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Review

A review on electrical and mechanical performance parameters in lithium-ion battery packs

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ABSTRACT

Lithium-ion batteries are the most prominent power source for electric vehicles. The continues use at different environmental conditions demand accurate electrical and mechanical functionality. Most of the research paper published provide information to describe these conditions covering only one or a very few parameters. It leaves aside a holistic and comprehensive study to evaluate performance in lithium-ion battery packs. This review paper presents more than ten performance parameters with experiments and theory undertaken to understand the influence on the performance, integrity, and safety in lithium-ion battery packs. However, when the parameters are reviewed, it is concluded, that vibration and temperature critically affect the electrical and mechanical performance and are inherent to the operation conditions. Through the present work, it was found that limited literature exist that clearly define the influence of temperature and vibration. Therefore, comprehensive research still needs to evaluate the influence of the thermo-mechanical coupled loads on the battery performance. This review concluded that it is fundamental to perform the mentioned research to improve the battery pack performance and safety. In addition, it proposes an innovative technical solution to the automotive industry and can be a novel contribution to academia.

1. Introduction

One of the major challenges today is to maintain a balance between the demand for energy and its negative side effects. (Dinçer et al., 2017). The consumption of fossil fuel bring with it emission of CO_2, air pollution, global warming, and degradation of the environment. (Gaur and Singhal, 2020)(Niu et al., 2019). Considering that 80% of the energy is derived from fossil fuel, global energy is dependant between countries causing geopolitical problems (Scrosati et al., 2015). A major alternative to undertake the problems of environmental pollution and energy dependency is to diversify the energy requirements in the transportation sector (He and Chen, 2013). One of the options comes under this diversification is the use of battery technology.

The adoption of electrification in vehicles is considered the most prominent solution. Most recently, lithium-ion (li-ion) batteries are paving the way in automotive powertrain applications due to their high energy storage density and recharge ability (Zhu et al., 2015). The popularity and supremacy of internal combustion engines (ICE) cars are still persist due to their lower cost and higher range in comparison with the electric vehicles (EV) (Warner, 2015). For this reason, efficiency in terms of battery performance is a key subject for development and research. Clearly, by improving the performance of the battery packs, not only would use the electric car for economical but also for an environmental reason.

One of the issues that directly influence performance in the battery is heat from the external environment or from the internal components (Dubarry et al., 2014). However, the environmental conditions also include the vibration induced by roads during driving (Shui et al., 2018). Consequently, the vehicle's safety, reliability and performance heavily depend not only on heat but also vibration. There are pieces of evidence to understand that both the academic and the industry have studied battery performance based on rather vibrations or thermal loads. However, there has been limited research that combines both, vibration and temperature, to assess the overall performance.

The presented review aims to summarise all the past published research which describes the parameters that influence performance in lithium-ion batteries. During this review, it has been found that most of the research papers provide information, covering only one or very few parameters to describe the decrement of power in the battery, leaving aside a holistic and comprehensive study to critically evaluate the

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performance. However, when the temperature and vibration parameters are critically reviewed, it has been found that a comprehensive effort is still required to evaluate the effects of thermo-mechanical coupled loads on the structure and power performance.

In this paper, the fundamental of battery technology is described initially to provide basic concepts to understand the battery functionality in the electric vehicles. Later, this review paper presents experiments and theory for more than ten performance parameters, intending to understand the effects in performance, integrity, and safety in lithium-ion batteries. Comprehensive knowledge of performance parameters will provide the ability to more clearly identify the influence of the temperature and vibration in a thermal-couple load. This review concludes that many research articles identify that variations in temperature and vibration during driving conditions are inherent to the operation of the battery pack in electric vehicles. However, when both concepts are review critically, it is evident that a comprehensive study on thermo-mechanical couple loads for performance evaluation can be a novel contribution to the academic and industrial domains.

This paper is organized as follows: Section 3 present the fundamentals of battery technology, introduction of battery management systems and vehicles configuration. This paper reviews the state of the battery such as state of charge (SOC), state of health (SOH), state of function (SOF), state of power (SOP), state of balance (SOB) and state of energy (SOE).

Section 4 describe different experimental methods published to evaluate safety, reliability and performance in the battery and cells. For example, mechanical durability test is conducted to assess the failure and safe functionality of the battery. Results from a shape battery test reveal the influence of vibration in the internal resistance and capacity rate. A non-uniformity of cell test indicates that the variation in the cell voltage influence the valence of the state of charge. Finite element (FE) method is implemented to evaluate the strength, stiffness, anti-vibration and impact resistance in battery packs. In cells, FE method is utilized to simulate crushing effects, cell compression, impact simulation, mechanical deformation, and failure.

