batteries

Review

Advancements in Vibration Testing: Effects on Thermal Performance and Degradation of Modern Batteries

Khursheed Sabeel, Maher Al-Greer * and Imran Bashir

School of Computing, Engineering and Digital Technologies, Teesside University, Middlesbrough TS1 3BX, UK; k.sabeel@tees.ac.uk (K.S.); i.bashir@tees.ac.uk (I.B.)
* Correspondence: m.al-greer@tees.ac.uk

Abstract: Lithium-ion cells are increasingly being used as central power storage systems for modern applications, i.e., e-bikes, electric vehicles (EVs), satellites, and spacecraft, and they face significant and constant vibrations. This review examines how these vibrations affect the batteries' mechanical, thermal, and electrical properties. Vibrations can cause structural issues, such as the separation of electrodes and the deformation of separators. These problems raise internal resistance and lead to localized heat generation. As a result, thermal management becomes more complicated, battery aging accelerates, and safety risks arise, including short circuits and thermal runaways. To tackle these challenges, we need more realistic testing protocols that consider the combined effects of vibrations, temperature, and mechanical stress. Improving thermal management systems (TMSs) using advanced cooling techniques and materials, e.g., phase change solutions, can help to alleviate these problems. It is also essential to design batteries with vibration-resistant materials and enhanced structural integrity to boost their durability. Moreover, vibrations play a significant role in various degradation mechanisms, including dendrite formation, self-discharge, and lithium plating, all of which can reduce battery capacity and lifespan. Our current research builds on these insights using a multiscale physics-based modeling approach to investigate how vibrations interact with thermal behavior and contribute to battery degradation. By combining computational models with experimental data, we aim to develop strategies and tools to enhance lithium-ion batteries' safety, reliability, and longevity in challenging environments.

Keywords: battery vibration; battery safety; battery management system; thermal management battery degradation; safe battery; thermal runaway

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1. Introduction

Lithium-ion batteries in high-performance energy storage applications are subjected to continuous mechanical stress, particularly vibrations arising from real-world operating conditions. Unlike controlled laboratory settings, these environments expose batteries to fluctuating forces that gradually degrade their internal structure, leading to microfractures, electrode delamination, and separator deformation. Over time, these structural instabilities contribute to increased internal resistance, localized heating, and accelerated thermal degradation, compromising battery safety and performance. Traditional testing methods often fail to capture the full extent of vibration-induced degradation, so developing more advanced testing protocols that integrate mechanical, thermal, and electrochemical stress factors is essential. A deeper understanding of how vibrations influence battery failure mechanisms is crucial for improving thermal management strategies, enhancing material resilience, and extending battery lifespan in demanding applications.

1.1. Research Background

Lithium-ion (Li-ion) batteries have become the dominant energy storage technology in various applications, from consumer electronics, i.e., smartphones and laptops, to large-scale systems such as EVs and renewable energy storage [1]. Lithium-ion batteries have gained widespread popularity due to their numerous advantages, such as high energy density, long cycle life, low self-discharge rates, and minimal maintenance needs compared to rechargeable batteries such as nickel-cadmium or lead-acid. With the growing demand for clean energy solutions, these batteries have become essential in revolutionizing industries, especially transportation and power generation [2]. As the UK's Net Zero goal aims to achieve zero carbon by 2050, so battery energy storage technology is pivotal in this effort. For instance, EVs are a key strategy to reduce greenhouse gas emissions, and efficient energy storage is essential to harness the full potential of renewable energy sources, including wind and solar [3,4]. However, the rapid adoption of Li-ion batteries also brings challenges related to their performance, safety, and durability, especially when subjected to harsh environmental conditions or mechanical and electrical stresses [5,6]. The discrepancy in Figure 1 arises because estimated battery life is often based on ideal conditions—consistent moderate temperatures, optimal charging practices, and regular maintenance. By contrast, actual battery life reflects the impact of factors such as extreme weather, frequent rapid charging, and variable driving styles, all of which can accelerate battery wear and reduce longevity.

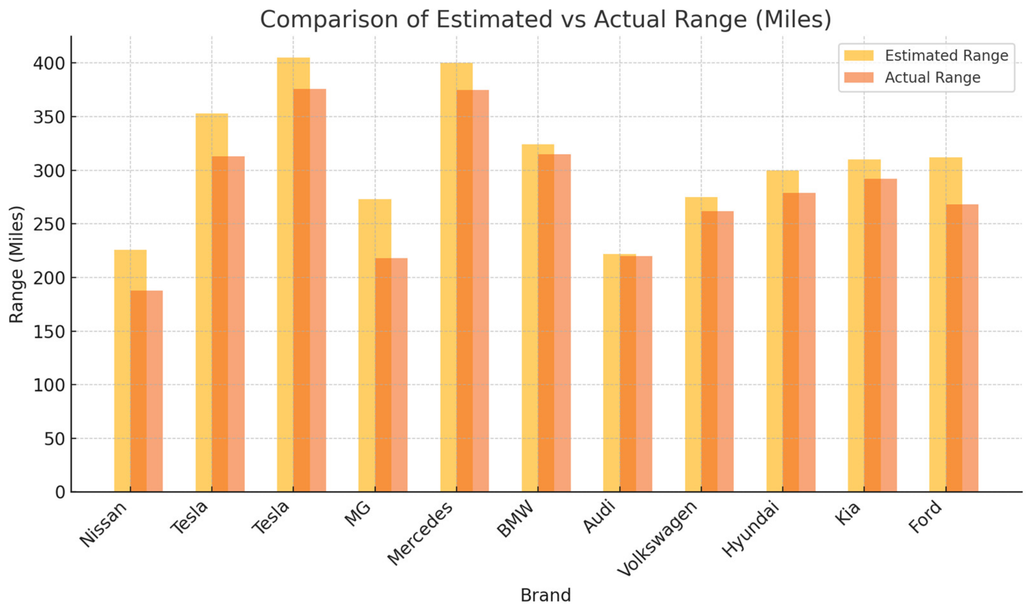

Figure 1. Comparison of estimated and actual range of EVs.

The difference between actual and estimated battery life in Figure 1 highlights how vibrations and factors, e.g., extreme weather and frequent rapid charging, contribute to battery degradation. This makes them critical factors in battery system design for EVs and other applications. This has driven significant efforts in recent years to improve battery modeling, enhance performance, and ensure safety while understanding how external factors impact battery life [7]. Li-ion batteries are sensitive to temperature, pressure, sudden electrical abuse, and other mechanical effects. Increased temperature can accelerate degradation and lead to thermal runaway, a dangerous situation during which the battery overheats and can catch fire or explode [8]. Proper TMSs are critical, especially in EVs. Brand et al. demonstrated that real-world vibrational loads could produce unique internal damage not typically seen in standardized testing. They emphasized the need for real-world vibration simulations to evaluate the true impact of mechanical stress on battery health [9]. It was found that prolonged vibrational stress leads to internal structural failures in lithium-ion batteries, such as short circuits and material displacement, with cylindrical cells especially at risk. He et al. developed an adaptive fuzzy inference model to assess lead-acid battery durability under vibrations, enabling accurate real-time detection without causing severe damage. This adaptable method offers potential for evaluating lithium-ion batteries, particularly as EVs face more complex mechanical environments [10]. Research on the robustness and safety of lithium-ion batteries across multiple applications emphasizes the importance of comprehensive testing for structural integrity and performance, especially under varied environmental stresses. Batteries undergo rigorous certification in aerospace and satellite applications, addressing potential failures due to vibration, short-circuiting, and extreme temperatures [11]. Vibration signal monitoring also serves as a novel method for pre-emptively diagnosing issues within lithium-ion cells, presenting a potential tool for battery management systems in high-stress applications [12]. This aligns with developments in transport shock and vibration monitoring systems, where MEMS technology is employed to enhance the sensitivity and precision of impact detection during transit [13]. The JARI Working Group introduced UN-standardized vibration testing, simulating multi-axial stress during transport. Their approach addressed large and small lithium-ion battery assemblies, setting the groundwork for consistent testing standards across different battery sizes and applications, from electric motorcycles to full-sized EVs [14]. Jung introduced numerical models to predict the performance of lithium-ion batteries with blended electrodes, demonstrating the application of these models in designing new batteries [15]. The team of researchers created a multistage vibration profile tailored for aviation, setting new standards for testing lithium-ion batteries in high-stress environments such as aircraft. Their research established a robust framework for evaluating battery performance, addressing criteria beyond typical vehicle application demands [16]. In an automotive context, pre-compliance vibration tests for LFP battery packs ensure long-term reliability by simulating real-world dynamic loads, thus helping to maintain structural stability during electric powertrain usage [17]. It was found that internal damage in 18650 lithium-ion cells, particularly in loosely designed mandrels, occurs without immediate performance decline under vibrations. Using computed tomography (CT) scans, researchers visualized subtle structural failures that became significant over time, emphasizing the need for robust internal cell design [18]. Electrochemical impedance spectroscopy (EIS) has become a pivotal tool in tracking internal resistance changes in cells subjected to vibrational forces, proving especially useful in EV battery health diagnostics [19]. Further research demonstrated that adding aluminum foam to TMS systems can reduce lithium-ion battery surface temperatures under mechanical stress, enhancing performance and lifespan. This method underscores the importance of temperature control in high-vibration environments such as EVs [20]. A comprehensive review examined temperature and vibrational effects on lithium-ion batteries, identifying a lack of studies combining these factors. The authors proposed a need for holistic thermal-mechanical coupled load testing, emphasizing that both temperature and vibrations are crucial for EV battery durability [21]. Sampath et al. presented a non-contact laser ultrasonic system for monitoring real-time state of charge (SOC). Their approach avoids the limitations of traditional contact-based testing, providing accurate SOC assessment while enhancing safety in EVs [22]. The Lithium-Ion Battery Analysis Guide advocated Fourier transform infrared (FTIR) techniques for monitoring chemical stability under long-term vibration, observing degradation in specific chemical bonds over time. This approach identifies early signs of failure, especially in high-frequency vibration environments [23]. Marco et al. documented unique failure patterns in motorcycle-specific vibration profiles, noting that these vibrations often cause higher battery failure rates than passenger vehicles. Their study provides insights for designing more durable battery systems tailored to two-wheeled transport needs [24]. High-impact research on six-degree-of-freedom vibrational stress revealed that battery aging accelerates under mechanical and thermal stresses, impacting internal resistance and capacity retention, which is critical for EV batteries [24,25]. Zhang et al. identified significant heat transfer improvements in PCM-based TMS systems when subjected to vibrations, suggesting enhanced cooling benefits in high-stress environments. This finding supports PCM's potential for managing EV battery temperatures efficiently without added energy costs [26]. Tian et al. examined dual-motor powertrain configurations in EVs, highlighting significant efficiency gains and reduced strain on battery systems. The dual-motor design enables more consistent power distribution, optimizing energy usage and extending battery life [27]. The 2023 Lithium-Ion Battery Analysis outlined QC protocols for lithium-ion batteries, including electrode material and separator testing. These methods ensure consistent battery quality, critical for safety and performance in large-scale EV deployments [28]. Further studies investigated the impact of vibrational stress on lithium battery cells' state of health (SOH), addressing its implications in applications such as EVs and aviation. Their findings suggest minor but noteworthy effects on charge capacity fade under vibrational conditions, pointing to mechanical vibrations as a factor that could influence ion transport within battery cells, impacting long-term performance. Furthermore, studies highlight the importance of environment-controlled testing setups for e-bike batteries, adhering to standards such as IEC 62133-2 and UN38.3 [29] for safe transportation and storage. Additional studies on the influence of operating conditions such as temperature and humidity further underline the need for robust seal designs to protect battery longevity, especially in flexible lithium-ion pouch cells [30]. Finally, feasibility analyses of lithium-ion batteries in unique environments, such as submarines, reveal that while these batteries provide high energy density and longevity, specific modifications are essential to meet stringent safety standards and functional requirements [31]. Zhao et al. proposed a method based on the vibration characteristics of over-discharged cells for fault detection in lithium-ion batteries. This method effectively distinguishes high-frequency vibration signals as indicators of potential over-discharge. It is suitable for integrating battery monitoring systems in EVs where safety is a concern due to high energy density and the potential for thermal runaway [32].

1.2. Research Hierarchy

Current gaps in lithium-ion battery testing pose significant risks for automakers, e.g., Tesla, Nissan, and Mercedes, as well as companies that build batteries for trucks, motorcycles, trains, cruise ships, and even space exploration.

The network visualization in Figure 2 illustrates the relationships and clustering of research topics related to lithium-ion batteries. The central themes "lithium-ion battery", "vibration", and "performance" connect to subtopics such as "safety", "EVs", and "durability". Each color represents a distinct cluster, showing how various concepts "temperature", "mechanical shock", and "battery packs" interlink across research areas. Current tests often fail to simulate the real-world effects on batteries' thermal behavior and degradation conditions, where batteries experience combined thermal and vibrational stresses that can accelerate degradation, compromise performance, and impact safety.

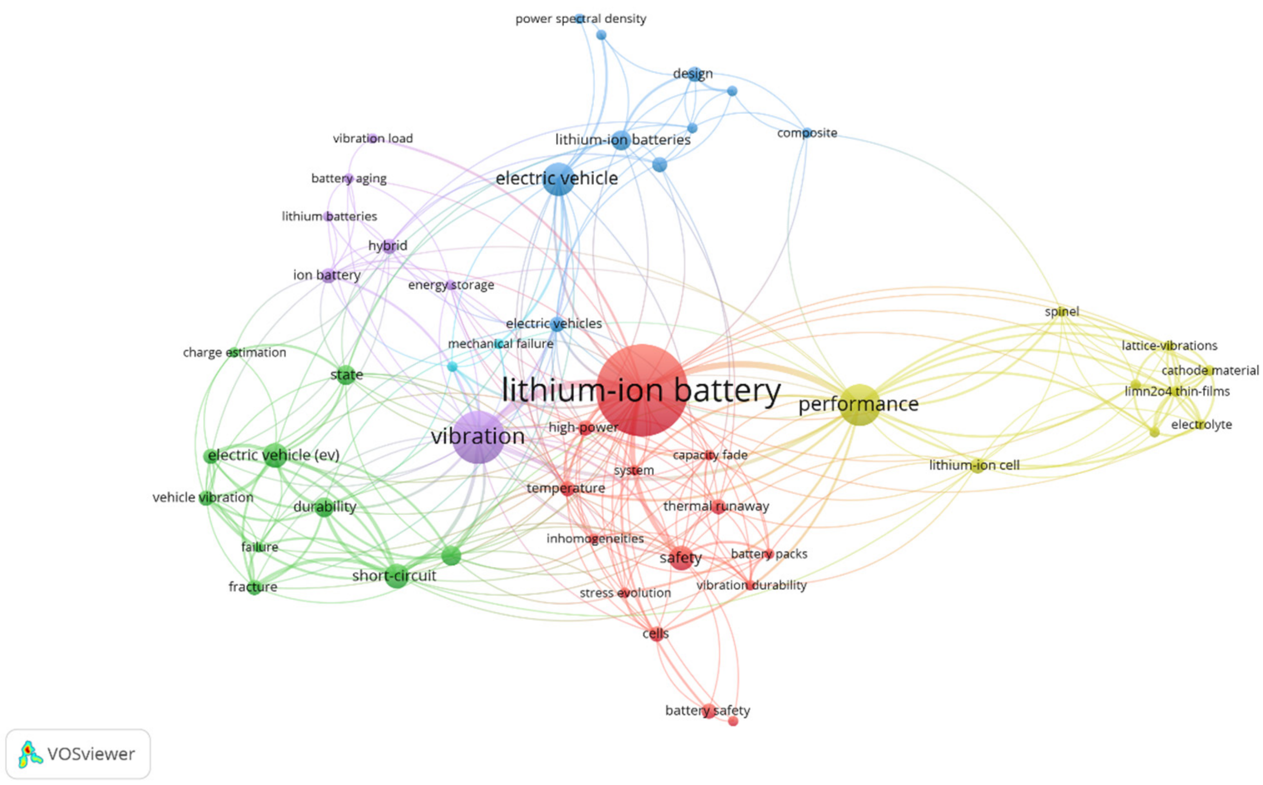

Figure 2. Literature focusing on lithium-ion battery vibration testing.

