompasses academic, computational, and investigative studies conducted in both academic institutions and industry over the past few years. As the market share of lithium-ion batteries continues to rise, it becomes imperative to enhance our comprehension of the impact of mechanical vibrations on the electrical performance and mechanical properties of these batteries [68].

Recent studies have shed light on the influence of vibrations on the degradation of battery cell materials and the structural integrity of battery packs. This review emphasizes the recent advancements in elucidating the effects of dynamic loads and vibrations on lithium-ion batteries, aiming to deepen our understanding of their structural dynamics. Depending on the specific problem or operating conditions, considering all scales becomes unavoidable. The review categorizes three interrelated yet distinct model classes—mechanical models, corresponding circuit models, and data-driven models. Each class is assessed in terms of its physical understanding, capabilities, and limitations. While previous studies have explored the impact of dynamic loads and random vibrations on the mechanical behavior of battery pack structures and established correlations between vibrations and battery cell electrical performance, there remains a critical need to clarify the mechanical degradation mechanisms influencing electrical performance and the protection of battery cells [68].

Literature Review

The primary objective of investing in research and development for Electric Vehicles (EVs) is to reduce reliance on oil, minimize emissions, and foster a healthier environment for humans [1]–[3]. The crucial component responsible for powering electric vehicles is the battery pack, comprising hundreds of batteries interconnected in series and parallel configurations [4]–[6]. The effective functioning of battery packs is overseen by the battery management system [7]–[12]. Lithium-ion (Li-ion) batteries serve as the fundamental energy storage devices in contemporary mobile mechanical equipment, including electric vehicles (EVs), spacecraft, and modern satellites. They are required to perform charge and discharge functions under conditions such as vibration and shock [1]–[17]. For instance, Li-ion batteries used in spacecraft or power satellites must withstand intense vibrations, especially during launch. Similarly, Li-ion batteries in EVs experience random vibrations from uneven road surfaces, and mechanical stresses from vehicle collisions and adverse road conditions can lead to significant battery safety concerns [18]–[27].

Consequently, batteries are designed to meet mechanical load-bearing requirements, ensure reliability, and operate safely under varying conditions. Li-ion batteries comprise not only the battery pack structure but also cells containing an anode and a cathode separated by a separator material to prevent direct contact, as illustrated in Fig. 1. The separators, typically made of polymers as depicted in Figure 2, are susceptible to breakage under dynamic loading conditions within the battery cell [28]–[33]. Research by Somerville et al. [34] indicates that separator material failure adversely affects battery life, performance, and safety. Furthermore, the battery pack structure is susceptible to damage in vibration and shock environments [43]–[50], and the electrical connections within the battery pack can become unstable under vehicle vibration [35]. Given the rising demand for Li-ion batteries in spacecraft and automobiles, it becomes imperative to enhance our understanding of failure mechanisms within batteries subjected to shock and vibration environments. This knowledge is crucial for improving the safety and performance of Li-ion batteries and power systems utilized in spacecraft and automobiles [68].

Kinds of models that could be used

There are three primary types of models: (1) electrochemical models, (2) equivalent circuit models, and (3) empirical models. Electrochemical models, often finite element or physics-based, demand expert knowledge of system behavior to derive meaningful solutions. Despite their complexity and computational intensity, discretization techniques can be applied to obtain reduced-order electrochemical models, primarily used for gaining a fundamental understanding of chemical behavior within batteries. Equivalent circuit models also necessitate a deep understanding of circuit systems and controller functions to predict battery performance over time. Empirical models, derived from artificial intelligence (AI) methods, are employed for estimating parameters such as state of charge (SOC), state of health (SOH), state of function (SOF), temperature distribution, voltage, etc [24]–[26] [68].

Interestingly, AI-based models can be integrated into systems, but their robustness and accuracy in the face of input variations remain a significant challenge. Factors like temperature and discharge rate variations within the battery pack, sudden impacts, or changes in road slope/friction conditions can lead to inaccurate battery performance estimation, potentially compromising electric vehicle monitoring efficiency. Additionally, insufficient attention has been given to evaluating the mechanical strength of batteries when subjected to sudden external impacts. Assessing the mechanical strength of batteries is crucial for the automotive industry's road safety efforts, as unforeseen impacts can lead to battery fires due to short circuits. Consequently, there is a need to develop a holistic approach that evaluates the battery's mechanical strength in the event of sudden impact. The proposed approach in this study involves employing finite element automated neural networks search (ANS) to model the mechanical strength of the battery under compressive loading conditions. Such a comprehensive methodology aims to provide a robust understanding of the battery's fundamentals and estimate its strength under uncertain input conditions [68].