Section 5 of this paper provides an efficient alternative to evaluate a battery pack design with multi-objective design paraments. Different optimization methodologies are described to reduce mass and weight, avoid high stresses and deformations, and maximise the resonant frequency. Optimization with surrogate models, parametric reduce order models and other numerical models are developed to account probabilistic force response to measure vibration caused by prestress and structural variations.

Section 6 describe the influence of thermal loads in the battery capacity, degradation and lifetime in relation with the operating temperatures. Different traditional management systems and their principles of operation are mentioned. Finally, the causes and consequence of thermal run away are described and the importance of detection and prevention. In the last table, a summary of performance parameters are listed with the limitations, key findings and relevant authors. Conclusion are presented at the end of the review paper.

2. Methods

With the objective to identify the performance parameters that influence the battery structural and power performance in lithium-ion battery packs. An extensive research in recent publications was conducted to obtain a comprehensive literature review. The information stablished in this article comprises four steps: (i) The journal articles were found by given key words in the search option of "Scopus" abstracts and citation database. (ii) By reading the title, abstract and conclusion, the papers for the study were selected. (iii) The relevant papers were read, and the research problem, methodology and limitations were conceptualized. (iv) Any content related to the improvement or deterioration of batteries were accounted to build the theory. Critical information describing performance base on vibration and temperature are the basis of the study.

2.1. Selection of data for literature review

The information for the literature review was founded using the abstract and citation databases Scopus and Google Scholar. The search criteria were related to structural and power performance evaluation of lithium-ion battery pack for electric vehicles under operating and environmental conditions. Key words were stablished and introduced in the search option of the engine database. For example, "Battery Pack, lithium-ion battery, Electric Vehicle, Vibration, temperature, Battery degradation, aging, optimization, battery design and thermal loads." As a result, more than 250 journal papers were listed, and then filtered by reading the title, abstract and conclusions, after that, the more relevant papers for the research were completely read for the literature review.

2.2. Extraction of relevant information for the research

After reading all the articles as a part of the literature review, the construction of the database was created considering the research problem, methodology and limitations of the research. Then, the objectives of the research and the research gaps were identified to outline the structure of the review paper. The relevant information which mentions decrement in the electrical and structural performance during operating conditions is selected for the elaboration of this review, as well as the methodology applied to recognise, measure, and solve this problem of decrement or failure.

In addition, information from standards, regulations, magazines, and books were valuable in this research and contributed significantly to the information for literature review and therefore for the contents of this review paper.

3. Fundamentals of battery technology

An automotive lithium-ion battery pack is a device comprising electrochemical cells interconnected in series or parallel that provide energy to the electric vehicle. The battery pack embraces different systems of interrelated subsystems necessary to meet technical and life requirements according to the applications (Warner, 2015). The expand of the technology depends on the cost, safety, cycle life, energy density and power density. For this reason, different material inside the cells are implemented to meet the characteristics and management systems and controls are introduced to maintain safety and reliability in the battery operation (Liu et al., 2019).

The application of the battery requires the interconnection of cells and modules to meet the voltage and current demand. In the parallel connection, the system capacity increase, and the cells are connected positive to positive or negative to negative. In the series connection, the system voltage increase when the cells are connected negative to positive (Dinçer et al., 2017; Warner, 2015). As the performance is restricted by the weakest cell, it is recommended to build modules with a minimum number of cells in a series connection and a minimum of two cells in parallel to ensure reliability (Huat et al., 2016).

Battery technology is an expanding subject due to the high demand in electric vehicles. Consequently, it combines different disciplines, sciences and technologies for the implementation of new products. However, the principles and concepts applied are similar despite the hight variation in multiple applications. The objective of this chapter is to recap basic concepts which are beneficial to understand the functionality of the cell, battery and systems.

3.1. Cell

The cell is a closed power source where the chemical energy is kept and release in its active materials. This chemical energy can be converted directly into electric energy by an electrochemical reaction

(Johnson Matthey Battery Systems, 2015). The electrochemical cell contains a positive and a negative electrode, which are electronic conductors usually made of aluminium or copper. In the electrodes, the redox reaction occurs in contact with the electrolyte, then, the current flows via the movement of the electrons.

Multiple variations in cell chemistry are used in electric vehicles. For example, Lead acid, nickel cadmium (NiCd), nickel metal hydride (NiMH), and lithium-ion (li-ion). However, big advantage in high energy density, high charging and discharging rates, low maintenance and cost make advantage in the lithium-ion cells with respect with other chemistries (Huat et al., 2016). Despite different materials are utilize in the lithium cells, the batteries are named in regard to the cathode composition such as lithium Cobalt oxide ($LiCoO_2$), Lithium Nickel Cobalt Aluminium Oxide (NCA), lithium-ion phosphate (LFP) and lithium manganese Oxide ($LiMnO_4$). The variations in the cathode provide different alternatives of battery characteristics for multiple applications.