1.3. Research Motivation

Despite their growing market share and importance, there is limited comprehensive knowledge regarding how vibrations impact Li-ion batteries' mechanical integrity, safety, and electrical efficiency. Figure 3 depicts a traditional vibration testing method for batteries. It involves analyzing parameters such as voltage, current, state of charge (SOC), and temperature to monitor battery behavior. A vibration tuner sets and controls the vibration profile, which is applied to the battery using a vibrator. The battery tester evaluates the electrical and thermal responses of the battery under vibrations, such as capacity, resistance, and heating effects. The process includes a feedback loop where test data inform adjustments to improve accuracy and reliability.

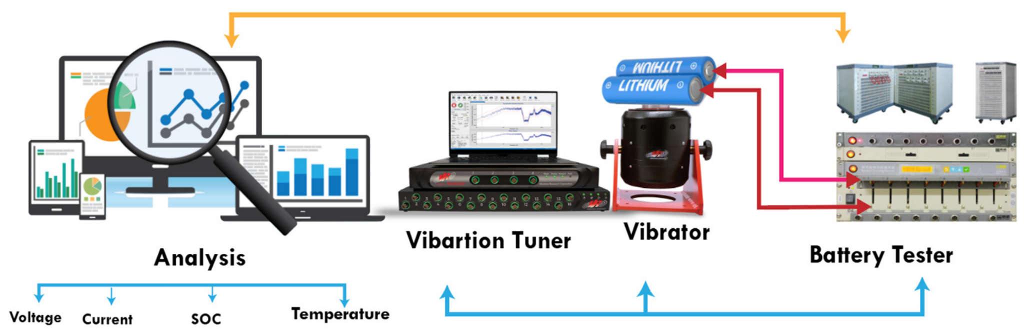

Figure 3. Traditional method used for battery vibration testing.

While a few studies have explored the fatigue and degradation of battery materials and pack structures under vibrational stress, the need to thoroughly assess and clarify the degradation mechanisms that compromise safety and performance remains critical [33].

1.4. Problem Statement

This review study aims to explore and synthesize the existing body of research on the thermal behavior and degradation mechanisms of lithium-ion batteries. It specifically focuses on the impact of vibrations, material behavior, and thermal properties on battery safety (BS) and performance, starting from modeling and examining its cycle performance under mechanical stress.

This study will explore simulation-based and hardware-based testing approaches utilized in the literature to model and assess the behavior of lithium-ion batteries under various mechanical and thermal stresses. This review will investigate the research landscape on thermal management and degradation in lithium-ion batteries, highlighting key findings related to the design of cells and packs and the thermal management strategies to mitigate these risks, as shown in Figure 4. A further application of [34] explores how mechanical and thermal factors contribute to the degradation processes observed in lithium-ion batteries. Furthermore, it will address these gaps by synthesizing industry and academia's latest computational, theoretical, and experimental research. It will offer valuable insights into how random vibrations and dynamic loads influence Li-ion batteries' mechanical and electrical characteristics, as shown in Figure 5 [35].

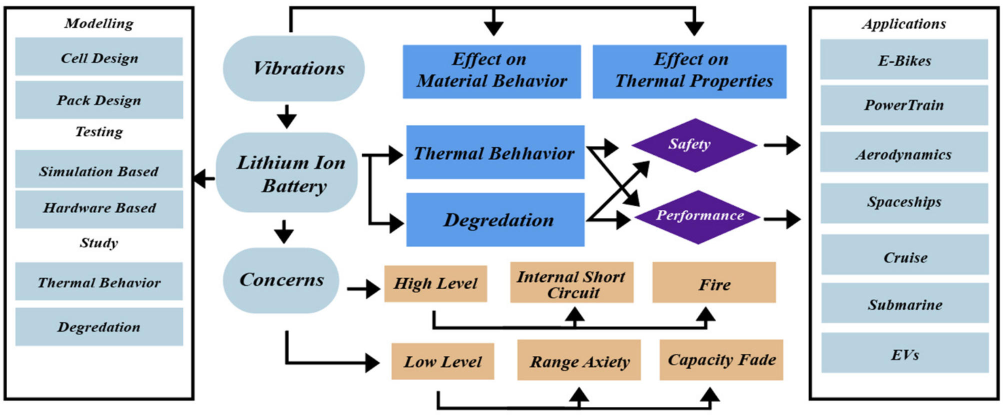

Figure 4. Methods of study for battery behavior under vibrations.

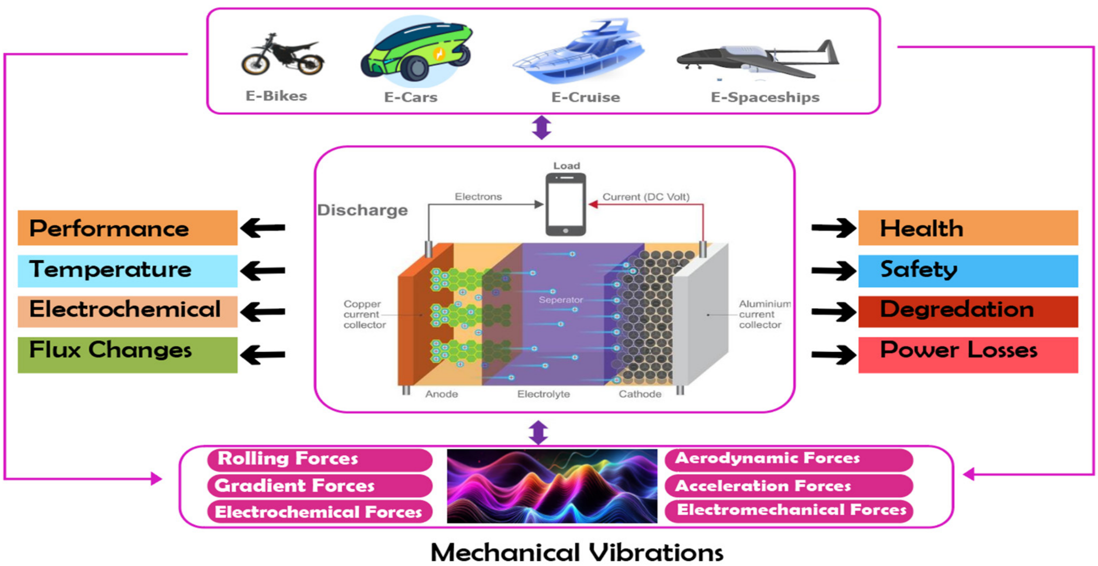

Figure 5. Importance of the study of vibrational impact on batteries.

Understanding these effects is crucial for advancing battery design and ensuring reliable performance in demanding environments.

1.5. Research Questions

The following research questions arise for this review study:

- What critical factors influence lithium-ion batteries' performance, thermal stability, and safety under vibrational conditions?
- To what extent do mechanical vibrations adversely impact the structural integrity, thermal behavior, and electrochemical performance of batteries?
- How do mechanical vibrations contribute to thermal runaway, electrochemical degradation, and long-term battery lifespan?
- Do vibrational forces compromise battery safety, operational range, and reliability in practical applications?

Figure 6 [36] highlights the importance of vibration studies and acoustic pressure in enhancing the performance of lithium-ion batteries for ships, airplanes, electric vehicles (EVs), and flying cars. Vibrations and noise can negatively affect battery performance, causing degradation or failure. Structural battery composites, which combine energy storage with structural support, must withstand these stresses. Vibration studies help to create batteries that endure mechanical forces and acoustic pressures in harsh environments. This research ensures that batteries are durable, efficient, and safe for ships, airplanes, and EVs. In flying electric vehicles, these studies are crucial for ensuring battery reliability during flight and ground operations, improving performance and safety across all applications.

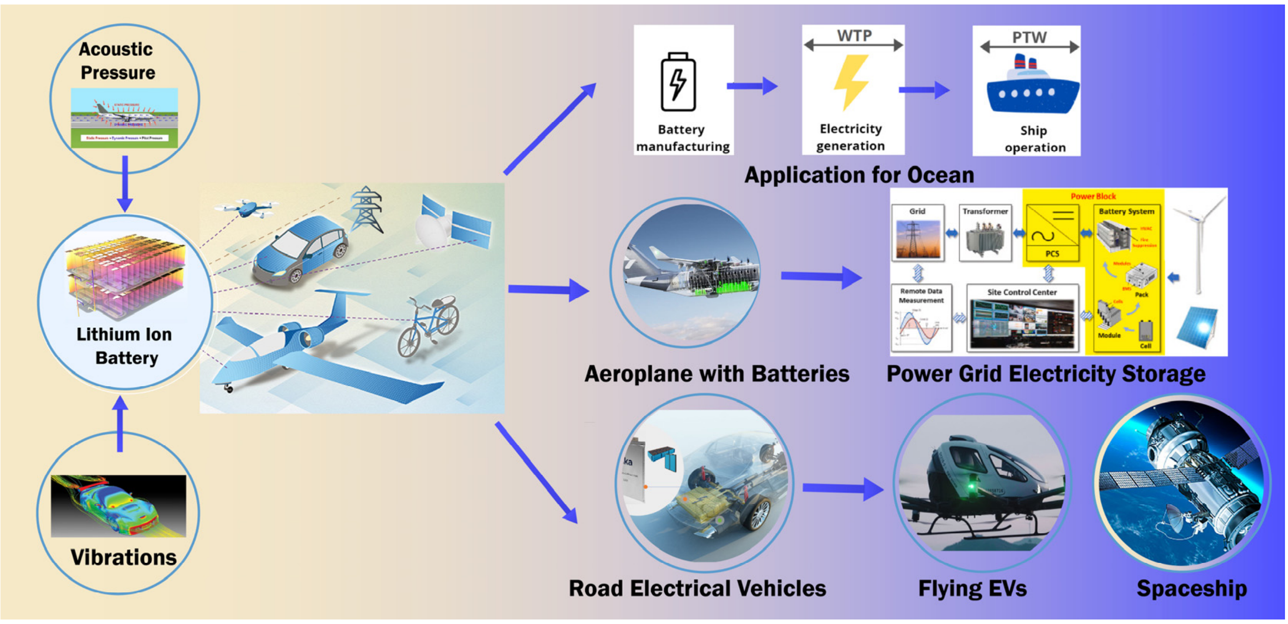

Figure 6. Application of battery vibration studies.

1.6. Research Aim and Objectives

This review highlights existing knowledge gaps and comprehensively understands how vibrations influence lithium-ion batteries' electrical and thermal behaviors in modern applications. This can be summarized as follows:

- Identify factors impacting battery performance and safety under vibrations.
- Assess the harmful effects of vibrations on battery systems.
- Investigate the effect of vibrations on the thermal behavior and degradation of batteries.
- Determine if vibrations compromise battery range, safety, and operational reliability.
- Review existing research on degradation mechanisms due to vibrations.

Section 2 explores advancements in battery modeling and vibration analysis, focusing on computational techniques like finite element analysis (FEA) and real-time monitoring to predict battery degradation. Section 3 examines how vibrations impact thermal behavior, leading to localized heating, electrolyte instability, and thermal runaway risks. Section 4 discusses degradation mechanisms, highlighting structural fatigue, electrode detachment, and electrolyte breakdown due to repeated mechanical stress. Section 5 links vibrations to thermal runaway, demonstrating how prolonged mechanical fatigue increases the risk of internal short circuits and heat propagation. Section 6 evaluates vibration-induced degradation in real-world applications, particularly its impact on charge cycles and energy retention in EVs and aerospace systems. Section 7 synthesizes the findings, identifying research gaps and assessing mitigation strategies. Section 8 recommends improvements in materials, structural reinforcements, and predictive modeling for enhanced battery resilience. Section 9 summarizes key insights, emphasizing the need for continued research to mitigate vibration-induced failures in lithium-ion batteries

2. Recent Advancements in Battery Modeling and Vibration Testing

Lithium-ion batteries are vital for energy storage in EVs and renewable systems, offering high energy density and long lifespans. However, real-world stresses and corresponding vibrations can cause structural damage, overheating, and accelerated degradation. Addressing these challenges requires advanced testing, improved designs, and modeling tools to enhance reliability and predict performance under various conditions [37].

2.1. Advanced Battery Modeling Techniques

Battery models now incorporate multiscale and multiphysics approaches, combining electrochemical, thermal, and mechanical factors to review Li-ion batteries' operation comprehensively [38]. Traditional models, starting from primary batteries and their equivalent circuit model (ECM), are still widely used for real-time applications because of their simplicity [39]. Still, more advanced models, like electrochemical-thermal models, have gained prominence due to their ability to simulate the behavior of batteries at a much deeper level [40]. These models can capture the interactions between the electrodes, electrolyte, and separator materials and the heat generation and mechanical stresses that occur during charging and discharging cycles.

Figure 7 provides an overview of the key considerations in the lifecycle of lithium-ion batteries, from raw materials to vehicle applications. It highlights critical aspects such as material sourcing, processing, and ethics; the development of precursors; electrode and component manufacturing; and cell formation and consistency. One of the breakthroughs in recent battery modeling is the development of physics-based models that can predict degradation mechanisms over time. This includes simulating solid–electrolyte interphase (SEI) layer growth, lithium plating, and capacity fade [41]. Models identical to these are invaluable for understanding long-term battery health and optimizing battery management systems (BMSs) that prolong battery life by controlling operational conditions as charging rates and temperature [42].

The bar graph in Figure 8 shows Europe's projected battery cell production capacities by format (cylindrical, prismatic, pouch, and unknown) from 2018 to 2030, reflecting the growing demand for EVs and energy storage. Moreover, machine learning and artificial intelligence advancements have been integrated into battery modeling to enhance predictive capabilities further. By analyzing large datasets generated from battery usage, machine learning algorithms can identify patterns and predict battery performance and failure modes with greater accuracy [43]. Integrating data-driven approaches with traditional models represents a significant step in improving battery design and lifecycle management.

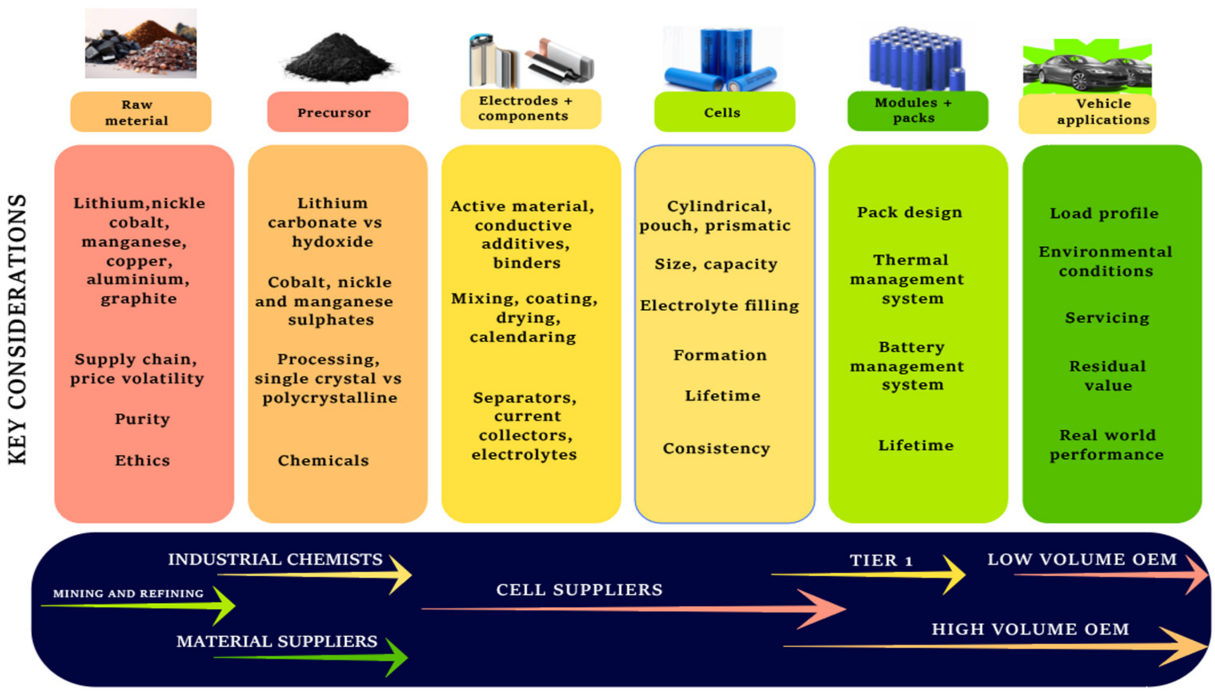

Figure 7. Battery cell modeling according to applications.