Battery construction & design

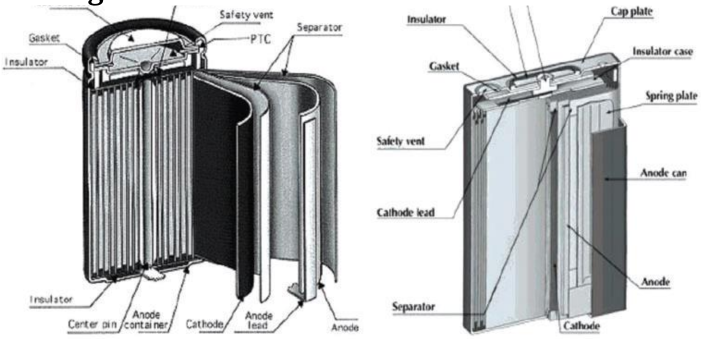

Fig. 1 : Schematic of typical Li-ion battery cells (a) button cell (b) stack lead-acid cell (c) spiral wound cylindrical cell (d) spiral wound prismatic cell [29] [68]

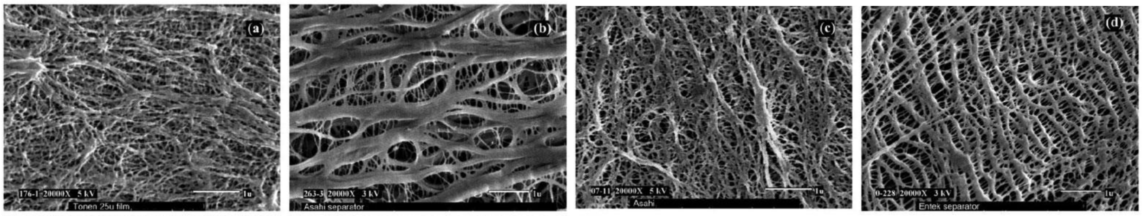

Fig. 2 : Scanning electron micrographs of separators of Li-ion battery cells (a) Tonen (Setela) (b) Asahi (Hipore-1) (c) Asahi (Hipore-2) (d) Entek (Teklon) [29] [68]

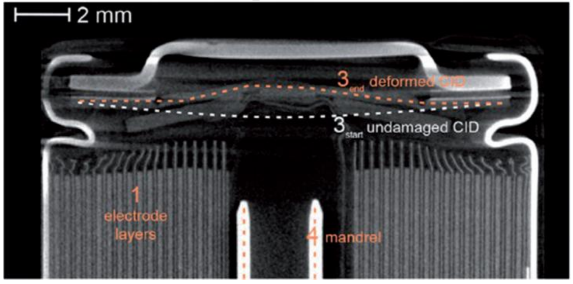

Fig. 3 : Deformed 18650 cylindrical lithium-ion cell after 300 shocks in z-direction according to UN 38.3 T4 standard, visible in mCT image [35] [68]

This discussion highlights intriguing facts pertaining to batteries, encompassing the global surge in production, cost reduction, key characteristics, and various technologies employed in the manufacturing process. Recent years have witnessed remarkable strides in battery development. Notably, the worldwide production of batteries for Electric Vehicles (EVs) has experienced a significant 66% increase [50]. This surge is undeniably linked to the growing sales of electric vehicles, with forecasts indicating a continued rise in battery demand [68].

Characteristics of the Batteries

Some of the characteristic properties of the batteries are [68]

Capacity:

Definition: The storage capacity is a crucial challenge in electric power, prompting significant investments in developing batteries with enhanced efficiency and reliability.

Measurement: Expressed in ampere-hours (Ah) or watt-hours (Wh), with the latter being more common in electric vehicles (EVs).

Significance: In EVs, battery capacity directly impacts vehicle autonomy. Advancements in technologies enabling higher energy storage in shorter durations are pivotal for the success of these vehicles. Table 2 illustrates data related to the battery capacities of EVs, revealing a continuous growth with expectations of vehicles featuring batteries exceeding 100 kWh soon.

Charge State:

Definition: Indicates the battery level concerning its 100% capacity.

Energy Density:

Definition: A critical aspect in battery development, energy density reflects the ability of a battery to accumulate a higher energy quantity with equal size and weight.

Measurement: Expressed as energy supplied per unit volume (Wh/L).

Specific Energy:

Definition: Represents the energy a battery provides per unit mass.

Measurement: Can be specified in Wh/L or Wh/kg.

Specific Power:

Definition: The power a battery can supply per unit weight (W/kg).

Charge Cycles:

Definition: A load cycle is completed when the battery has been used or loaded 100%.