The interconnection of different cells with a tap is considered to be a battery system and therefore requires a management system to control the electrical properties and a cooling system to remove the heat and maintain safety at different operational temperatures (Schröder et al., 2017). The topology of the cells depends on the outer shape, most commonly divided as pouch, prismatic and cylindrical, cell as shown in Fig. 1.

3.2. The state of a battery

The battery state is utilized as an input for electrical management and control and for the user to estimate the expected lifetime of a battery. The battery state estimations are critical for the BMS optimization and function in order to provide reliable operations and safety management to the battery pack (Piller et al., 2001).

The state of the battery is mainly defined by two parameters: state of charge (SOC) and, state of health (SOH). Both parameters influence performance in the battery and are dependant on each other (Jossen et al., 1999). However, other basic operations of the BMS such as the estimation of the function, remaining power and energy, balance control, and thermal management, demands other useful estimation of the battery states, for example, the state of function (SOF), state of power (SOP), state of energy (SOE), state of balance (SOB) and state of temperature (SOT).

3.2.1. State of charge (SOC)

For a definition, SOC is the ratio of current capacity "Q(t)" to the nominal capacity "Qn" as shown in equation (1), where the nominal capacity represents the maximum amount of charge capable to store in the battery given by the battery manufacturer (Chang, 2013). The value is usually given in percentage.

$$SOC = \frac{Q(t)}{Qn} \tag{1}$$

The Coulomb method is perhaps the most common technique implemented to calculate the SOC. It considers both, the battery current (I_{batt}) and the battery consumed by the loss reaction (I_{loss}). Consequently, the current flow is integrated and added to the initial SOC (Chang, 2013). In equation (2), CN is the rated capacity (Piller et al., 2001).

$$SoC = SoC_{initial} + \frac{1}{C_N}\int_{t_0}^{t}\left(I_{Battery} - I_{loss}\right)d\tau \tag{2}$$

The state of charge estimates the reliability of a battery and provides information such as remaining available energy and time. SOC also guides the design for charging and discharging strategies, which are very important in a high current application, where different capacity values in the cells are possible to appear due to variations in aging, degradation, and manufacturing variations (Zhang and Lee, 2011). The SOC and voltage sequences are implemented to calculate the / discharge energy (RDE) which are the fundamentals for the estimation of driving range in the electric vehicle (Lai et al., 2022b).

3.2.2. State of health (SOH)

The state of health is fundamental to evaluate the lifespan, health prognosis and condition of the lithium-ion batteries. The estimation of the SOH reflects the fraction of allowable performance left before the end of life (Wang et al., 2013). The SOH is characterised by the capacity degradation and the increase in the internal resistance (Balagopal and Chow, 2015). It is considered 100% at the beginning of life and 0% at the end of life. In automotive applications, when the battery of the vehicle reaches 80% of SOH, it is assumed that the battery life ends (Wang et al., 2013) and it has to be retired from the electric vehicle for safety. Then, the secondary utilization of the battery in other applications is relevant to extend the life cycle and maximise its value (Lai et al., 2022a)

$$SOH = \frac{Qmax}{Qnew} \tag{3}$$

The *Qmax* is the maximum available capacity and the *Qnew* is the available capacity when the battery is new (Wang et al., 2020).

3.2.3. State of function (SOF)

The SOF determine if the battery has sufficient power capability to support the application in its current state to carry out a specific function. This functionality is derived from a transient behaviour and it is an instant yes/no parameter. In many cases the SOF is quantify by using SOC, SOH and temperature to predict the actual conditions and performance of the battery (Zhang and Wierzbicki, 2015). In Fig. 2, Vocv is the open-circuit voltage, r_0 and r_1 are two different resistance and i is the current.

The Randle equivalent circuit voltage of the battery is utilized to calculate the maximum power within the voltage limits (Juang et al., 2012).

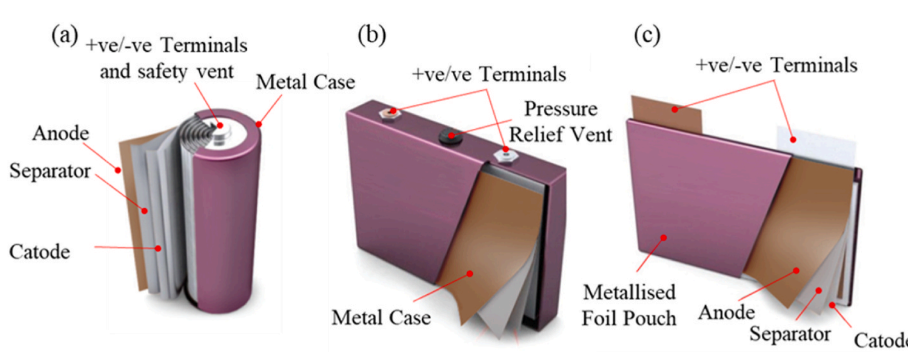

Fig. 1. Types of cell construction. (a) Cylindrical cell; (b) Prismatic cell; (c) Pouch cell (Johnson Matthey Battery Systems, 2015).