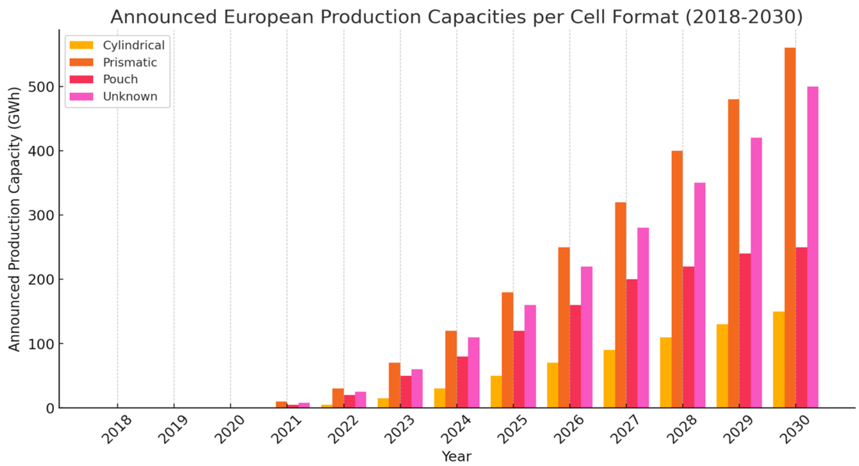

Figure 8. Battery cell design types and production used in different EVS models.

Recent advancements, as shown in Figure 9, in physics-based battery modeling have focused on integrating multiple domains, such as electrochemical, electromechanical, and electromagnetic physics, alongside AI-driven analytics to create highly accurate and predictive models. Electrochemical modeling captures charge transport and reaction kinetics, while electromechanical coupling accounts for stress and strain effects on battery components due to intercalation and thermal expansion. Electromagnetic analysis is used to study high-frequency effects and optimize current collection. This multidisciplinary approach offers enhanced insights into battery behavior, aiding in the design of safer, more efficient, and longer-lasting energy storage systems. Vibrational studies using COMSOL Multiphysics involve coupling mechanical, thermal, and electrochemical physics to analyze the effects of vibrations on battery performance and degradation. The process begins with a detailed geometry definition, including electrodes, separator, and casing, followed by assigning materials with properties such as Young's modulus, thermal conductivity, and diffusivity, which may be temperature or stress dependent. The Solid Mechanics interface is used to model vibrational loads through harmonic forces or sinusoidal displacements, with modal analysis identifying natural frequencies to avoid resonance. The Heat Transfer interface is included to model heat generation from electrochemical reactions and mechanical friction, while cooling mechanisms such as convection are applied to mimic thermal management. Coupling is achieved using the Thermal Stress multiphysics interface for thermal–mechanical interactions and manual linking of stress fields to degradation parameters in the Electrochemistry interface, accounting for stress-enhanced SEI layer growth or lithium diffusivity change.

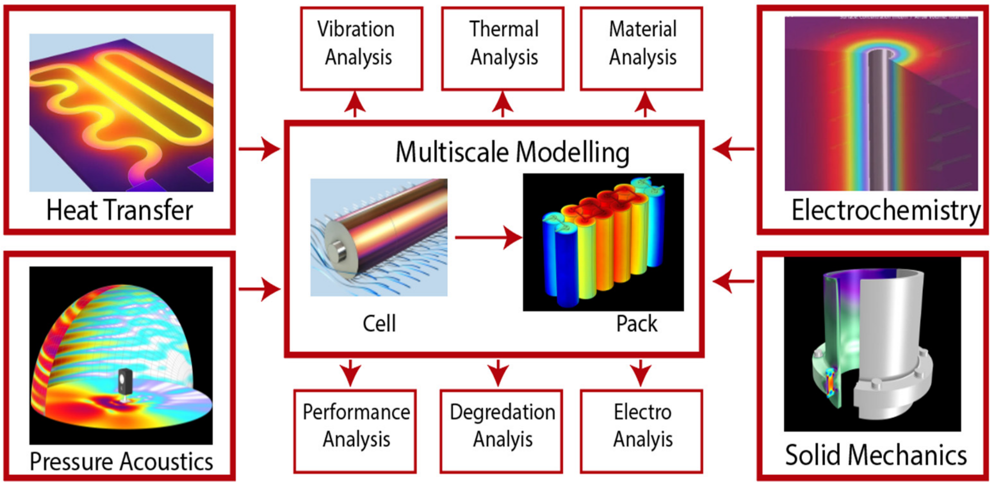

Figure 9. Physics-based battery modeling and analysis.

2.2. Battery Testing Procedures in COMSOL Multiphysics

COMSOL Multiphysics offers a range of methods and features to study vibrations inside systems such as batteries, combining advanced simulation capabilities in the Solid Mechanics, Heat Transfer, and Electrochemistry interfaces:

- Modal Analysis: Identifies natural frequencies and mode shapes to avoid resonance and localize vibration-sensitive areas [44,45].
- Frequency Domain Analysis: Models system responses to harmonic vibrations and identifies critical frequencies where thermal or mechanical failure occurs [46].
- Time-Dependent (Transient) Analysis: Captures real-time responses to shocks or impacts, such as stress wave propagation and transient heating [47].
- Multiphysics Coupling: Integrates the Solid Mechanics, Heat Transfer, and Electrochemistry interfaces for coupled thermal-stress effects, stress-enhanced degradation, and fatigue analysis [48].
- Parametric and Sensitivity Analysis: Explores effects of varying vibration amplitudes, frequencies, and material properties on battery behavior [49].
- Meshing and Solver Techniques: Includes adaptive meshing for stress hotspots and segregated solvers for large-scale multiphysics problems [50].

Vibration analysis is crucial for assessing lithium-ion battery performance, especially in high-stress applications like EVs and aerospace. The modal analysis identifies natural frequencies to prevent resonance-induced failures, while frequency domain analysis detects critical vibration points that may cause mechanical or thermal issues. Time-dependent analysis captures real-time responses to shocks and impacts, improving safety assessments. Multiphysics coupling integrates the Solid Mechanics, Heat Transfer, and Electrochemistry interfaces to study stress-induced degradation, enhancing lifespan predictions. Parametric analysis optimizes battery design by evaluating the effects of vibration amplitude, frequency, and material properties.

2.3. Battery Performance and Safety

One of the core challenges in battery performance is improving energy density, power density, choking time, and cycle life, which directly affects how much energy the battery can store relative to its weight or volume. Energy density (E) is defined as follows:

$$E = C \cdot V \tag{1}$$

where C is the battery capacity (in ampere hours), and V is the nominal voltage (in volts). While reliable, traditional lithium cobalt oxide (LCO) cathodes offer limited capacity, nickel-rich layered oxides, such as nickel-manganese-cobalt (NMC) cathodes, have demonstrated significantly higher capacities due to their ability to store more lithium ions [51]. Improving the performance of Li-ion batteries has been a primary focus of research and development, especially in the context of increasing energy density, enhancing charging speed, and extending cycle life [52]. Understanding the effects of mechanical vibrations on batteries is critical, particularly for drones used in agriculture. As shown in [53], agricultural drones experience varying operating conditions, making vibration analysis essential for assessing battery performance and reliability. Energy density remains one of the most critical performance metrics, as it determines how much energy the battery can store relative to its size and weight [54]. Advancements in materials science have led to the development of high-performance cathode materials, such as nickel-rich layered oxides, which offer higher energy capacities than traditional lithium cobalt oxide (LCO) cathodes. However, silicon's significant expansion (up to 300%) during lithiation presents challenges, as this expansion leads to mechanical stresses that degrade the anode's structural integrity over time. On the anode side, the shift from graphite to silicon-based anodes offers the potential for dramatic increases in energy density. Silicon's theoretical capacity (4200 mAh/g) is much higher than that of graphite (372 mAh/g) [55]. However, silicon's significant expansion (up to 300%) during lithiation presents challenges, as this expansion leads to mechanical stresses that degrade the anode's structural integrity over time. The following degradation rate model can describe the relationship between battery capacity and cycle life:

$$C_n = C_o\left(1 - \frac{n}{L}\right) \tag{2}$$

where C_n is the capacity of the battery after (n) discharge, and C_o is the capacity at the start. On the anode side, the shift from graphite to silicon-based anodes holds great promise for significantly increasing energy density. Silicon has a much higher theoretical capacity for lithium storage than graphite. Additionally, electrolyte improvements, such as developing solid-state electrolytes, enhance battery performance by addressing safety concerns associated with liquid electrolytes [56]. Solid-state batteries offer the potential for higher energy densities and improved safety by eliminating the flammable liquid electrolyte used in conventional Li-ion batteries.

Although still in the research and development phase, solid-state technologies are expected to transform battery performance in the coming years. Figure 10 [57] shows how the driving range of a new battery is limited by reserving a grace capacity. After approximately 900 cycles, the upper grace capacity starts to be utilized. Software adjustments can extend the battery's lifespan by adding more grace capacity, as depicted in the graph, but this comes at the cost of reducing the driving range. Battery safety remains a critical concern in developing Li-ion technology, mainly because of the risks associated with thermal runaway [58]. Lithium-ion batteries generate heat; this heat can degrade performance and shorten the battery's lifespan if not effectively managed. Heat generation can be modeled as follows:

$$Q_{heat} = I^2 R_{int} \tag{3}$$

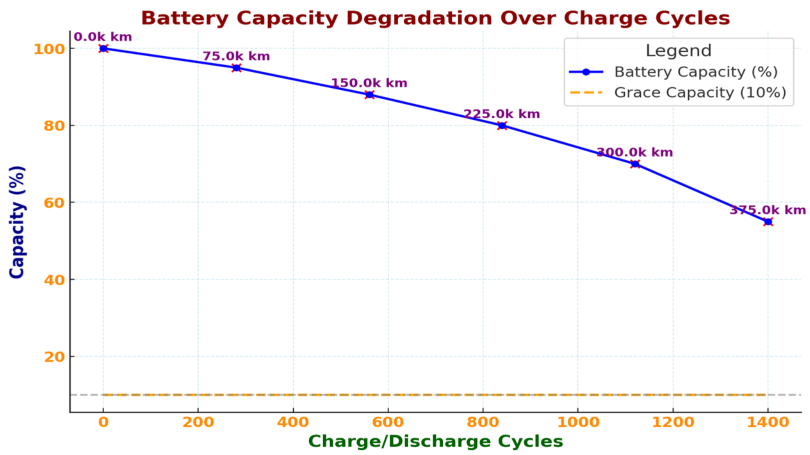

Figure 10. Energy band of an aging EV battery.

2.4. Battery Thermal Runaway

Thermal runaway is a self-propagating reaction when the battery's internal temperature rises uncontrollably due to internal short circuits, overcharging, or external heat exposure [47]. This process can lead to battery fires or explosions if not managed effectively. Battery safety has always been a key concern in developing and deploying Li-ion batteries, mainly because of the risks associated with thermal runaway due to the internal chemical process, as shown in Figure 11.

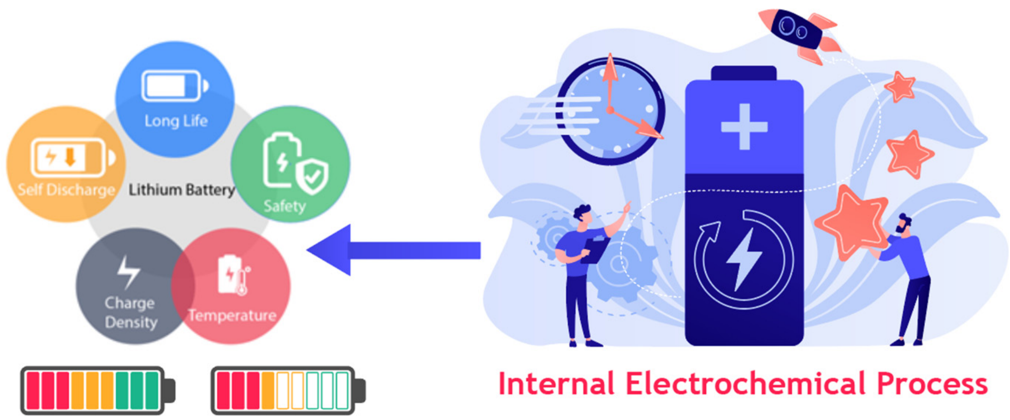

Figure 11. Safety and performance parameters of lithium batteries.

These safety features can lead to overheating, fire, or explosion if subjected to electrical or mechanical abuse [59]. Ensuring battery safety has become even more critical as the number of large battery packs in EVs and grid storage systems has increased. Recent advancements in safety mechanisms include integrating TMSs that actively regulate battery temperature during operation [60]. Lithium-ion batteries degrade over time, affecting their performance, as shown in Figure 11, due to an unknown self-internal process. The two main factors contributing to degradation in EVs are calendar aging (degradation over time, even when the battery is not in use) and cycle aging (degradation due to repeated charging and discharging).

$$k = Ae^{-\frac{E_a}{RT}} \tag{4}$$

The Arrhenius equation [61] is often used to describe how temperature accelerates the degradation rate, with higher temperatures leading to faster capacity loss. These systems use liquid cooling, phase change materials, or heat pipes to dissipate heat effectively and prevent hotspots from forming within the battery pack. BMSs also play a crucial role in safety by monitoring voltage, temperature, and current levels to detect and prevent abnormal conditions that could lead to failure. The graph in [62] shows how temperature affects battery capacity and life. Capacity is highest between 20 °C and 35 °C and decreases at extreme temperatures. Battery life drops significantly at temperatures above 30 °C and below −20 °C. Another area of focus in improving safety is the development of safer electrolyte formulations, including non-flammable electrolytes and additives that suppress dendrite formation—needle-like structures that can pierce the separator and cause short circuits [63]. These innovations and robust safety testing standards have significantly reduced the risk of catastrophic battery failure.

The section highlights how vibrations accelerate lithium-ion battery degradation, impacting structural integrity, thermal performance, and long-term reliability in EVs and aerospace applications. By integrating multiphysics modeling, advanced testing protocols, and AI-driven predictive tools, researchers can better assess failure risk and develop strategies to enhance battery safety and durability. Addressing these challenges requires vibration-resistant materials, improved thermal management systems, and optimized battery designs to ensure stable performance in high-vibration environments. The following section will focus on vibrations and their effects on thermal behavior and material properties. It will examine how mechanical stress influences heat generation, electrolyte stability, and structural fatigue, leading to performance loss and safety concerns in lithium-ion batteries.

3. Vibrations and Their Effects on Thermal Behavior and Material Properties

Vibrations refer to mechanical oscillations in systems due to dynamic forces, mechanical stress, or external excitations. In engineering systems, vibrations can arise from operational machinery, external environmental factors, or inherent material behavior [64]. Vibrations can significantly affect components' thermal behavior and material properties in automotive systems, aerospace, and battery technology applications. Heat generation due to vibrations can be explained using principles from thermodynamics and mechanics [65]. The following equation represents the heat generated in a material due to damping (energy dissipation) caused by vibrations:

$$Q_{vibration} = \frac{1}{2} m a^2 C_{damp} \tag{5}$$

where $Q_{vibration}$ is the heat generated by vibrations, m is the mass of a vibrating object, a is the amplitude of vibration, and C_{damp} is the damping coefficient. This equation shows that the heat generated is proportional to the vibration amplitude and frequency, meaning that higher vibrations (more significant a or f) lead to increased heat production.

Studies [66,67] have proven that an annular heat exchanger is effective for thermal energy storage systems operating at low frequencies. The phase change material (PCM) melts faster in this configuration than in a cubic one. The study demonstrated temperature contours and the solid–liquid melting interface, showing accelerated melting at low frequencies in the annular setup, enhancing heat transfer efficiency [67]. In systems, i.e., batteries, increased vibration-induced heat raises the internal temperature, which increases internal resistance (R_{int}). As the resistance increases, Joule heating generates more heat [68].