Lifespan:

Definition: Measured by the number of charging cycles a battery can endure. The goal is to develop batteries with a longer lifespan capable of enduring numerous loading and unloading cycles.

Internal Resistance:

Definition: Batteries' components offer resistance to electricity transmission, resulting in thermal loss during charging.

Impact: Internal resistance plays a significant role in high-power charges, with quick charging inducing higher temperatures. Decreasing this resistance is crucial to reducing charging times, a notable drawback in current electric vehicles.

As lithium-ion (Li-ion) batteries become more prevalent, research is essential to understand the effects of standard vibration and shock tests, as well as long-term vibration, on battery cells. Recent studies, such as those conducted by Brand et al. [35] and Hooper et al. [36], have examined the impact of vibrations and shocks on Li-ion battery cells. These studies involved various tests, including sine vibrations, mechanical shocks, and long-term vibrations, providing insights into the degradation and failure mechanisms experienced by cylindrical and pouch battery cells under these conditions. The results underscore the importance of understanding and mitigating the effects of mechanical stresses on battery cells to enhance the reliability and safety of electric vehicles [68].

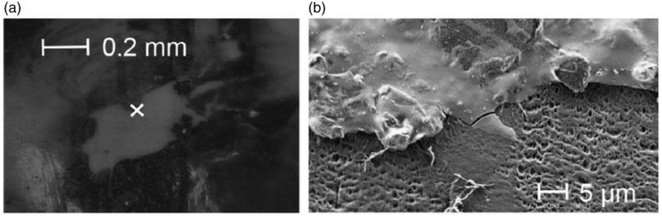

Fig. 4 : Demonstration for internal shorts in 18650 Li-ion battery cell after long-term vibration tests (a) optical micrograph of the scorched separator (b) scanning electron micrograph of partially melted separator layer [35]

The authors detailed experimental tests aimed at assessing the degradation of a nickel manganese cobalt (NMC) oxide cylindrical cell due to prolonged and intense vibrations. The study revealed that the cell's natural frequency underwent changes associated with internal cracking, delamination, fracture, and orientation relative to the vibrations. Moreover, a connection was identified between the cell's state of charge and performance degradation, although the exact quantification of this relationship proved challenging. Another experimental investigation by Hooper et al. [37] focused on a different type of 18650 battery cell—specifically, a nickel cobalt aluminum oxide (NCA) cell. Their findings indicated that vibrations typical of a vehicle's lifespan have minimal impact on the electrical performance and mechanical properties of the cell [68].

In a study conducted by Zhang et al. [38], a statistical method was employed to analyze experimental test data from Li-ion batteries, specifically 32 individual Li-ion 18,650 cells subjected to single-axis vibration. The primary investigation targeted the z-axis, known for its pronounced impact on battery performance despite the cells experiencing vibrations in all three primary axes. The study dismissed the potential effects of resonance, as prior research suggested its limited prevalence in 18,650 cells. The notable findings included a significant increase in the internal resistance of the battery post-vibration testing, accompanied by a subsequent decrease in battery capacity. Additionally, the study introduced the concept of statistical modeling, presenting an accurate model for theoretically estimating battery life from an electrical perspective without the necessity for extensive experimental trials [68].

Zhang et al. [39] utilized the Neware BTS4000 battery test platform to assess the electrical performance of commercial 18,650 Li-ion batteries under varied temperature and vibration conditions. Their study analyzed the impact of temperature, vibration frequency, and vibration direction on battery discharge performance. Findings indicated that these factors collectively influenced battery discharge capability, with temperature exhibiting a more substantial effect compared to vibration frequency and direction. Expanding on their prior work [36], Hooper et al. [40] adopted a six-degree-of-freedom (DOF) simultaneous testing approach, diverging from single-axis vibration methods, to study the influence of vibrations equivalent to 100,000 miles of vehicle durability tests on NMC oxide cylindrical cells. The evaluation encompassed electrical properties based on impedance, open circuit potential, and energy capacity, while mechanical properties were assessed through natural frequency. Results revealed a significant increase in direct current resistance under vibrations representative of a 10-year European vehicle life, yet overall electromechanical performance did not experience substantial degradation [68].