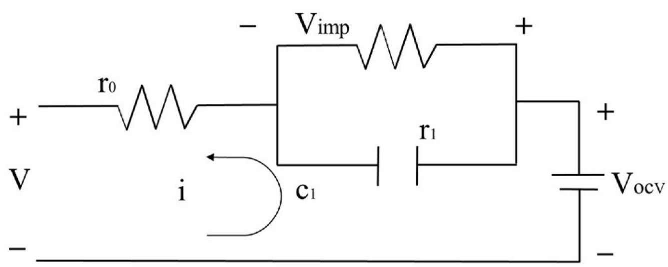

Fig. 2. Randle battery equivalent circuit model (Juang et al., 2012).

$$SOF = \begin{cases} 1 \; if \; Vmin, \geq Vlimit \\ 0 \; if \; Vmin, < Vlimit \end{cases} \tag{4}$$

The objective of the SOF is to predict the current voltage at specific charge or discharge events. It is commonly used in HEV application to identify whether the battery can response to a vehicle duty such us acceleration, deceleration, and standstill periods. The prediction of the values by the BMS define If the actual energy strategy should be sufficient or needs to be updated. The application is useful for management consumption because the SOF can define the phase for boost charging or discharging when is economically convenient (van Bree et al., 2009).

3.2.4. State of power (SOP)

It is the battery capability to provide charge and discharge power under certain voltage and current limit. It is measured as the percentage between the peak power and the rated power. The peak power cannot exceed the thresholds and is the maximum power measured in a short period of time. The prediction of the SOP in the BMS is important for battery users to predict the available power in the immediate future (Wang et al., 2020).

To calculate the SOP, it is considered the charge and discharge power capabilities. When voltage is set to its maximum in the battery the discharge power is obtained, and the discharge power capability is found when minimum voltage value is account (Wang et al., 2011). Consequently, the maximum power that the battery can deliver is driven by the voltage limit (Juang et al., 2012) as expressed in Eq. (5).

$$SOP = \frac{Vlimt(Vocv - Vlimit)}{ro + r1} \; [W] \tag{5}$$

3.2.5. State of balance (SOB)

The SOB is designed to evaluate the characterization of the cell capacity balance state and regulation as well as the comprehensive characterization and balance for the complete battery pack. The factors considered for the estimation process of the SOB are the internal resistance, maintenance current, temperature, cell voltage and pack voltage. The adjustment process is done base on the equalization strategies, credibility and preferences (S. Wang et al., 2016a)

Despite SOB is a novel concept proposed by wang el. al, in high power battery packs (Huang et al., 2021), resent studies has introduced SOB to describes the balance state in lithium-ion applications. For example, Wang et al., utilized the SOB to descries the balanced state of an aeronautical lithium-ion battery pack for parallel and serial connected cells and proposed and investigated how the SOB influence in the SOC estimation (Wang et al., 2018).

3.2.6. State of energy (SOE)

The main function of the battery is to store and release energy. For this reason, it is highly significant to describe the state of the battery from the viewpoint of energy. The SOE estimation provides the running distance and endurance time for EV considering the remaining energy relative to the maximum available energy in percentage (Mamadou et al., 2012). It is meaningful for the vehicle to identify the range to predict how far drivers can travel (Wang et al., 2020).

The definition of SOE was first mentioned by Mamaduo et al., they developed an algorithm to calculate the SOE considering the available energy when the battery is discharging down to its lowest voltage.

$$SOE\alpha[\%] = \frac{e^{Ynom|SoE\alpha}}{E^{nom}} \tag{6}$$

When the battery is in a discharge condition, the purpose is to express the available energy, as is shown in Eq. (5), where $SOE\alpha$ is any state of energy, e ^{Ynom} is the nominal discharge condition and E^{nom} is the original energy.

3.3. Battery management system (BMS)

The BMS is an essential component in a battery pack of multiple cells (Johnson Matthey Battery Systems, 2015). It consists of software with algorithms to determine the battery states (Berecibar et al., 2016). The BMS has electronic controllers that monitor the temperature and voltage, control the charging and discharging, balances the cells, manage the safety function of the cell, and communicates with the vehicle (Warner, 2015). The performance of the battery not only depends on the BMS that controls the charge and discharge but also depends on the stability of the battery in the vehicle as vehicle steering characteristics and vibration changes on account of the ground roughness (Fan and Sun, 2017).