Figure 12 [69,70] presents how battery performance and safety issues affect vehicle types, such as 2-wheelers, 3-wheelers, and electric vehicles (EVs). Vibrational stress, thermal challenges, and other degradation mechanisms occur on uneven roads. This increase in temperature can accelerate material degradation, reduce efficiency, and lead to thermal runaway in extreme cases, especially in temperature-sensitive systems corresponding lithium-ion batteries. Prolonged exposure to vibrations can also lead to thermal fatigue [71].

As materials heat up due to vibrational energy, repeated thermal cycling (heating and cooling) can cause cracks or degradation, especially in materials that experience cyclic stress, such as metals and composites. Materials exposed to constant vibrations experience cyclic loading, which leads to mechanical fatigue. Fatigue is the weakening of a material caused by repeated loading and unloading cycles, leading to microcrack formation and, eventually, structural failure. By enhancing natural convection heat transfer, vibrations reduce temperature rise and create a more consistent thermal environment. Specifically, a vibration frequency of 10 Hz results in a marked cooling effect, while a frequency of 50 Hz optimizes temperature uniformity. Additionally, increased vibration amplitude further contributes to thermal stability, reducing the battery's peak temperatures and temperature differentials. Fatigue can be modeled using the S–N curve (stress–life curve) [72], which represents the relationship between the cyclic stress (σ) and the number of cycles to failure (N):

$$\sigma \cdot N^{b} = C \tag{6}$$

where σ is the applied cyclic stress (in Pa), N is the number of cycles to failure, b is a material-dependent fatigue exponent, and C is a constant related to the material's properties. The combined effects of vibrations and thermal cycling cause thermo-mechanical fatigue, a key failure mode in high-performance materials and systems such as turbines, engines, and battery systems. Thermo-mechanical fatigue can be modeled by combining the mechanical stress and thermal cycling effects, as follows:

$$\epsilon_{total} = \epsilon_{mechanical} + \epsilon_{thermal} + \epsilon_{vibration} \tag{7}$$

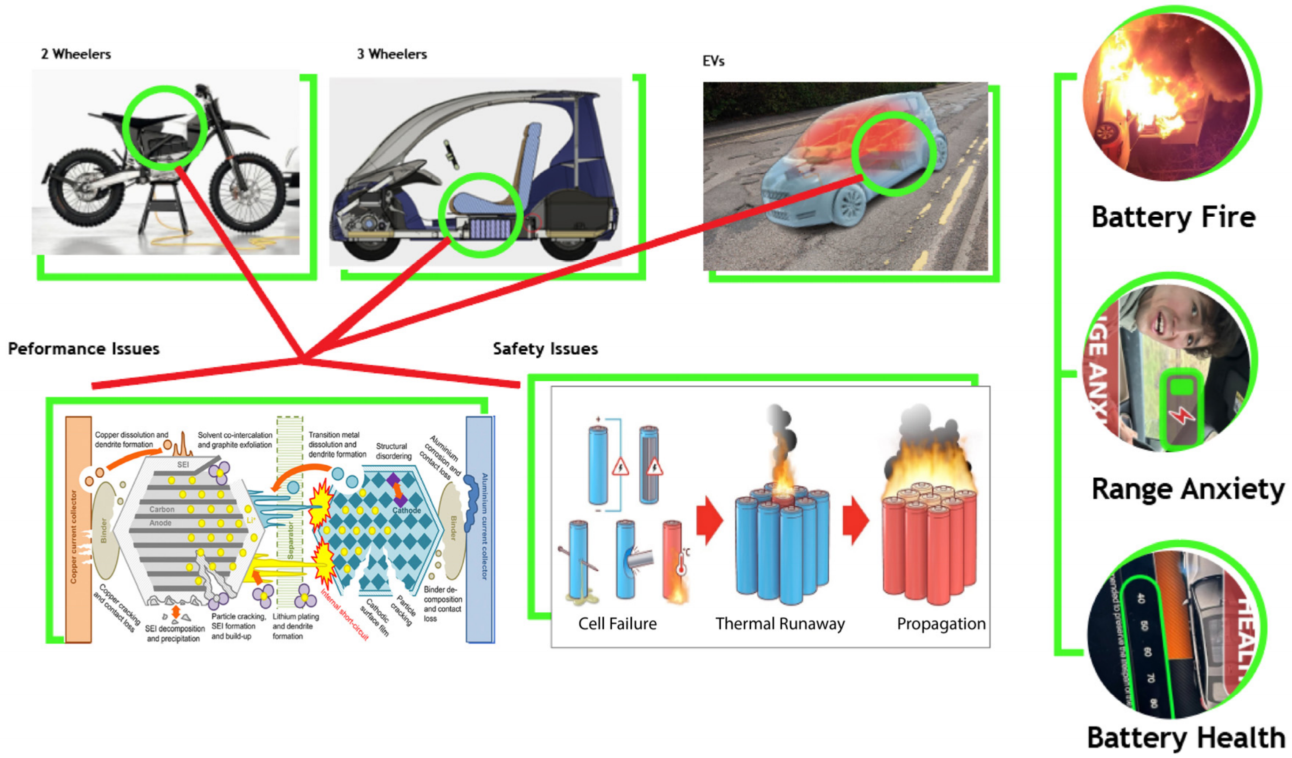

Figure 12. Effect of shocks and mechanical vibrations on batteries and related issues.

The interaction of these two factors accelerates the material degradation rate, particularly in temperature-sensitive components, such as lithium-ion battery cells and turbine blades. Repeated vibrations may cause plastic deformation in materials, particularly metals and alloys. Plastic deformation occurs when a material undergoes permanent strain after being subjected to stresses beyond its yield strength. Vibrations can lead to plastic deformation by causing localized yielding due to cyclic loading. The stress–strain relationship for plastic deformation can be modeled as follows:

$$\sigma = E \cdot \epsilon \tag{8}$$

where σ is the stress applied to the material (in Pa), *E* in Young's modulus (in Pa), and ϵ is the strain experienced by the material. As cyclic loading continues, the material may yield and deform plastically, leading to loss of structural integrity, lower strength, and failure.

3.1. External Mechanical and Electrical Effects on Batteries

Li-ion batteries, especially in demanding applications such as EVs and aerospace, are often exposed to external mechanical and electrical abuses. Mechanical abuse can come in the form of vibrations, which may cause physical damage to battery components, such as electrode cracking or separator degradation. These effects can lead to internal short circuits, capacity loss, and safety hazards. Studies have shown that batteries subjected to repeated mechanical stresses can experience accelerated degradation, reducing their effective lifespan [71]. Electrical abuse, such as overcharging, over-discharging, or operating the battery outside its recommended voltage window, also harms battery life. Overcharging can lead to lithium plating on the anode, which reduces capacity and increases the risk of internal short circuits, while over-discharging can cause irreversible damage to the cathode material, making it difficult for the battery to regain its original capacity [73]. Addressing these issues requires the development of more resilient battery designs and improved management systems that can protect against these external stresses. By integrating advanced sensors and control algorithms, battery management systems can detect and mitigate mechanical and electrical abuses before they cause considerable damage.

3.1.1. Thermal Effects on Lithium-Ion Battery Performance and Safety

Temperature plays a pivotal role in determining the electrochemical performance of lithium-ion batteries, directly influencing key metrics such as capacity, power output, charge rate, and efficiency. The operating temperature of a Li-ion battery has distinct effects depending on whether the temperature deviates toward higher or lower extremes.

3.1.2. Low-Temperature Performance Degradation

At low temperatures, particularly below 0 °C, the performance of Li-ion batteries is notably diminished. The reduced ionic conductivity of the electrolyte at these temperatures slows down lithium-ion mobility between the cathode and anode, decreasing overall capacity and power output [74]. Moreover, the increased internal impedance limits the discharge power, particularly in high-power applications such as EVs and energy storage systems (ESSs). Cold conditions also impair the efficiency of charging processes, as the sluggish kinetics of the intercalation reactions lead to poor charge acceptance. Critically, lithium plating on the anode can occur when fast charging is attempted under such conditions, causing irreversible capacity loss and contributing to safety hazards [75].

3.2. High Temperature and Accelerated Degradation

High-temperature operation (above 40 °C) introduces a separate set of challenges. Elevated temperatures accelerate the chemical reactions inside the battery, temporarily increasing ion transport and enhancing capacity in the short term [76]. However, prolonged exposure to high temperatures leads to faster degradation of the electrolyte, cathode, and anode materials. This accelerates the formation of the solid–electrolyte interphase (SEI) layer on the anode, consuming active lithium and reducing the amount available for reversible intercalation. Consequently, the battery's cycle life is shortened, as is its ability to maintain capacity over extended usage periods.

3.2.1. Thermal Effects on Safety

The safety of lithium-ion batteries is intimately tied to their thermal behavior, with extreme temperatures posing significant risks. Both high and low temperature extremes can initiate processes that compromise the structural integrity of the battery, increasing the possibility of failure modes such as thermal runaway, internal short circuits, and, in the worst case, fire or explosion [77]. These reactions generate further heat, leading to a cascading rise in temperature. The initial trigger for thermal runaway is often overheating, whether due to high ambient temperatures, excessive current loads, or internal short circuits [78]. As the temperature rises, the separator that physically isolates the cathode and anode may melt or become deformed, leading to internal shorting.

3.2.2. Impact of Overcharging and Temperature Synergy

Another significant safety concern arises from the synergistic effects of overcharging and high-temperature conditions. Overcharging leads to an excessive accumulation of lithium ions at the anode, which increases the possibility of lithium plating. This process reduces capacity and heightens the risk of internal short circuits [79]. This can trigger thermal runaway in combination with high temperatures. Moreover, high charging rates at elevated temperatures compound the risks by inducing localized hotspots within the cell, which can lead to the breakdown of materials and gas generation.

3.2.3. Long-Term Effects of Temperature on Cycle Life

The long-term impact of temperature on lithium-ion batteries is most evident in cycle life degradation. Elevated temperatures accelerate the deterioration of active materials and promote side reactions that consume electrolytes and lithium, reducing the battery's ability to maintain capacity over multiple charge–discharge cycles [80]. Conversely, while temporarily reducing capacity and power output, low temperatures can contribute to long-term degradation through lithium plating and increased internal resistance. Therefore, effective thermal management is essential for maintaining immediate performance and extending the usable life of lithium-ion batteries [81].

This section explored how vibrations impact lithium-ion batteries' thermal behavior and material properties. Vibrational stress increases internal resistance and Joule heating, leading to uneven heat distribution and accelerated thermal degradation. Prolonged exposure weakens material integrity, causing microcracks, electrode delamination, and separator damage, which contribute to capacity loss and thermal runaway risks. Additionally, cyclic loading and thermal fatigue further degrade structural components, reducing battery lifespan. Addressing these challenges requires vibration-resistant materials, optimized battery enclosures, and advanced cooling techniques to enhance battery durability. The following section will focus on degradation mechanisms in lithium-ion batteries under vibrations, examining how electrode deterioration, electrolyte instability, and mechanical fatigue contribute to long-term performance decline.

4. Mechanisms of Degradation in Lithium-Ion Batteries Under Vibrations

Degradation in lithium-ion batteries arises from several interacting mechanisms that gradually impair their performance and safety over time. These processes are typically divided into calendar aging (degradation over time regardless of use) and cycle aging (degradation resulting from repeated charge and discharge cycles).

4.1. Process of Degradation in Batteries

The primary degradation mechanisms include loss of active lithium, electrode material degradation, solid–electrolyte interphase (SEI) layer growth, lithium plating, and electrolyte decomposition. These mechanisms result in progressive capacity, power output, and efficiency decline while introducing significant safety risks [82].

Figure 13 presents the degradation mechanism in lithium-ion batteries, highlighting key processes that lead to capacity loss, safety risk, and failure. It shows that overcharging and high-rate charging cause excessive lithium deposition, leading to dendrite formation, which can penetrate the separator and cause internal short circuits. Low-temperature charging slows lithium-ion diffusion, increasing the likelihood of lithium plating, during which inactive lithium accumulates on the anode, further contributing to performance degradation [83]. The SEI (solid–electrolyte interphase) layer forms on the anode surface and is essential for battery stability. Still, its non-uniform growth or degradation leads to increased resistance, lithium loss, and reduced battery efficiency. Self-discharge and non-uniform discharging create local high-current regions, accelerating dendrite growth and separator damage. Temperature fluctuations further degrade the SEI layer and increase stress on the battery components, leading to structural instability and a higher risk of thermal runaway [84,85]. These interconnected degradation mechanisms significantly affect battery lifespan and safety, underscoring the importance of proper charging protocols, effective thermal management, and advanced materials to mitigate performance decline and improve the reliability of lithium-ion batteries.

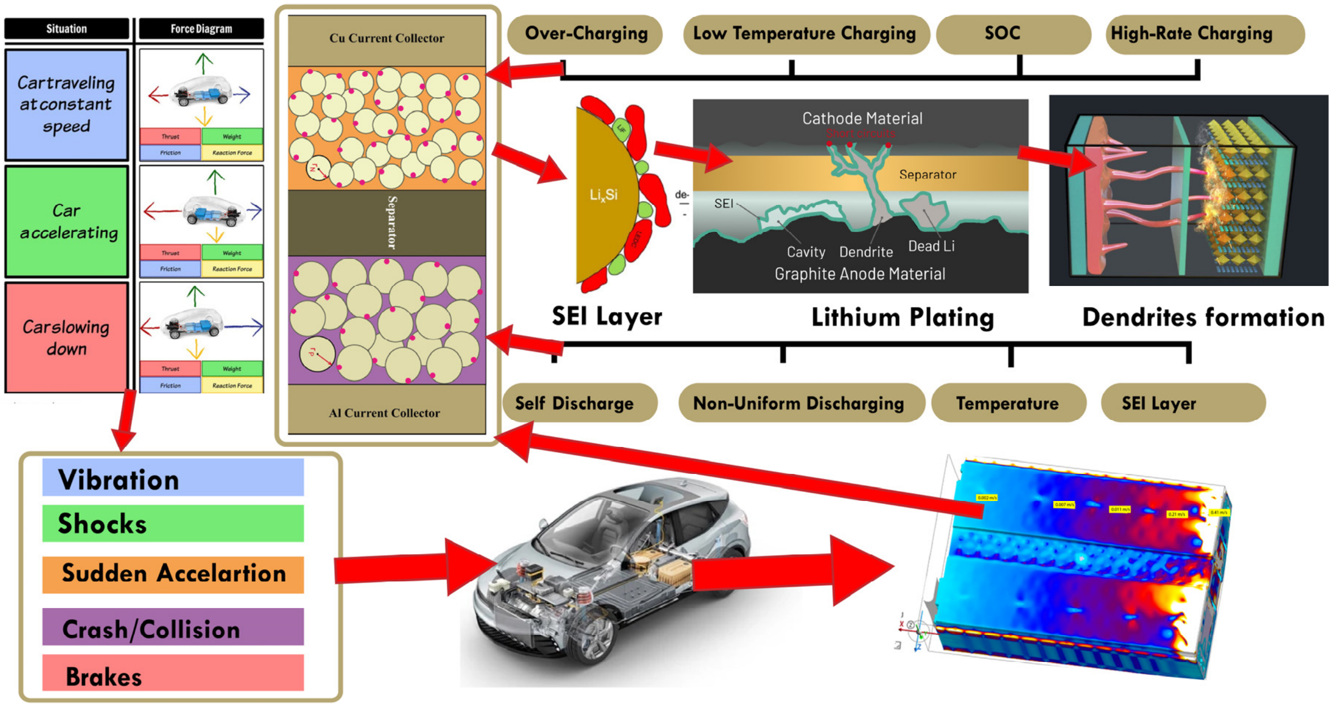

Figure 13. Mechanism of battery degradation.

4.1.1. Solid–Electrolyte Interphase (SEI) Layer Growth

One of the most critical degradation mechanisms is the formation and growth of the SEI layer on the anode, typically made of graphite. The SEI is initially formed during the first few charge–discharge cycles, acting as a protective barrier that allows lithium-ion transport while preventing further electrolyte decomposition [86]. However, over time and with repeated cycling, the SEI layer grows thicker as it continually consumes lithium ions and electrolyte components, resulting in the loss of active lithium. This process reduces the available lithium for electrochemical reactions, lowering the battery's capacity. Excessive SEI layer growth can increase internal resistance, reducing the battery's power delivery capabilities.