Somerville et al. [34] pioneered the identification of the electromechanical mechanism causing performance degradation in Li-ion cells due to vibrations. Employing X-ray photoelectron spectroscopy on NMC cells during vibration tests, they observed the removal of selectively formed surface films, replaced by films resulting from electrolyte decomposition. This induced surface film led to increased cell degradation, capacity loss, and cell impedance. Berg et al. [41] explored the effect of inner cell design on the vibration durability of battery cells through vibration tests on 18 different 18,650 cells, applying both standard Society of Automotive Engineers J2380 profiles and more severe profiles. While there was no significant electrical performance degradation, certain cell designs exhibited mechanical damage to negative current collector tabs, emphasizing the importance of inner cell design for vibration durability. In a related study, Berg et al. [42] experimentally investigated the structural dynamics of individual Li-ion prismatic cells. Results indicated high sensitivity of cell structural dynamics, including natural frequencies, damping ratios, and mode shapes, to the cell's state of charge and temperature. Furthermore, significant changes in structural dynamics were observed with cell aging [68].

Effect of vibrations on the battery pack structure

Shui et al. [43] delved into the investigation of deformation and vibration behavior in a battery pack enclosure subjected to dynamic loading and random vibrations. They developed a four-phase design optimization methodology to enhance battery pack enclosures by minimizing maximum deformation, maximizing the first natural frequency, and minimizing overall mass. The approach involved using ANSYS software for basic design and finite element analysis, followed by the development of empirical models and multi-objective optimization to select optimum design parameters. The optimized design demonstrated a 22% increase in battery strength, a 3% increase in the first natural frequency, and a 12% reduction in battery pack weight. Similarly, Zhou et al. [44] established a simulation procedure for fatigue analysis on a bus battery bracket. They simulated the road spectrum using software, performed transient dynamics analysis using Adams software to simulate vehicle body acceleration and dynamic loads on the battery bracket, and utilized ANSYS for finite element stress analysis. The study calculated the battery bracket's fatigue life based on the SN curve of the bracket materials [68].

Hong et al. [45] introduced a novel method for predicting the structural dynamics of hybrid electric vehicle battery packs. Unlike other studies, they considered not only the battery pack enclosure but also the cell structures and cell-to-cell structural variations. Their proposed parametric reduced-order model (PROM) significantly reduced computational burdens while maintaining accuracy in dynamic predictions when compared with full finite element models. Using PROMs, they investigated the sensitivity of battery cell vibration amplitude and fatigue life to small cell-to-cell structural variations. Building on this, Lu [46] further developed PROMs to enable statistical optimization analysis considering linear and nonlinear structural variations. The method demonstrated that optimizing space arrangement could significantly reduce the vibration response of the entire battery pack. Choi et al. [47] suggested a single-axis acceleration test method for battery fixing brackets as an alternative to the slower, less reliable, and costlier six-degree-of-freedom acceleration test method. This experimental approach converted measured vibrational acceleration signals into a power spectrum diagram and correlated testing time with the acceleration factor, offering a conversion formula for driving distance based on testing time [68].

Hooper and Marco [48] explored typical vibration levels experienced by a range of battery packs in electric vehicles (EVs) while driving on representative road surfaces. Their findings indicated that typical vibration frequencies for battery durability were below 7 Hz, with additional frequencies above 300 Hz potentially induced by electric devices, the transmission system, or the cooling mechanism. Lang and Kjell [49] performed battery vibration measurements while driving a battery electric vehicle (BEV) and emphasized the importance of considering three directions for standard battery vibration testing. They identified wide vibration ranges with frequencies above 200 Hz, attributed to electronic devices. Lastly, Hooper and Marco [50] experimentally evaluated various EVs under high-voltage battery vibration inputs and different road conditions, comparing them with a representative vehicle service life. The study revealed that battery packs could experience vibration frequencies beyond the range defined by current standards.

Conclusions

A diverse range of Li-ion battery models exists, each tailored for specific tasks, making the selection of the most suitable model a challenging task. This study addresses this challenge by providing a comprehensive overview of various simulation and experiment-based approaches aimed at understanding the characteristics of lithium-ion battery systems. The selection process involves considering factors such as required accuracy, insight into the battery, simulation time, and training or parameterization needs. The safety and performance of Li-ion batteries play a crucial role in the development of modern spacecraft, satellites, and electric vehicles. The study emphasizes the importance of reliability analysis and optimization for both internal and external complex structures in battery pack development. This is particularly critical during the design stage, especially when considering shock and vibration environments, to eliminate potential safety hazards. While existing studies have explored the mechanical behavior of battery pack structures under dynamic loading and random vibrations, and have established correlations between vibrations and reduced electrical performance in battery cells, they often overlook the mechanisms causing the performance reduction. The study identifies research opportunities in gaining a more comprehensive understanding of the mechanical degradation responsible for the decline in electrical performance. This understanding is essential for supporting the development of more robust electrical systems. Furthermore, the study suggests that future works should incorporate health monitoring of battery cells to assess the degradation of internal materials. Such insights hold significant importance for industries associated with Li-ion batteries, including aerospace, automotive, and renewable energy sectors.

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