The main objectives of the BMS are to protect the cell, protect the battery, maintain the battery according to requirements of the application and interface with the host application (Johnson Matthey Battery Systems, 2015). The BMS protects the battery against over-charging, over-discharging, high temperature, low temperature, and short circuits. The BMS ensures the best performance of the battery at any time, provide control of the operational conditions, prolong life and guarantee safety (Rahimi-Eichi et al., 2013).

3.4. Vehicle configuration

In traditional vehicles, powered by an internal combustion engine (ICE), the chemical energy is converted from the fuel into heat in the combustion chamber. Then, the heat is utilized to produce the kinetic energy in a way of rotation (Dinçer et al., 2017). In battery electric vehicles (BEV), the electric motor use electric power directly from an onboard battery to propel the vehicle. In theory, the electric vehicles don't produce gas emission to the environment during its operation but in practice, the pollution impact depends on the energy production source used to charge the battery.

If a vehicle utilizes more than one form of onboard energy to provide propulsion, it is considered a hybrid vehicle. In hybrid electric vehicles the energy source is storage in a conventional fuel tank and a battery pack, so the energy is utilized by an internal combustion engine and an electric motor to propeller the car. These cars are closer to internal combustion engine vehicles because they depend only in fuel for consumption as the battery store the energy from a regenerative brake which convert kinetic energy into electric energy (Dinçer et al., 2017).

The operation of the plug-in hybrid electric vehicles (PHEV) is comparable to the hybrid electric vehicles but the advantage of plugging the battery into an external source for recharging, increase the driving range of the car. This vehicle combines all kind of energy sources of electric vehicles, given more options to customer needs, proving a real alternative for internal combustion vehicles.

In PHEV, usually the internal combustion engine works in parallel with the electric motor, where the electric motor is located in between the transmission and the engine. This configuration offers the same driving range as the traditional ICE vehicles (Warner, 2015).

The extended range electric vehicle (EREV) is a hybrid in series where the motor is not in line with the engine. Despite the electric motor is predominant in the operation instead of the engine, the vehicle can use one or the other of both at the same time as an energy source. However, the electric motor always powers the vehicles propulsion. The battery is not recharged in this mode, the engine operates as a generator to power the electric motor meanwhile the battery is as its minimum charge until it is plugged in for recharging (Warner, 2015).

4. Performance evaluation for the battery pack

From the mechanical perspective, vibration resulting from acceleration, surface road, and collision are the influence factors with affect the mechanical performance of the battery pack (Shui et al., 2018), and so, it is important to clearly understand the vibration magnitude and frequency absorbed by the battery. The experimental methods can be designed to evaluate fail and safe functionality of the battery pack or to assess the mechanical durability of the complete system (Choi et al., 2013; Zhang and Wierzbicki, 2015). Due to the application of battery technology is relatively new in electric vehicles, standardization of battery tests are limited and not yet properly defined. For example, the methods and procedure vary between standards given discrepancy in the results. For instance, the selection of standards is subjective to validation engineers that eventually determine the status of the battery even though the test might not be the most adequate for the application.

When a battery pack is integrated into the vehicle, it becomes a more complex system encountering many safety problems. The problems are at micro level which requires a deeper understanding of fundamentals in physics and chemistry in the cell. Other problems are at macro level such as shocks, vibration and insulation (Garg et al., 2016) which require analysis of the mechanics in the enclosure. The safety and performance are evaluated on experimental or numerical methods; both can be implemented at micro and macro level. However, limitation for obtaining measurements at micro level sometimes imply expensive and difficult forensics inspection while the numerical methods are more economical and suitable than experimental methods.

4.1. Experimental test in components

Vibrating components exposed to time-varying loads are highly susceptible to fatigue failure. Nonetheless, the components have to accomplish a durability certification test before the production face. The test can be conducted in a real prototype or by using computer-aided engineering (CAE) models for the simulation (Halfpenny, 2006). In the automotive industry, the validation of the batteries are approved by prototype test, even though simulation is less cost. There are still limitations to correlate experimental test with CAE models due to complexity in non-linearities in the behaviour of the parts. Complex models demand extensive computational time, and therefore, new mathematical methods and algorithms are developing to reduce processing time.

The tests are conducted during the development process to ensure that the subassemblies and components are robust and fit-for-purpose. The test also allows original equipment manufacturers (OEMs) to obtain valuable information for CAE, manufacturing and simulations, and confirms that the components meets specifications for vehicle homologation (Brand et al., 2015). In addition, testing make available a lot of data that can be stored. If any failures occur during the product guaranty, test data can be used to investigate the root case and provide a solution to the problem.