4.1.2. Electrode Material Degradation

Degradation of electrode materials, particularly the cathode, significantly reduces capacity and efficiency. Cathode materials, such as lithium cobalt oxide ($LiCoO_2$) or nickel manganese cobalt (NMC) oxide, undergo structural changes due to repeated lithium insertion and extraction during cycling. These changes include phase transformations, mechanical stress, and particle fracture, which reduce the cathode's structural integrity and limit its ability to store lithium ions effectively [87]. Anode materials, particularly those using graphite, can also experience mechanical degradation, especially in high-energy-density designs where large volumes of lithium are intercalated and de-intercalated. This mechanical stress may cause microcracks in the material, further accelerating performance loss.

4.1.3. Lithium Plating

Lithium plating occurs when lithium ions are deposited as metallic lithium on the anode surface rather than intercalating into the anode material. This degradation mechanism is particularly prominent at low temperatures or during high-rate charging, during which lithium deposition becomes kinetically favored [88]. Lithium plating not only leads to capacity loss but also poses a significant safety risk, as metallic lithium can form dendrites—needle-like structures that can grow and puncture the separator, causing an internal short circuit. This increases the chances of thermal runaway and, consequently, fire or explosion.

4.1.4. Electrolyte Decomposition

Decomposition of the electrolyte is another key factor in lithium-ion battery degradation. Electrolyte decomposition is often initiated by high operating temperatures, overcharging, or sustained cycling at high voltages, which promote unwanted side reactions that reduce electrolyte volume and increase the concentration of byproducts [89]. The decomposition products can coat the electrode surfaces, further increasing internal resistance and impeding lithium-ion transport. In addition to performance loss, the breakdown of electrolyte components can generate gases, raising the cell's internal pressure and creating safety risks, especially in sealed battery packs.

4.2. Performance Decline Due to Degradation

The degradation mechanisms outlined above contribute to several observable performance issues in lithium-ion batteries over time. These performance declines are typically reflected in capacity fade, increased internal resistance, reduced power output, and efficiency loss.

4.2.1. Capacity Fade

Capacity fade is the gradual reduction in the battery's charge over time. This decline is driven by the loss of active lithium, the degradation of electrode materials, and the increased impedance caused by SEI layer growth and electrolyte decomposition. As the battery loses capacity, its ability to power devices for extended periods diminishes, shortening the runtime between charges for consumer electronics and reducing the driving range of EVs.

4.2.2. Increased Internal Resistance and Power Loss

Internal resistance increases as the battery ages, due to thickening of the SEI layer, electrode degradation, and electrolyte decomposition. Higher internal resistance reduces the efficiency of charge and discharge cycles, as more energy is lost as heat within the cell. This results in lower power output, particularly in high-current applications, and can limit the battery's ability to deliver energy during periods of peak demand. This leads to slower acceleration and diminished overall performance in EVs, while in grid storage, it reduces the system's ability to respond to dynamic energy needs [90].

4.2.3. Reduced Coulombic Efficiency

Coulombic efficiency, the ratio of charge extracted during discharge to the charge input during charging, decreases as the battery degrades. Reduced efficiency is typically a result of parasitic side reactions, such as SEI formation, electrolyte oxidation, and gas generation, which consume lithium ions and reduce the amount available for electrochemical reactions. This degradation-induced loss of efficiency means that more energy is required to charge the battery for the same amount of usable output, contributing to overall inefficiencies in EVs and energy storage systems.

4.2.4. Safety Risks Arising from Degradation

As degradation progresses, the structural and chemical changes within the lithium-ion battery impair its performance and increase the prospect of safety failure. These risks are primarily associated with the breakdown of internal components, such as the SEI layer, electrolyte, and electrodes, which can lead to internal short circuits, thermal runaway, and other hazardous events.

4.2.5. Increased Risk of Thermal Runaway

The potential for thermal runaway increases significantly as the battery degrades. Thermal runaway occurs when the exothermic decomposition reactions within the cell exceed the battery's ability to dissipate heat, leading to a self-sustaining increase in temperature that can cause fires or explosions [91]. Degradation exacerbates this risk in several ways:

- SEI Layer Failure: If the SEI layer becomes unstable or grows excessively thick, it can crack, exposing the anode to the electrolyte and initiating exothermic reactions.
- Electrolyte Decomposition: Degraded electrolytes can produce flammable gases, increasing the cell's pressure and raising the fire risk if the gases are ignited.
- Lithium Plating and Dendrite Formation: Lithium plating can cause the formation of lithium dendrites, puncturing the separator and causing internal short circuits. These generate heat and further increase the probability of thermal runaway.

4.2.6. Short Circuit and Gas Generation

Internal short circuits resulting from dendrite formation, separator failure, or electrode material fracture are direct consequences of degradation. When short circuits occur, localized heating is produced, which can initiate further degradation and, in extreme cases, thermal runaway [92]. Additionally, gas generation from electrolyte breakdown products raises the internal pressure, potentially leading to cell venting or rupture.

4.2.7. Mechanical and Structural Instability

The mechanical degradation of electrodes, particularly in high-capacity designs, can lead to particle fracturing and loss of contact between active materials and current collectors. This reduces battery performance and increases the risk of structural failure within the cell, leading to electrical isolation of portions of the electrode or the development of hotspots due to uneven current distribution [93]. Mechanical instability is a key safety concern in high-power applications, where rapid cycling can exacerbate structural damage and lead to sudden performance failures.

This section examined how vibrations accelerate degradation in lithium-ion batteries, impacting performance, lifespan, and safety. Battery degradation occurs through calendar aging (time-dependent capacity loss) and cycle aging (repeated charge–discharge wear). Vibrations exacerbate key degradation mechanisms, including SEI layer growth, electrode material breakdown, lithium plating, and electrolyte decomposition, leading to higher internal resistance, capacity fade, and efficiency loss. Vibrational stress weakens electrode structures, causing particle detachment, microcracks, and separator damage, which increase the risk of internal short circuits and thermal runaway. Additionally, vibrations contribute to uneven lithium deposition, worsening dendrite formation and separator punctures, which can trigger electrical failures and safety hazards. As vibrations accelerate mechanical fatigue and heat generation, they further degrade the battery's thermal stability, increasing the likelihood of overheating, gas buildup, and ignition risks in high-vibration applications. The following section will focus on how vibrations influence thermal runaway in lithium-ion batteries, examining how mechanical stress intensifies heat generation, disrupts thermal regulation, and increases the probability of catastrophic failure.

5. Effects of Vibrations on Thermal Runaway in Lithium-Ion Batteries

Lithium-ion batteries, especially in dynamic applications such as EVs, aerospace, and marine industries, are exposed to mechanical vibrations during operation. Vibrations affect the structural integrity, electrical performance, and thermal behavior of the battery. Mechanical vibrations introduce complex mechanical–electrochemical interactions in lithium-ion batteries. The resulting micromovements and strain affect the battery's internal components, including the electrodes, separator, and current collectors. This leads to higher internal resistance and increased heat generation, as shown in Figure 14.

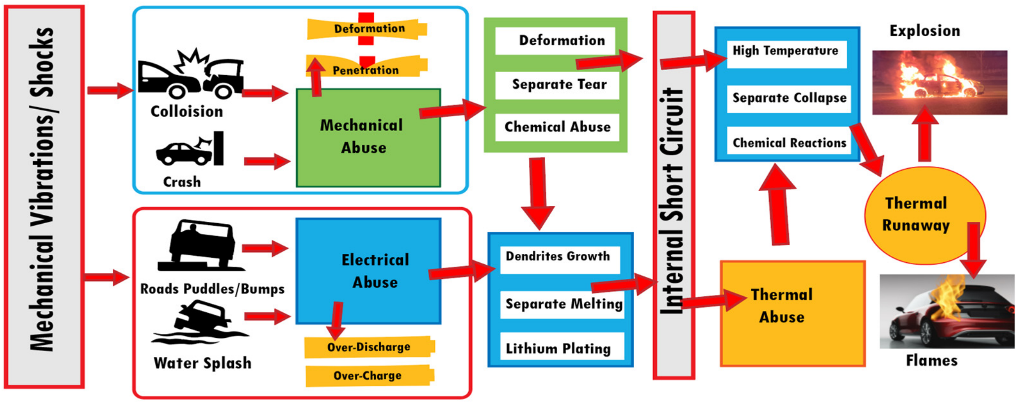

Figure 14. Mechanism of thermal runaway due to vibrations.

Mechanical vibrations and shocks play a significant role in the degradation and failure of lithium-ion batteries (LIBs), leading to internal short circuits and, in extreme cases, thermal runaway. Figure 14 illustrates the pathways through which mechanical, electrical, and thermal abuses contribute to battery failure, ultimately resulting in catastrophic outcomes such as explosions or vehicle fires.

5.1. Mechanical Abuse

Mechanical vibrations and external shocks arise from conditions such as road bumps, puddles, or vehicle collisions. These external stimuli lead to mechanical abuse, manifesting in penetration and deformation of battery components. Structural damage can further induce chemical abuse, causing separation tears and internal material failures [94,95]. Such deformations compromise the battery's structural integrity and increase the risk of short circuits.

5.2. Electrical Abuse and Internal Short Circuits

Vibrations also impact the electrochemical stability of LIBs. Road irregularities and water splashes can introduce electrical abuse conditions, including overcharge and over-discharge, accelerating dendritic lithium growth [95]. These lithium dendrites may penetrate the battery separator, causing internal short circuits that generate localized heating and intensify thermal stress [94]. Lithium plating and separator melting also contribute to further performance degradation and safety hazards.

5.3. Thermal Abuse and Thermal Runaway

Once an internal short circuit occurs, the battery experiences thermal abuse, leading to high temperature, separator collapse, and exothermic chemical reactions. These reactions trigger a thermal runaway event, wherein excessive heat buildup leads to flames and explosions [4]. This chain reaction is particularly hazardous in electric vehicles (EVs), where battery packs contain multiple interconnected cells. The interplay between mechanical vibrations, electrical instability, and thermal abuse highlights the necessity for robust battery management systems and vibration-resistant battery designs.

5.3.1. Heat Generation Mechanisms in Lithium-Ion Batteries

Heat generation in lithium-ion batteries primarily comes from three sources: Ohmic (Joule) heating due to resistance in internal components like electrodes and electrolytes, reversible heat generation associated with entropy changes during electrochemical reactions, and irreversible heat generation from side reactions such as solid–electrolyte interface (SEI) formation and degradation processes.

Vibrations can significantly exacerbate heat generation mechanisms in lithium-ion batteries. By introducing additional internal resistance and contributing to mechanical degradation, vibrations lead to higher internal energy loss, thereby increasing heat generation within the battery, as shown in Figure 15.

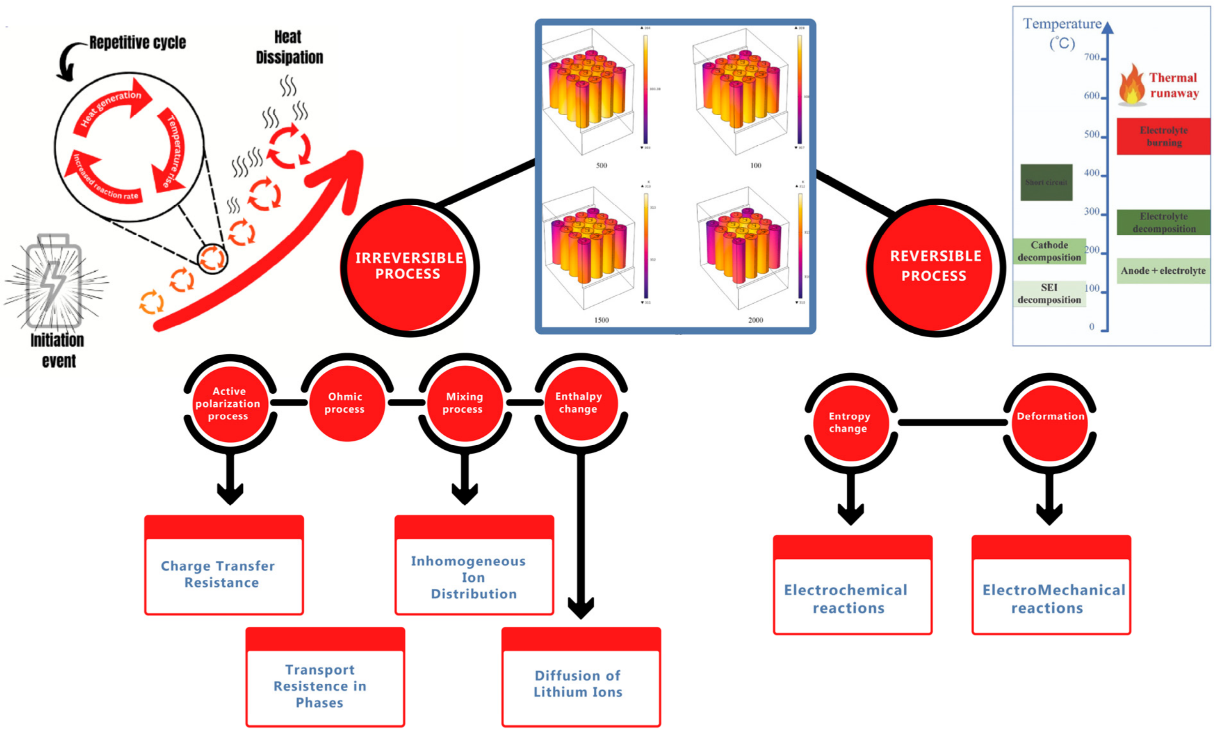

Figure 15. Thermal and mechanical processes in lithium-ion batteries: reversible and irreversible dynamics.

5.3.2. Vibration-Induced Internal Resistance Increase and Heat Generation

Vibrations have a direct impact on the internal structure of lithium-ion batteries. Introducing mechanical strain and deformation [96] increases internal resistance, affecting the battery's performance. Increased resistance (R_{int}) is a primary factor in heat generation within the cell. The relationship between internal resistance and heat generation can be modeled by Equation (1) under vibrations. Microscopic mechanical movements in the battery can cause poor contact between electrode particles, microcracks in the electrode materials, or slight misalignment of current collectors, which increase internal resistance and affect degradation, as shown in Figure 15. As R_{int} increases, the heat generation according to the equation for Q_{heat} increases with the current, making the battery more susceptible to overheating under vibrations at high discharge rates.

5.3.3. Impact of Vibrations on Electrochemical Reactions and Heat Generation

Vibrations can also disrupt the uniformity of lithium-ion diffusion within electrode materials. This uneven diffusion can lead to localized concentration gradients, causing non-uniform current densities and exacerbating heat generation in specific battery regions. The heat generated due to non-uniform current distribution is linked to the overpotential (η) in the battery, representing the difference between the actual operating and thermodynamically predicted voltage. The heat generated due to overpotential can be expressed as follows:

$$Q_{overpotential} = I \cdot \eta \tag{9}$$

where $Q_{overpotential}$ is the heat generated due to overpotential (in watts), I is the current (in amperes), and η is the overpotential (in volts). Vibrations cause mechanical fatigue in the electrodes, which can alter the local distribution of lithium ions and affect the kinetics of the electrochemical reactions. This leads to an increase in overpotential and, thus, more heat is generated.

5.3.4. Mechanical Strain and Heat Generation

Vibrations introduce mechanical strain in battery components, leading to material deformation and failure modes such as microcracking of the electrodes and delamination of electrode coatings from the current collectors [97]. The mechanical energy imparted by vibrations is partially converted to heat due to frictional loss and material deformation. This heat generation can be modeled as follows:

$$Q_{vibrations} = \frac{1}{2} a^2 m f C_{damp} \tag{10}$$

where $Q_{vibrations}$ is the heat generated due to mechanical strain (in watts), m is the mass of the battery (in kilograms), a is the acceleration caused by the vibrations (in meters per second squared), f is the frequency of vibrations (in hertz), and C_{damp} is the damping coefficient, which represents the material's ability to dissipate vibrational energy as heat.

In practical applications, such as automotive systems, vibrations typically occur in the frequency range of 5–200 Hz, and the damping coefficient depends on the specific materials used in battery construction [98]. Prolonged exposure to these vibrations increases the battery's temperature, further accelerating degradation processes.