4.2. Experimental test in cells

Internal short circuits are the most common failure of cells during the normal operations; hence, experimental methods have been adopted to mitigate the consequences and understand the effects of short circuit events. The mechanical tests developed use mechanical deformation to damage the cell, as the well-known example of a nail penetration test (Cai et al., 2011). The tests are limited as an evaluation technique because it is no possible to replicate an accident of a vehicle, nonetheless, the technique only shows the consequences and behavior of the cell under an abusive event or a damage condition.

At the cell level, there are several tests utilized to validate models and simulations. For example, static tests, which mainly focused on obtaining data for materials, cover mechanical stress and strain, bending, creep, force-displacement, and tolerance change during discharge and charge. And the dynamic test, which mainly focused on crashworthiness and robustness of the cell due to crush, penetration, impact resistance, mechanical shock, and the effects of temperature and decompression (Hooper et al., 2016).

The dynamic and static research is determined by vehicle crash homologation, accreditation requirements, and transport legislation. The safety performance of the EV relies on the safety performance of the battery pack under different environments. Thereby, research on battery pack safety is considered seriously in recent years (Li et al., 2017). As a result, the reliability and safety of battery packs represent the biggest challenges to the large-scale electromobility in the public and private sector (Arora et al., 2016).

4.3. Experimental test in shape batteries

The shape of the battery pack influences the performance and stability when the battery is exposed to vibration and shock (Yoon et al., 2019). Yoon et all., measured the internal parameters before and after the experiments in a cube and a rectangular parallelepiped battery pack as illustrated in Fig. 3. The test demonstrated that the “rate of capacity decrease” is lower, and the “rate of resistance” increase is high in the cube battery in comparison with the parallelepiped battery (Yoon et al., 2019).

Although, the experiments and analysis were conducted to identify a suitable shape for a battery pack for aerospace applications. A precise information of the internal parameters in the cell and the battery provides information for an accurate prediction of the SOC and SOH, which can be applied in automotive application with the implementation of an electric circuits and battery degradation models.

4.4. Non-uniformity of cell design

The total performance of the battery rely on the individual performance of the cell and the connection arrangement of the cells (Niu et al., 2019). Base on this statement, the ideal capacity and the life cycle depend on the uniformity of the performance parameters such as capacity and voltage (Niu et al., 2019), as it is represented in Fig. 4.

The Imbalance of cells is triggered by internal or intrinsic sources and external or extrinsic sources to the cell properties. The internal sources involve manufacturing alterations in physical volume, self-discharge rates, and internal impedance. The external sources consist of thermal differences across the battery pack or variations in the contact resistance amount of the cell (Gallardo-Lozano et al., 2014).

For battery management, it is required to accommodate such internal imbalance and to diminish the impact from the external attributes to minimise the risk of cell degradation and failure (Warner, 2015). For batteries configurated in series, voltage balancing techniques exist in the battery BMS to protect the cell for degradation and increase the battery life (Kizilel et al., 2008; Lee and Cheng, 2005). However, due to the different electrochemical characteristics in each cell, the voltage balancing in the pack does not ensure a balanced SOC (Kim et al., 2010). Consequently, the cell can be over-charged or over-discharged.

The frequent battery charging and discharging currents trigger repeatedly imbalance voltages which force continuous circulation of balancing current in the BMS circuit affecting the loss of the energy of the battery and the thermal design (Kim et al., 2019). In Fig. 5, imbalance SOC can be observed at 3.5V when a discharge current of 4A is applied in 10 lithium-ion new cells in a series arrangement (Kim et al., 2010).

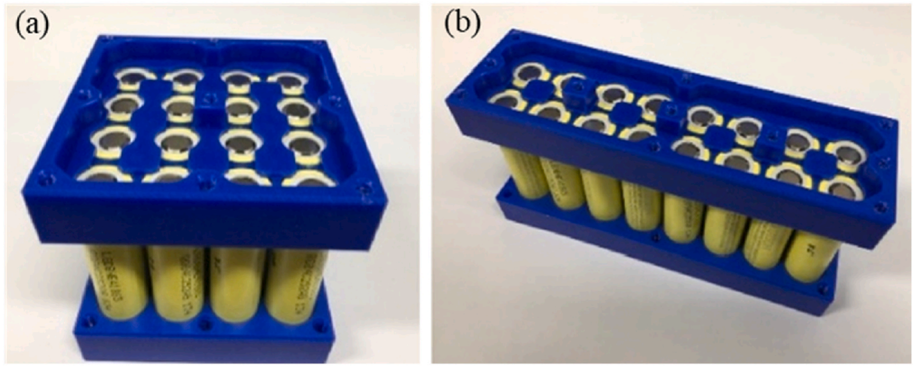

Fig. 3. Battery pack design shapes. (a) Cube; (b) Rectangular parallelepiped (Yoon et al., 2019).