5.3.5. Thermal Feedback and Heat Accumulation

Vibrations increase internal resistance and mechanical strain and contribute to a thermal feedback loop. The battery's temperature rises as heat is generated from mechanical vibrations and increased resistance. Elevated temperatures, in turn, increase internal resistance, further enhancing heat generation according to the $\boldsymbol{i^2R_{int}}$ relationship. The overall heat balance in a battery under vibrations can be represented as follows:

$$Q_{total} = i^2R_{int} + I \cdot \eta + Q_{vibrations} - Q_{dissipated} \quad (11)$$

where Q_{total} is the total heat generated in the battery (in watts); i^2R_{int} represents the heat generated due to internal resistance of the battery as current flows through it; $I \cdot \eta$ is the heat generated due to over potential, as previously discussed; $Q_{vibrations}$ is the heat generated due to mechanical strain from vibrations; and $Q_{dissipated}$ is the heat dissipates through cooling mechanisms, such as convection, conduction, or radiation (in watts). If the generated heat exceeds the dissipation capacity of the battery's thermal management system, the battery's temperature can rise uncontrollably, leading to thermal runaway in extreme cases [99].

Table 1 provides a detailed overview of how different types of mechanical vibrations and shocks impact lithium-ion battery performance, particularly in terms of heat generation and the risk of thermal runaway. Low-frequency vibrations, such as those from road unevenness, cause gradual SEI layer growth and minor electrode misalignment, leading to a moderate increase in internal resistance and heat buildup, with a low to moderate risk of thermal runaway. These findings highlight the need for improved battery designs, advanced thermal management strategies, and robust battery management systems to mitigate the effects of mechanical vibrations and shocks. Future studies should focus on real-time monitoring solutions and innovative materials that can withstand mechanical stress while maintaining optimal thermal stability.

Table 1. Impact of vibrations on thermal runaway.

Type of Shock/Vibration	Effect on Battery Components	Heat Generation Mechanism	Risk of Thermal Runaway
Low-Frequency Vibrations (Road Unevenness)	Gradual SEI layer growth, minor electrode misalignment	Increased internal resistance leading to moderate heat buildup	Low to Moderate
High-Frequency Vibrations (Motor Operation)	Accelerated electrode wear, increased lithium plating	Localized heating due to lithium plating and resistance rise	Moderate
Sudden Impacts (Potholes, Speed Bumps)	Internal microcracks, separator weakening	Sudden temperature spikes from localized internal stress	Moderate to High
Crash/Collision Shocks	Severe structural damage, high risk of short circuit	Extreme heat generation due to short circuits and thermal runaway	Very High
Continuous Micro-Vibrations (High-Speed Driving)	Increased internal resistance, gradual heat buildup	Progressive heat accumulation from increased resistance and loss	Moderate to High

5.4. Battery Risks in EV Crashes

EVs are equipped with advanced braking, power electronics, and battery systems to ensure safety during sudden stops and collisions. However, sudden braking, vehicle crashes, and impacts with stationary objects (e.g., buildings, barriers, or poles) can introduce vibrational stress, mechanical deformation, and electrical failures in EVs. These factors can significantly affect battery integrity, thermal stability, and overall system performance, posing risks such as thermal runaway, high-voltage failures, and post-crash hazards, as shown in Figure 16.

The safety of EVs depends on the ability of the battery system to withstand sudden mechanical shocks and maintain its thermal and electrical stability under extreme conditions. As the adoption of EVs continues to grow, improving battery pack designs, integrating intelligent battery management systems, and developing more robust crash protection mechanisms will be crucial in preventing fire hazards and ensuring long-term vehicle reliability.

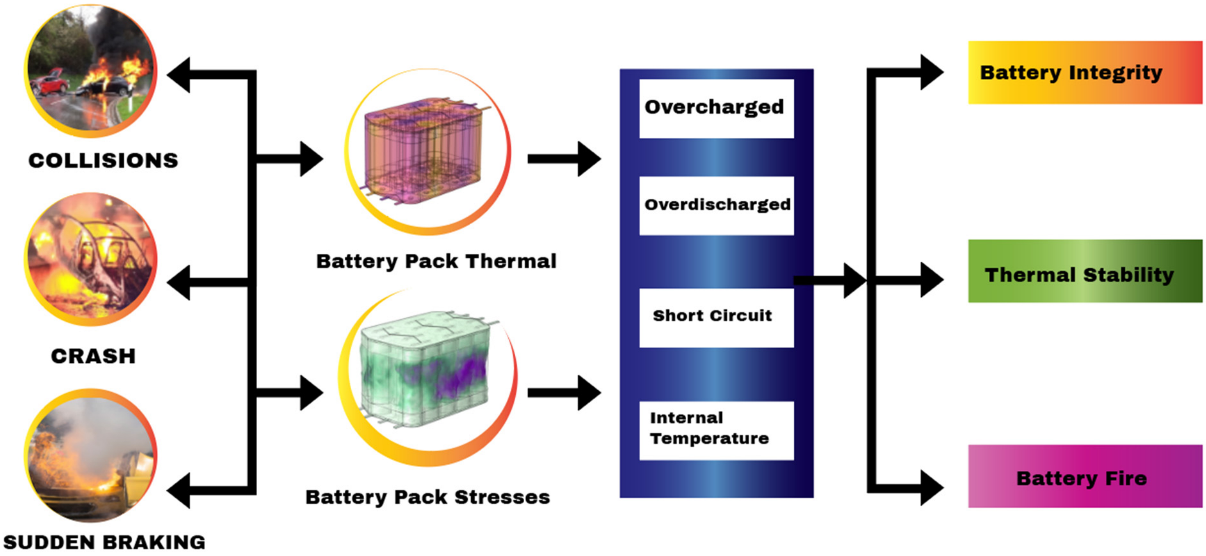

Figure 16. Battery failure analysis under adverse conditions.

5.4.1. Sudden Brake Vibrations

Unlike conventional vehicles, EVs primarily use regenerative braking supplemented by mechanical friction braking. During hard braking or emergency stops, oscillatory forces act on battery modules, generating high-frequency vibrations that stress interconnects, terminals, and cooling plates. These vibrations have been shown to reduce battery efficiency and induce microstructural damage in lithium-ion cells. Studies indicate that regenerative braking also leads to voltage fluctuations, which may trigger false fault detections in the battery management system and result in unnecessary power limitations or shutdowns.

5.4.2. Collision Vibrations

Collisions and exceptionally high-impact crashes introduce additional risks for battery packs and EV safety systems. Lithium-ion cells are prone to short internal circuits when subjected to mechanical deformation, which can trigger thermal runaway. Side impact collisions are particularly concerning, as they can cause direct battery intrusion, leading to module displacement and cooling system failures. If the cooling plates are punctured or disconnected due to the impact, thermal regulation becomes ineffective, accelerating internal heating. Battery enclosure crumpling is another significant factor, especially in underbody impacts, where road debris or structural elements can penetrate the pack. Studies analyzing EV crashworthiness have found that structural deformation exceeding 12% of battery enclosure space significantly raises the likelihood of thermal events. Post-collision fire hazards remain one of the most critical concerns in EV crashes. Thermal runaway can occur immediately upon impact or be delayed for hours or even days due to residual stress within the cells.

5.4.3. Collision with Buildings, Poles, and Barriers: Unique Challenges

Collisions with stationary objects such as buildings, barriers, and poles introduce unique challenges in EV safety. Unlike vehicle-to-vehicle impacts, where energy dissipation is distributed across both vehicles, crashes with stationary objects cause localized force concentrations. This increases pressure on specific vehicle sections, such as the front-end, underbody, or battery casing. Front-end collisions may compromise the power electronics, affecting inverter and BMS operation, while side impacts often pose direct threats to battery safety due to potential penetration into the enclosure.

5.4.4. Unique Challenges

Collisions, crashes, and sudden braking in electric vehicles (EVs) create significant risks for battery safety due to thermal and mechanical stress on the battery pack. These events can lead to structural deformation, electrical failures, and temperature imbalances, increasing the chances of thermal runaway and fire hazards. The impact of crashes or sudden braking generates excessive force on the battery pack, causing internal mechanical stresses that weaken the structural integrity of battery modules.

5.4.5. Failure Analysis Testing

Failure analysis of electric vehicle (EV) batteries under collisions, sudden braking, and vibrational stress requires mechanical, thermal, electrical, and computational testing. Crash impact and vibration testing assesses structural integrity, identifying microcracks, weld failures, and module displacement. Thermal runaway and fire suppression tests evaluate heat propagation and containment strategies, ensuring post-crash safety. Electrical safety tests, including short circuit analysis and insulation resistance measurement, detect high-voltage failures and electrocution risks. Computational simulations such as finite element analysis (FEA) and AI-driven battery monitoring predict failure risks by analyzing stress distribution, thermal anomalies, and voltage inconsistencies. Integrating these methods can enhance battery resilience, enabling the development of safer, crash-resistant EV systems.

This section examined how vibrations contribute to thermal runaway in lithium-ion batteries. Mechanical stress causes electrode misalignment, separator damage, and increased internal resistance, leading to localized heating and performance degradation. Sudden shocks, collisions, and road irregularities accelerate lithium dendrite formation and short circuits, triggering uncontrolled heat buildup and thermal runaway risks. Vibrations also disrupt lithium diffusion, increase overpotential, and amplify heat generation, creating a thermal feedback loop that can overwhelm battery cooling systems. These effects underscore the need for vibration-resistant designs, advanced thermal management, and failure detection systems to enhance battery safety and durability. The next section will explore vibration-induced degradation in lithium-ion batteries, focusing on structural wear, capacity fade, and long-term performance loss.

6. Vibration-Induced Degradation in Lithium-Ion Batteries

Vibrations play a significant role in the degradation of lithium-ion batteries, particularly in applications such as electric vehicles, aviation, and marine systems, where mechanical vibrations are unavoidable. These vibrations cause mechanical stress, material fatigue, and structural failures in battery components, accelerating key degradation processes.

Mechanical vibrations and shocks are inevitable in electric vehicles (EVs) due to road irregularities, acceleration, braking, and other dynamic conditions. These external mechanical stimuli significantly impact lithium-ion batteries' electrochemical and structural integrity (LIBs), leading to performance degradation, capacity loss, and inaccuracies in state of charge (SOC) estimation. Figure 17 [100] illustrates how mechanical vibrations affect battery components and the resulting implications for battery health and EV range anxiety. Mechanical stress increases reactivity within the battery, accelerating unwanted side reactions at the electrode–electrolyte interface. One of the most critical consequences is the accelerated formation of the solid–electrolyte interphase (SEI) layer. While the SEI layer is essential for stabilizing battery chemistry, excessive growth increases internal resistance, reduces charge transfer efficiency, and contributes to long-term capacity fade. The mechanical agitation of electrode materials also leads to microcrack formation, exposing fresh electrode surfaces to the electrolyte and further increasing SEI formation. As a result, repeated exposure to mechanical shocks results in reduced Coulombic efficiency and progressive loss of usable capacity over multiple charge–discharge cycles [101]. Beyond electrochemical effects, mechanical vibrations induce structural damage within the battery. Stress on the cathode, anode, and separator can weaken the physical integrity of these components, leading to separator deformation or misalignment of active materials. Damage to the current collectors, particularly copper and aluminum foils, increases the risk of internal short circuits, leading to localized heating and, in severe cases, thermal runaway [102]. These degradation mechanisms compromise battery safety and impair the accuracy of SOC estimation, leading to discrepancies between the apparent SOC reported by the battery management system (BMS) and the actual remaining charge. This inconsistency causes EV users to experience range anxiety, as the displayed battery level may not accurately reflect the actual available energy [103]. As the figure demonstrates, these degradation pathways ultimately affect battery health and operational reliability. The growing mismatch between the apparent and actual SOC results in premature charging, inefficient energy utilization, and increased operational costs for EV users. Additionally, excessive battery degradation can shorten the overall lifespan of the battery pack, increasing the frequency of replacement and raising sustainability concerns. Addressing these challenges requires advanced diagnostic tools capable of detecting early-stage mechanical degradation and improved battery designs that can withstand vibrational stress without significant performance loss. The impact of mechanical vibrations on battery behavior underscores the need for further research into resilient electrode materials, robust separators, and advanced BMS algorithms to mitigate performance loss.

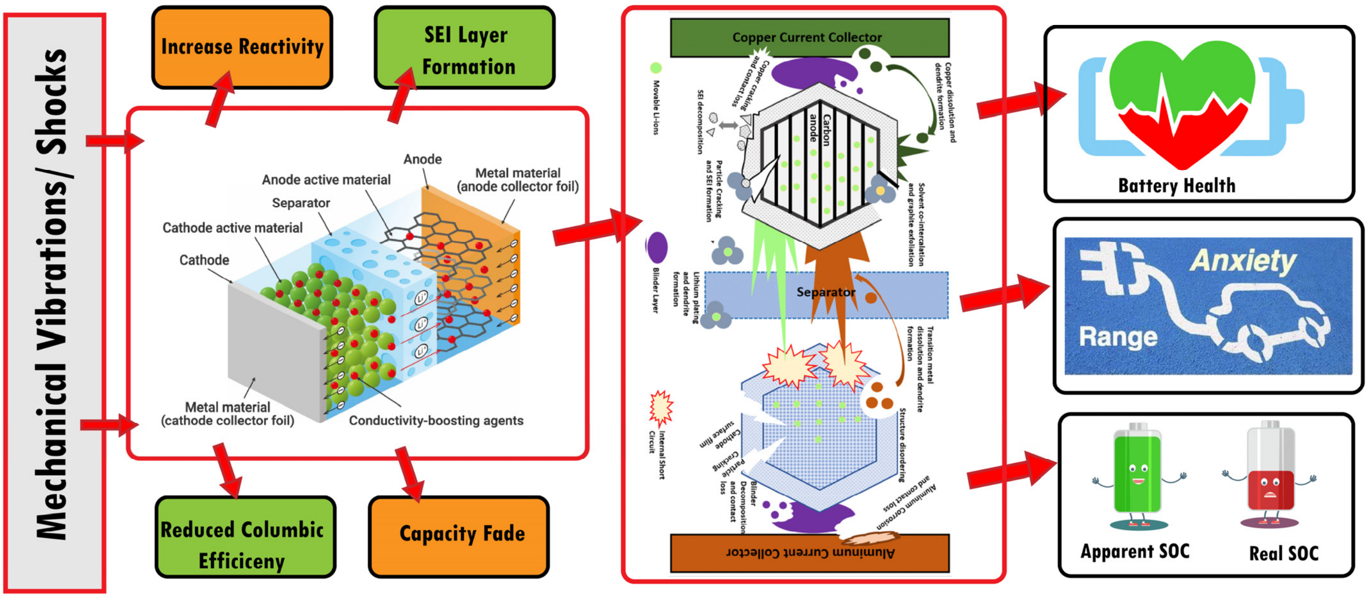

Figure 17. Mechanism of degradation due to vibrations.

6.1. Mechanisms of Degradation Under Vibrations

The primary degradation mechanisms influenced by vibrations are:

Mechanical Fatigue: Repeated mechanical stress causes the battery's material components (electrodes, separators, and current collectors) to undergo fatigue and microstructural changes.

Electrode Delamination: Vibrations can cause the active material to delaminate from the current collector, increasing internal resistance and reducing active material utilization.

Separator Damage: Vibrations can induce physical strain on the separator, which increases the prospect of short circuits and accelerates degradation.

Increased Resistance and Heat Generation: Vibrational stress can disrupt the internal contact between electrode particles, increasing internal resistance and further accelerating ageing through excessive heat generation.

Figure 18 [104] provides an overview of the effects of vibrations on lithium-ion batteries and the application of multiphysics analysis to understand their behavior as an effect of thermal behavior. It highlights the key processes and mechanisms within the battery—such as structural degradation, thermal dynamics, and stress distribution—caused by vibrations during operation. The battery's performance under real-world conditions is simulated using tools as a vibration controller and vibrating machine. Multiphysics thermal and stress analysis enables the visualization of heat distribution and mechanical deformation, ensuring better design and safety, which is in high demand. These mechanical and electrochemical processes interact to degrade battery performance. Mathematical models can describe how vibrations contribute to these mechanisms.