Fig. 4. Non-uniformity criteria in cells of a battery pack (Niu et al., 2019).

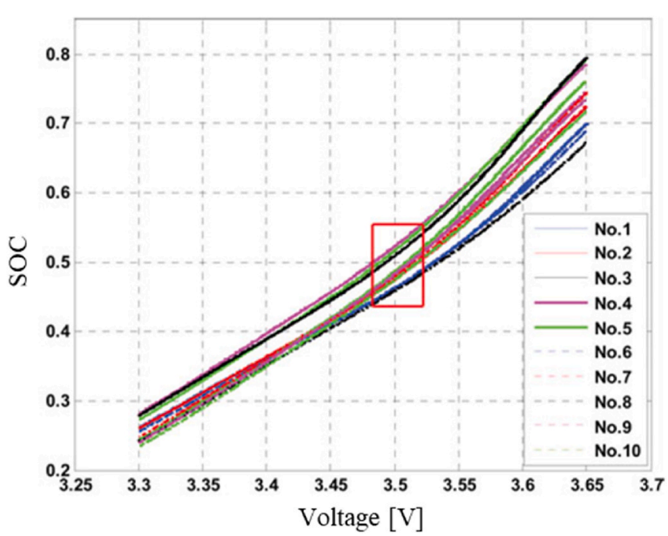

Fig. 5. Discharging curves of fresh cells with a discharging current of 4A (Kim et al., 2010).

The capacity loss occurs when cells in series connection have different initial capacity (Kim et al., 2010). When they are used together, and the cells are not balanced, the battery has less available capacity (Baughman and Ferdowsi, 2006; Cadar et al., 2010). This unbalance causes that the weakest cell reaches the minimum discharge level before the rest of the other cells. When frequent discharge and charge currents are applied, voltage imbalance in the cells constantly emerges and triggers a continuous circulation of balancing current as mentioned (Kim et al., 2010).

In a series connection, the capacity of the battery depends on the capacity of the weakest battery cell because, in the discharge and charge process, this cell reaches the minimum or maximum discharge level before the rest of the cells (Kim et al., 2010). Consequently, the variation between cell to cell due to the manufacturing process influences the performance of the battery model which depends on the weakest cell (Kenney et al., 2012). Fig. 6, shows a capacity mismatch in a battery and how the cell with lower capacity (weakest cell) limits the total capacity of the series string connection (Kim et al., 2010).

An accurate simulation battery pack can be achieved when cell-to-cell variations are considered in the model. Dubarry et al., use a generic equivalent circuit model, validated with single-cell experimental data, to predict single-cell model performance essential for the accuracy in the battery pack performance simulation results (Dubarry et al., 2009).

The cell balancing is achieved by converting the excess energy of the highest SOC cell into heat. This passing balancing method use a resistor integrated into the BMS slaves. In an active balancing system, the higher energy of the SOC cells is transferred to the lower energy SOC cells (Warner, 2015). Although, this method doesn't waste anergy, the external hardware requires more space in the battery and add an extra cost. As a result, the passive balancing is predominantly used in batteries for electric vehicles.

It is important to keep the voltage of the cells between the design limits, otherwise, damage in the cells will arise. For example, deep discharge can destroy the battery, and overcharging can destruct the cell with overheating (Cadar et al., 2010).

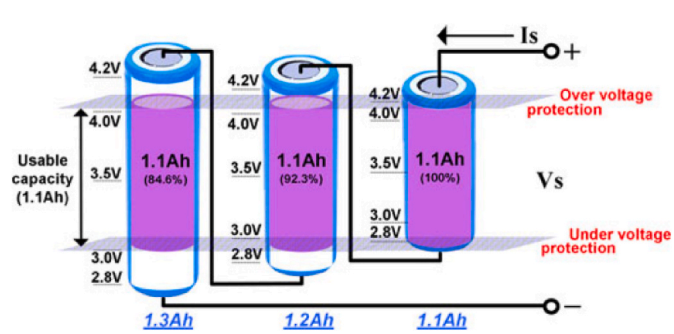

Fig. 6. Different capacity in each cell affects the performance of the battery (Kim et al., 2010).

4.5. Numerical method (finite element analysis)

Finite element (FE) analysis has proved to be an efficient analysis method to assess the structural strength and stiffness and therefore it is also used to analyse battery pack anti-vibration and impact resistance (Li et al., 2017).

In cell applications, FE methods are utilized to simulate crushing effect in cylindrical cells. For example, Avdeev et al., obtained experimental data to define the stress-strain curve in a finite element model for crushing simulation of a cylindrical cell between two plates. In the experiments, the nonlinear deformation was observed using a high-speed camara and the lateral characterization by computer tomography. In this study two homogenization methods were developed and compered for the jellyroll of the cylindrical cell (Avdeev and Gilaki, 2014).