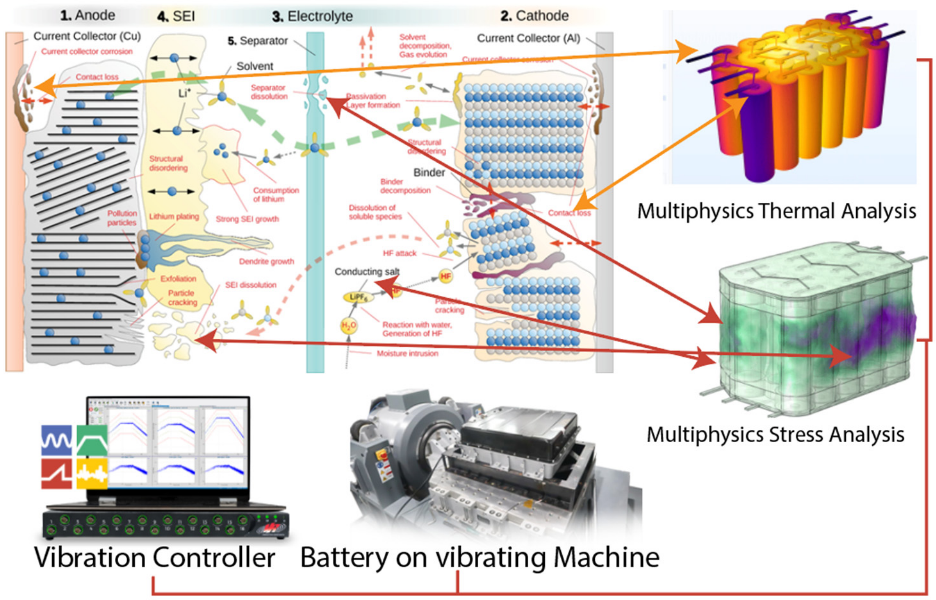

Figure 18. Battery degradation mechanisms under vibrations.

6.2. Electrode Fatigue and Delamination Due to Vibrations

Electrode fatigue refers to the weakening of electrode materials due to repeated mechanical loading caused by vibrations. As vibrations propagate through the battery, they induce cyclic strain in the active materials [105,106]. This cyclic loading creates microcracks in the electrodes, reducing the available surface area for lithium intercalation and increasing internal resistance. The fatigue behavior of materials under cyclic loading is described by S–N curves (stress–life curves), which relate the stress amplitude (σ) to the number of cycles to failure (N), as follows:

$$\sigma \cdot N^b = C \tag{12}$$

where σ is the applied stress (in Pa), N Is the number of cycles to failure, N^b is a material-dependent fatigue exponent, and C is a constant that depends on the material's properties. As σ increases due to higher vibration amplitudes, the cycle number before failure decreases, meaning that the battery degrades more quickly under stronger or more frequent vibrations. Electrode delamination arises when vibrational forces degrade the adhesion between the active material and the current collector. This mechanical stress causes the electrode coating to detach from the collector, diminishing electrical conductivity and impairing active material utilization. As a result, internal resistance increases, and the battery's capacity is compromised. The delamination rate is closely tied to the amplitude and frequency of vibrations, which inject strain energy into the system, further accelerating the deterioration of the battery. The strain energy density (U_{strain}) can be modeled using the energy associated with this delamination, as follows:

$$U_{strain} = \frac{1}{2} 2\sigma \cdot \epsilon \tag{13}$$

where U_{strain} is the strain energy density (in J/m^3), σ is the applied stress (in Pa), and ϵ is the strain induced by vibrations. As strain increases due to vibrations, delamination progresses more rapidly, further contributing to the battery's degradation.

6.3. Separator Damage and Short Circuit Risk

The separator plays a vital role in preventing direct contact between the anode and cathode while still permitting the flow of lithium ions. However, vibrations can cause mechanical stress on the separator, resulting in fatigue and the formation of small tears. Any damage to the separator raises the risk of internal short circuits, which can drastically speed up degradation and potentially cause catastrophic failure, such as thermal runaway [107]. The probability of separator failure due to vibrations can be modeled using fatigue failure models based on the accumulated strain (ϵ) over time. The relationship between strain and failure probability is often described by the Coffin–Manson equation, which is used to predict fatigue life in cyclically loaded materials, as follows:

$$N_f = \frac{\Delta\epsilon}{C_{sep}} \tag{14}$$

where N_f is the number of cycles to failure for the separator, $\Delta\epsilon$ is the vibration-imposed strain range, and C_{sep} is a constant that depends on the separator material's properties. As the vibration frequency and amplitude increase, Δϵ increases, leading to a decrease in N_f (i.e., faster separator degradation). Internal shorts may develop once the separator is compromised, leading to safety issues and rapid capacity loss.

6.4. Vibration-Induced Resistance Increase and Heat Generation

As mechanical vibrations disrupt the battery's internal structure, internal resistance increases due to poor contact between electrode particles and current collectors. Increased resistance causes more heat generation, as described by Joule's law in the equation. i^2R_{int}. The increase in internal resistance (R_{int}) can be modeled as a function of the vibration amplitude (A) and frequency (f), as follows:

$$R_{int}(A, F) = R_o + K_1A + K_1f \tag{15}$$

where R_o is the baseline internal resistance (in ohms), A is the vibration amplitude (in meters), f is the vibration frequency (in hertz), and $K_1$and K_2 are constants related to the battery's material and structural properties. As vibrations increase in amplitude and frequency, internal resistance rises, generating more heat [108]. This heat further accelerates degradation mechanisms such as electrolyte decomposition and SEI layer growth.

Table 2 highlights the impact of various shocks and vibrations on battery heat generation. Low-frequency vibrations, such as those from road unevenness, gradually increase SEI layer thickness and internal resistance, leading to moderate heat buildup. More severe shocks, such as those from crashes or collisions, can cause extreme structural damage, increasing the risks of internal short circuits and thermal runaway. Continuous micro-vibrations from high-speed driving progressively degrade battery components, causing steady heat accumulation and increasing thermal instability. Understanding the effects of mechanical shocks and vibrations on battery heat generation is crucial for improving lithium-ion battery safety and performance in electric vehicles. Addressing these challenges requires enhanced battery designs, advanced materials, and real-time monitoring systems to mitigate thermal risks and extend battery lifespan.

Table 2. Impact of vibrations on battery materials, safety, and performance.

Type of Vibration	Effect on Electrode	Effect on Separator	Effect on Battery	Effect on Internal Resistance	Effect on Thermal Runaway	References
Low-Frequency Vibrations (Road Unevenness)	Minor electrode misalignment, SEI layer thickening	Minimal impact, slight deformation over time	Slight capacity fade over time	Slight increase over time due to SEI layer growth	Low risk, but prolonged stress can contribute to localized heating	[1,9,15,21]
High-Frequency Vibrations (Motor Operation)	Accelerated electrode wear, increased contact resistance	Increased mechanical stress, risk of separator thinning	Increased resistance, reduced cycle life	Noticeable increase, leading to efficiency loss	Increased heat generation, reduced thermal stability	[6,10,18,25]
Sudden Shocks (Potholes, Speed Bumps)	Microcracks in electrode material, loss of active material	Potential small tears, localized damage	Accelerated degradation, loss of efficiency	Sharp increase in resistance due to material fractures	Sudden energy release may trigger localized overheating	[6,9,17,24]
Crash/Collision Impact	Severe structural damage, detachment of active material	High risk of complete separator failure	Severe capacity loss, potential safety hazard	Extreme increase, leading to power loss and safety failure	There is a high likelihood of thermal runaway due to short circuits and heat buildup	[6,14,20,27]
Continuous Micro-Vibrations (High-Speed Driving)	Gradual electrode degradation, uneven lithium deposition	Gradual wear leading to increased resistance	Progressive performance decline, reduced lifespan	Gradual rise in resistance, affecting efficiency over time	Long-term heat accumulation can lead to self-heating and instability	[9,15,19,26]

This section explored how vibrations accelerate the degradation of lithium-ion batteries, where mechanical stress is unavoidable. Vibrations induce mechanical fatigue, electrode delamination, and separator damage, leading to increased internal resistance, capacity loss, and heat generation. Repeated mechanical stress accelerates SEI layer growth, disrupts lithium diffusion, and weakens electrode materials, causing progressive efficiency to decline and potential short circuits. Key degradation mechanisms include electrode fatigue, separator wear, and increased Joule heating, which raise thermal instability and the likelihood of thermal runaway. Vibrations also affect state of charge accuracy, creating inconsistencies that contribute to range anxiety and inefficient battery utilization in EVs. Resilient electrode materials, advanced separators, and enhanced battery management systems are essential to mitigate vibration-induced degradation.

7. Discussion

This review of studies on lithium-ion battery performance under vibrational conditions reveals the multifaceted impact of mechanical vibrations on battery safety, range, and operational reliability. The following discussion summarizes the findings, evaluates how well the review's objectives were met, and highlights emerging research gaps. The studies indicate that thermal management, structural resilience, and environmental conditions are crucial factors affecting battery performance under vibrational stress. Research shows thermal management, structural resilience, and environmental conditions influence battery performance under vibrational stress. High temperatures and mechanical vibrations significantly degrade battery performance and reduce lifespan. Studies have consistently reported that increased internal resistance and capacity fade are primary degradation mechanisms caused by thermal and mechanical stress. These findings highlight the critical relationship between external abuse and battery performance decline. However, while the individual effects of these factors are well documented, there are limited data on how combined stressors, such as temperature, pressure, and vibrations, interact to impact battery performance.

Table 3 summarizes the studies investigating the impact of vibrations on lithium-ion batteries, focusing on thermal behavior, degradation mechanisms, and experiment types. Thermal investigations are often secondary to mechanical durability or state of health evaluations, with only a few studies directly addressing heat generation under vibrational stress. Studies like [11,17,24] identified the risks of overheating during short circuits or high vibration amplitudes, while others like [13,15] did not explore thermal behavior, concentrating instead on structural integrity or compliance with transportation safety standards. Degradation mechanisms, however, are more comprehensively studied, with many papers [18,19,24] linking vibrations to increased internal resistance, capacity fade, and structural damage. Vibrations cause delamination, separator thinning, and electrode degradation, contributing to performance loss over time. While practical experiments dominate this area of research, simulation studies like [21,31] focused more on state of charge (SOC) estimation or feasibility analysis in extreme environments.

Table 3. Technical overview of thermal and degradation studies on lithium-ion batteries under vibrations.

Ref.	Thermal Investigation Results	Degradation Investigation Results	Experiment Type
[11]	Risk of overheating during short circuit and overcharge tests.	Vibration and shorting tests revealed overheating risk.	Practical
[8]	Focused on mechanical effects on batteries rather than thermal aspects.	Vibrations and shocks impact cell performance.	Practical
[15]	Concentrated on SOH under vibrations, no thermal evaluation.	Minimal capacity fade was observed across different vibrational conditions.	Practical
[18]	Resistance buildup with vibrations suggests heat increase.	Increased resistance and reduced capacitance were observed under vibrations.	Practical
[17]	High heat release under vibrational stress.	Structural integrity is compromised under severe vibrational conditions.	Practical
[24]	Higher heat output under vibrations.	Increased resistance and capacity fade.	Practical
[22]	Studied thermal issues in various stress conditions.	Investigated degradation rates under different environmental conditions.	Practical
[13]	Focused on safe battery transport protocols.	No degradation focus, the study emphasized vibration testing for transportation.	Practical
[29]	Monitored temperature for compliance.	Ensured safety under different stress tests.	Practical
[19]	Effects of temperature and vibrations on battery lifespan.	Degradation rates are higher under stress conditions.	Practical
[21]	No thermal analysis, SOC estimation study.	SOC accurately tracked under various operating conditions.	Simulation
[23]	No thermal analysis, focused on durability in motorcycle vibrations.	Tested unique motorcycle vibration patterns on battery durability.	Practical
[11]	Mechanical vibrational effects were explored without thermal aspects.	Linked abnormal vibration patterns to potential battery degradation.	Practical
[16]	No thermal investigation, focused on vibration testing in powertrains.	Vibration resistance was checked in prototype testing.	Practical
[32]	High-frequency signals indicated over-discharge faults.	Demonstrated over-discharge risks through vibration signals.	Practical
[12]	Shock and vibration monitoring for transportation, thermal impact not studied.	The MEMS system is adequate for transport monitoring.	Practical
[30]	No thermal effect was noted, the environmental impact on battery performance was emphasized.	Assessed the influence of pressure, humidity, and temperature on battery performance.	Practical
[26]	A thermal study was not conducted, the focus was on unique powertrain vibrations.	Evaluated performance under dynamic load conditions.	Practical
[20]	Review paper on performance, no new thermal testing.	Mechanical and electrical performance parameters summarized.	Review
[14]	Vibrational effects on electrical performance but no thermal analysis.	Performance impact observed under continuous vibration.	Practical
[9]	Thermal aspects are secondary, focused on lead-acid battery vibrations.	Performance evaluated under vibrational effects.	Practical
[33]	Dynamic loads but thermal effects were not included.	Studied dynamic load impact on battery life.	Practical
[27]	Nondestructive testing focus, no thermal study.	SOC monitored using structural changes.	Practical
[25]	Phase change materials evaluated without thermal assessment.	Evaluated thermal management through the use of phase change materials.	Simulation
[28]	SOC under vibrations, no thermal focus.	Analysis under variable vibrational stress levels.	Practical
[6]	Comparative study, thermal focus secondary to mechanical evaluation.	Failure mechanisms under mechanical abuse were explored.	Practical
[31]	Thermal management was explored under vibrations for submarine use.	Analyzed feasibility of battery use in high-stress environments.	Simulation

Several studies highlight that vibrations exacerbate internal resistance buildup, causing localized heat generation and further accelerating degradation. However, some investigations [20,28] lack direct thermal evaluation and instead focus on environmental or electrical performance impacts. Simulation-based studies tend to overlook the combined thermal and mechanical effects seen in real-world conditions, whereas practical studies excel in identifying specific risks but often lack detailed thermal models.

7.1. Harmful Effects of Vibrations on Battery Systems

The studies support that vibrations are harmful to lithium-ion battery systems. For instance, prolonged exposure to mechanical stress results in physical damage to internal components, such as electrode delamination and separator deformation. Vibration-induced structural damage increases the risk of internal short circuits, which poses significant safety hazards and accelerates capacity loss. The review successfully assessed the harmful effects, confirming that vibrations are a risk factor for battery degradation and safety. However, further investigation is needed to quantify the specific vibration thresholds that delineate safe operating limits. These could help to establish guidelines to minimize battery damage, particularly in high-vibration environments such as EVs or aerospace applications.

Table 4 highlights the effects of different vibrational conditions on lithium-ion batteries. Low-frequency vibrations cause minor capacity fade and negligible safety concerns, while high-frequency vibrations result in specified hotspots, increased resistance, and heightened thermal runaway risks. Six-degree-of-freedom vibrations lead to moderate heat rises, capacity loss, and safety risks from separator damage. Shock vibrations cause electrode cracking, severe capacity fade, and high safety risks from short circuits. Random vibrations show minimal heat effects but significantly increase resistance and structural risks over time. Coupled cycling and vibrations accelerates SEI layer growth, heat rise, and capacity fade, increasing safety risks. Over-discharge with vibrations triggers severe overheating, capacity loss, and thermal runaway risks. Marine vibrations show negligible thermal and performance impacts with minimal safety concerns, particularly in LFP batteries. Studies such as [1,8,17] revealed internal resistance increases of up to 257.82% in 18,650 cells subjected to random vibrations, attributed primarily to tab loosening and structural deformation. These findings provide valuable insights into mechanical degradation but lack material-level analyses. Incorporating advanced diagnostic tools like SEM or XPS could have helped to uncover critical degradation mechanisms, such as cathode cracking and SEI instability, to better predict long-term performance and safety. High-frequency vibrations were extensively studied in [15,76,80], showing localized hotspots of 2–3 °C, impedance growth of up to 40%, and 4–6% capacity fade, mainly due to cracking in NMC cathode materials. These studies effectively link mechanical stress to electrochemical performance loss. However, they fail to address the compounding effects of gas generation or prolonged electrolyte decomposition, which are critical safety concerns in extended operations. Future work should explore these prolonged degradation pathways and their impact on thermal runaway risk. In [16,18,24], six-degree-of-freedom vibrations led to 3–4 °C uniform thermal rises, 18.8% ohmic resistance increase, and capacity losses of up to 0.78 Ah after 200 cycles. While these studies successfully demonstrate the connection between mechanical stress and electrochemical degradation, they lack evaluations under high C-rate cycling conditions typical of electric vehicles. Such data are critical to optimizing battery design for demanding applications. Other papers [13,15,76] reported that shock vibrations caused 2–4 °C heat rises, separator deformation, electrode cracking, and capacity losses of 5–10%. These degradation mechanisms introduce high safety risks, such as internal short circuits and gas generation, which can lead to thermal runaway. However, critical evaluations of real-world thermal and mechanical stress interactions remain unexplored.

Some studies [5,17,80] focused on low-amplitude vibrations in marine applications, demonstrating minimal capacity fade (<1%) and negligible temperature rise (<1 °C). LFP batteries consistently outperformed NMC batteries in durability under these conditions. However, the effects of prolonged exposure to environmental factors such as salinity or humidity were not addressed, leaving a gap in the understanding of long-term marine battery performance. Research on PCM use for thermal management under vibrations [16,57,76] showed that PCM reduced the temperature rise by 2–4 °C, but uneven stress distribution within PCM layers was noted. These studies highlight PCM's potential for enhancing thermal performance but lack insights into its long-term durability under combined vibrational and cycling stress. Significant findings in [1,19,24] indicated 3–6 °C thermal increases and 5–12% capacity fade under coupled cycling and vibrations. These impacts were driven by accelerated SEI layer growth and lithium plating, which pose performance and safety concerns.

Table 4. Vibrational effects on lithium-ion battery performance and safety.

Vibrational Conditions	Thermal Impact	Performance Impact	Safety Impact	Citations
Low frequency: 5–20 Hz	Temperature rise of up to 3 °C (some papers do not confirm thermal impact)	Minor capacity fade (<2%); increased SEI layer growth and minor lithium loss observed in long-term vibration tests.	Low safety concerns: no critical deformation observed under low-stress conditions.	[1,7,8,24]
High frequency: 100–1000 Hz	Localized hotspots; temperature increase of 2–3 °C (validated)	Resistance increased by 10–40%; cathode cracking and SEI layer thickening caused a 4–6% capacity fade.	Increased internal pressure from electrode damage raises thermal runaway risks under high-stress conditions.	[18,19,76,80]
6-DOF Vibrational Stress: 20–200 Hz	Heat rise not explicitly discussed in some studies, 3–4 °C validated in others	Capacity loss of 0.78 Ah after 200 cycles; ohmic resistance increased by 18.8%.	Safety concerns arise from mechanical fatigue leading to separator damage, increasing short circuit risks.	[9,16,24,80]
Shock Vibrations: 30–100 Hz, Amplitude > 2 mm	Temperature increase of up to 4 °C (verified where noted)	Electrode cracking, separator deformation, and polarization resistance increase caused 5–10% capacity loss.	High safety risk from internal short circuits and gas generation during severe shocks.	[13,15,18,76]
Random Vibrations (SAE J2380)	No significant heat generation; temperature rise < 1 °C (validated)	Internal resistance increased up to 257.82%, especially in cylindrical 18650 cells.	Safety risks include tab loosening and structural deformation, which could lead to electrical faults over time.	[8,17,24]
Cycling and Vibrations Coupling	Heat rise of 3–6 °C validated	SEI layer growth accelerated; capacity fade between 5–12% over extended cycling with vibrations.	Increased safety risk from accelerated degradation and gas generation under prolonged stress.	[8,24,80]
Over-discharge Coupled Vibrations	Overheating observed; temperature rise to 55 °C validated	Severe capacity fade of 10–15%, driven by anode degradation and electrolyte decomposition.	High safety risk from thermal runaway triggered by anode collapse and rapid heat generation.	[18,19,76]
Marine Vibrations (low amplitude)	No measurable heat rise; confirmed negligible thermal impact	Negligible capacity fade (<1%); stable performance with no structural damage observed.	Minimal safety concerns; LFP batteries demonstrated high resilience under low-amplitude vibrations.	[5,17,80]

Despite identifying key degradation mechanisms, these studies fail to propose mitigation strategies, such as developing vibration-damping materials or optimized battery enclosures. Railway applications, analyzed in [5,15,18], showed controlled thermal impacts (<1 °C) and capacity fade of up to 12%, with LFP batteries showing superior vibration resistance compared to NMC batteries.

However, actionable recommendations such as advanced anti-vibration mounts or structural reinforcements are not proposed, leaving a practical gap in improving long-term performance. Aerospace-specific research [10,18,24] showed that long-term vibration exposure resulted in minor capacity fade and structural deformation in 18650 cells. However, these studies lack real-time monitoring of impedance and temperature, which are critical for ensuring safety during satellite missions. Incorporating advanced sensing systems could significantly enhance reliability evaluations. Innovative fault detection methods, explored in [7,11,12], focused on abnormalities such as tab loosening and electrode misalignment. While these methods demonstrate high sensitivity, they are not scalable or validated in dynamic field conditions for large modules. Future work could focus on the scalability and field implementation of these techniques. Papers such as [18,19,76] highlight SEI layer thickening and increased charge transfer resistance under sinusoidal vibrations. However, they fail to establish direct correlations between these impedance changes and physical damage mechanisms, such as electrolyte decomposition or electrode fractures. Coupling EIS with imaging techniques (e.g., SEM, TEM) could provide a more comprehensive understanding of the degradation pathways.

7.2. Effects of Vibrations on Battery Thermal Behavior and Degradation

Vibrations were found to increase the thermal load within batteries, as evidenced by studies showing up to a 5 °C rise in surface temperature under vibrational stress. This thermal response exacerbates degradation, as higher temperatures accelerate aging mechanisms such as electrolyte decomposition and electrode damage. Additionally, the review found that vibrational stress amplifies the need for robust thermal management systems, especially for high-energy-demand applications. This insight aligns with investigating vibration effects on thermal behavior and highlights that managing heat in vibrating environments is critical to prolonging battery life. Still, a gap remains in identifying optimal thermal management solutions tailored to mitigate the dual challenges of thermal and vibrational stress. Studies examining the efficacy of phase change materials, enhanced cooling channels, or advanced TMSs under vibrations could provide valuable insights.

7.3. Compromises to Safety, Range, and Operational Reliability

The studies confirm that mechanical vibrations can compromise battery safety and reliability, directly impacting range and operational stability. For example, vibrations induce capacity fade and increased internal resistance, diminishing energy output and reducing the range of EVs. Additionally, vibration-induced thermal effects exacerbate safety concerns by increasing the chances of thermal runaway under extreme conditions. This aligns with determining if vibrations compromise battery range and safety. However, existing research primarily focuses on immediate impacts, while long-term studies examining the cumulative effects of low-level, chronic vibrations on battery range and reliability are limited. Addressing this research gap could enhance predictions of battery lifespan in practical applications. Table 5 summarizes the factors influencing battery performance under various conditions. Vibrations cause structural failures, increased resistance, and degradation, which are analyzed using simulations and CT scans and are critical for applications such as EVs and aerospace. High temperatures accelerate degradation and thermal runaway, necessitating advanced thermal management for safer EV design.

Table 5. Factors affecting battery performance: analysis, methods, and applications.

Factor Affecting Battery Performance	Discovery	Testing/Analysis Methods	Application/Implication
Vibrations	Cause battery degradation, internal structural failure, and increased resistance.	Real-world vibration simulations, MEMS-based monitoring, CT scans.	EVs, aerospace, and transportation applications.
Temperature	High temperatures accelerate degradation and risk of thermal runaway.	Thermal management systems, temperature monitoring.	It is essential in EV battery design to prevent overheating and improve safety.
Mechanical Stress	It can lead to short circuits, material displacement, and internal damage in cylindrical cells.	Six-degree-of-freedom vibration tests, mechanical abuse simulations.	Impacts EV, motorcycle, and aerospace batteries due to structural concerns.
Environmental Conditions (Humidity, Pressure)	They influence battery life and require robust seals in lithium-ion cells.	Environment-controlled tests.	Critical for durability in EVs and e-bike battery transport.
Over-discharge	High-frequency vibration signals can indicate over-discharge, a potential safety concern.	Vibration signal monitoring for pre-emptive diagnostics.	Useful in high-energy-density applications like EVs to detect faults early.
Battery Health Monitoring	Innovations like laser ultrasonics and FTIR for SOC and degradation tracking.	Non-contact SOC monitoring, FTIR for chemical stability.	Enhances safety and longevity, especially in high-stress applications.
Phase Change Materials (PCMs)	Vibration-enhanced PCM-based TMSs show potential for improved cooling.	PCM-based thermal management testing under vibrations.	Applicable in EVs for temperature control without high energy costs.
Dual-Motor Powertrains	Reduce strain on battery systems, enabling consistent power distribution.	Real-time performance assessment.	Optimizes energy usage in EVs, extending battery life.
Fourier Transform Infrared (FTIR)	Identifies chemical stability changes over time due to vibrations.	FTIR techniques for initial failure signs detection.	It is essential for detecting early degradation signs in high-stress setups.
Standards and Testing Protocols (IEC 62133-2) [29]	Establishes consistency across battery applications, especially for large battery assemblies.	UN-standardized vibration testing protocols.	Critical for safety across industries like automotive and aerospace.
Structural Integrity	CT scans reveal hidden structural failures in batteries under vibrations.	Computed tomography scans.	Strong internal design in cylindrical cells (e.g., 18650).

7.4. Review of Degradation Mechanisms Due to Vibrations

The studies comprehensively examine degradation mechanisms, including capacity fade, impedance increases, and structural damage under vibrational stress. Various techniques, such as EIS and incremental capacity analysis, provide valuable insights into these mechanisms. The review meets its objective by identifying specific degradation pathways, confirming that vibrational stress can lead to mechanical failures that, in turn, impair electrochemical performance. However, despite these insights, there is a gap in understanding how different vibration frequencies and intensities impact degradation. A more granular exploration into how varying vibration profiles influence degradation mechanisms across different battery chemistries could improve the design of vibration-resistant battery systems.

8. Recommendations for Future Research

As lithium-ion batteries continue to play a pivotal role in modern energy storage solutions across industries such as EVs, drones, aerospace, and renewable energy systems, there remains a demanding need to address the challenges posed by their performance, safety, and longevity under diverse operating conditions. Vibrations, temperature extremes, mechanical stress, and environmental influences significantly impact battery reliability and efficiency. While significant progress has been made, gaps in understanding and technological innovation persist. Future research must focus on developing advanced diagnostics, robust materials, and innovative designs to optimize battery performance, ensure safety, and meet the demands of next-generation applications. This section highlights key areas for further exploration to advance lithium-ion battery technology.

8.1. Real-World Application Testing

Existing research has yet to fully simulate real-world vibration profiles under various operational conditions. For example:

Electric Vehicles (EVs): Studies like [24,80] highlight the need to replicate high-frequency vibrations caused by uneven road surfaces and braking scenarios. Future studies should integrate vibration profiles with dynamic cycling to reflect actual EV operations.

Aerospace Vibration Profiles: Research in [10] shows insights into long-term structural impacts of vibrations in satellite missions. However, it lacks real-time monitoring of impedance or thermal responses. Future work could include combined low-pressure and vibrational stress scenarios.

Marine Applications: Low-amplitude marine vibrations were studied in [5,17], showing minimal thermal and performance impacts. However, the influence of salinity and long-term exposure to humidity remain unexplored.

Such real-world simulations would ensure battery designs meet the durability and safety requirements of automotive, aerospace, and marine environments.

8.2. Material-Level Diagnostics

Microstructural and chemical degradation mechanisms remain underexplored. For example:

Advanced Imaging Techniques: Incorporating scanning electron microscopy (SEM) and transmission electron microscopy (TEM), as used in [18,76], can help to visualize microcracks, cathode fractures, or separator deformation under vibrations.

Electrochemical Impedance Spectroscopy (EIS): Studies like [19,29] revealed increased charge transfer resistance under sinusoidal vibrations. However, coupling EIS with X-ray photoelectron spectroscopy (XPS) could better correlate impedance growth with SEI changes.

These advanced diagnostics would provide a comprehensive understanding of vibration-induced material degradation.

8.3. Vibration-Tolerant Battery Design

Enhanced battery designs are necessary to mitigate vibrational impacts. Examples include:

Vibration-Damping Materials: Studies like [16,76] suggested using elastomers or composites to absorb vibrational energy. However, further exploration is needed to optimize such materials for different frequency ranges.

Structural Optimization: As highlighted in [13,15], evenly distributing mechanical stress across battery modules reduces localized damage. Innovative designs could integrate optimized enclosures and anti-vibration mounts.

Phase Change Materials (PCMs): Research in [57,76] demonstrated that PCMs reduced temperature rises by 2–4 °C during vibration. Future work should focus on their long-term stability and effectiveness under combined cycling and vibrational stress.

Improved designs will enhance both performance and safety in vibration-prone applications.

8.4. Combined Thermal and Mechanical Stress Testing

Few studies simultaneous address thermal and mechanical stresses, although their coupled effects are critical in real-world conditions. For instance:

Simulating Coupled Stresses: Studies like [24,80] highlighted significant heat rises (3–6 °C) during cycling and vibration. Extending these studies to include high C-rate cycling or high-frequency vibrations could provide valuable insights.

Thermal Runaway Risks: High-temperature scenarios combined with vibrations, as discussed in [29,76], increase the risk of catastrophic failure. Real-time thermal and structural monitoring systems should be developed to capture early warning signs.

Understanding the interplay between thermal and mechanical stresses will guide safer battery operation and design.

8.5. Predictive Modeling and AI Integration

Machine learning can revolutionize vibration research. For example:

Predictive Models: AI-based modeling, as suggested in [12,80], can predict degradation patterns under vibrations, reducing testing time and costs.

Digital Twins: Virtual replicas of battery systems could simulate vibration and stress scenarios, identifying weak points without extensive physical testing.

Such tools will streamline research and development while improving battery reliability.

8.6. Addressing Long-Term Safety Concerns

Safety concerns from vibration-induced damage require more attention. For example:

Gas Generation Analysis: Research in [19,76] identified gas formation as a significant risk under high-frequency vibrations. Future studies should quantify gas buildup and its impact on thermal runaway risks.

Real-Time Monitoring: Real-time systems discussed in [8,29] could detect early signs of mechanical damage, such as tab loosening or impedance growth. Standardized protocols addressing these concerns will significantly enhance battery safety under vibrational stress.

8.7. Gaps and Future Directions

- Thermal Runaway Risks: Most studies fail to investigate vibration-induced thermal runaway under combined thermal and mechanical stress.
- Advanced Diagnostics: Limited use of advanced characterization techniques (e.g., SEM, TEM, XPS) to correlate microstructural changes with performance degradation.

- Real-World Scenarios: Few studies simulate real-world conditions (e.g., EV dynamics, aerospace vibration profiles), leaving applicability gaps.
- Mitigation Strategies: The research lacks proposals for effective vibration-damping materials or optimized cell designs for enhanced durability.

9. Conclusions

This review explores how vibrations affect lithium-ion batteries' performance, degradation, and thermal behavior, which is crucial for technologies such as EVs, aerospace systems, and marine applications. Vibrations can cause structural damage, such as electrode delamination and separator deformation, which increases internal resistance and generates hotspots. These effects make thermal management more challenging and accelerate battery aging. Vibrations also significantly contribute to dendrite formation, self-discharge, and lithium plating. These processes reduce the battery's capacity and lifespan and increase safety risks such as short circuits and thermal runaway. To address these challenges, there is a pressing need for more realistic testing protocols that replicate the combined effects of vibrations, temperature, and mechanical stress. Enhancing TMSs with advanced cooling techniques and materials, such as phase change solutions, can help to mitigate these issues. Additionally, designing batteries with vibration-resistant materials and improved structural integrity will be crucial for increasing their durability. Long-term studies focused on the cumulative effects of vibrations and their role in promoting dendrite growth, self-discharge, and lithium plating are essential for better predicting battery life and reliability. Building on this, our current research uses a multiscale physics-based modeling approach to explore how vibrations interact with thermal behavior and contribute to battery degradation. At the same time, we are developing an electromechanical system to analyze the impact of mechanical degradation on thermal and electrical performance. This work focuses on understanding how vibrational stresses influence key processes such as internal resistance rise, SEI layer growth, dendrite formation, and lithium plating. It also examines how they affect the battery's structural and thermal stability. By combining computational models with experimental data, this research aims to develop tools and strategies to improve lithium-ion batteries' safety, reliability, and lifespan in demanding environments.

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