Xu et al., studied the mechanical integrity of a prismatic cell based on mechanical strength theory subjected to dynamic loads. By considering the experimental data, the FE analysis was calibrated to predict the dynamic behaviour of the cell (Xu et al., 2015). Most of the studies in cells are focused on quasi-static behaviours to identify safety issues. However, several electrical and mechanical damage emerge due to extreme dynamic loads such us impact and crushing where the mechanical integrity and failure mode still needs to be solved.

The finite element method is utilized in pouch cells and assembly of cells to predict mechanical deformation and failure (Choi et al., 2013; Sahraei et al., 2012). The application of computational models in individual cells and modules provides data for advanced optimization in strength and weight as well as information for safety assessments in lithium-ion batteries (Sahraei et al., 2012).

Vibration is an important issue for the design of battery packs and optimization software such as OptiStruct is used to rise the natural frequencies of the battery housing above the range of model vehicle exciter frequencies (Hartmann et al., 2013). The design pretended to increase the stiffness of the battery pack and reduce the thickness of the wall to reduce the weight.

Impact tests for crashworthiness homologation of battery packs are very expensive and time-consuming (Uerlich et al., 2020). Consequently, simulation using numerical methods arise as a viable alternative for testing. Finite element analysis (FEA) has been applied in crash simulation for analysis in vehicles and component modelling (Thaler and Watzenig, 2014).

4.6. Vibration inputs for mechanical durability, safety, and performance

The consequences of mechanical loads occurring in a real-world driving condition usage on lithium-ion batteries needs to be considered. However, little research has been published on this topic (Brand et al., 2015). Moreover, mechanical tests given by standards aim to dictate only a pass-fail statement. Thus, the battery behaviour is classified as Pass or Fail (Brand et al., 2015).

Large car structures have low resonance frequencies and the damage is produced by the low resonance frequency content. However, for small structural components, the critical frequencies exist on high spectral orders. Bearing in mind that a battery pack contains large structures and small components, the vibration inputs for the tests can be sinusoidal or random excitation (Kjell and Lang, 2014).

In summary, there is a variation between the mechanical loads proposed in standards and measured in real-world (Hooper and Marco, 2014; Lang and Kjell, 2015). This is because the tests, according to standards, have to be conducted faster compared to the long-term usage in real world battery applications (Hooper and Marco, 2014). Standard tests often aim to represent worst case scenarios, and consequently, mechanical loads are higher, and the frequency ranges are broader in comparison with everyday usage. It is uncertain whether the intense tests according to standards reflects the same effects as the long-term loads in the battery packs (Hooper and Marco, 2014).

4.6.1. Mechanical durability testing

Vibration durability test is used to understand the behaviour of the vehicle when subjected to an induced vibration. It can represent the driving conditions during the vehicle life, equivalent between 100.000 and 150.000 miles of customer use (Hooper et al., 2016). One of the major challenges, that the automotive and the road transport sector are facing to validate the battery packs, is the characterization of the in-vehicle input (Hooper and Marco, 2014). There is a lack of information regarding the in-use characteristics of electric vehicles, and therefore, it is not a surprise, that the test concepts and experience are driven by internal combustion (IC) vehicles (Hooper and Marco, 2014).

The first evidence of a significant study on the parameters that influence the life cycle of battery packs in EV was published by Martin and Krueger (Martin et al., 2011). This study outlines the parameters that influence the life cycle of a battery for EV in comparison with traditional vehicles. For example, the in-use characteristics of EV due to the limited energy storage are different with respect to IC vehicles. A vibration test profile was derived, by collecting data from different road surfaces such as freeway, highway, and roads in town as shown in Fig. 7. A tri-axle accelerometer was placed on the B-pillars of a MINI vehicle (Martin et al., 2011). The author also applied a multi-sine test method to cover one million cycles and reduced the testing time from 84 h to 21 h. The lessons were learned in the field of structural durability testing of the battery (Martin et al., 2011).

Hooper and Marco identified a limited choice of homologation test standards for manufactures and system integrators to evaluate the mechanical integration of a battery pack (Hooper and Marco, 2014). They also acknowledged that most standards for testing have been derived from the internal combustion engines (ICE) and are created for failure safe testing and abuse testing. As a result, they studied the vibration frequencies and magnitude in EV to examine the mechanical integration. Hence, understanding the effects of vibration during the vehicle's predictive life, potential durability failures can be avoided as well as warranty claims for vehicles manufacturers (Hooper and Marco, 2014).

The tests utilized accelerometers to collect vibration data in three EV "Nissan Leaf, Mitsubishi iMiEV, and the Smart ED", and one IC engine vehicle "Vauxhall Astra". The cars were driven at different durability surfaces on the Millbrook Proving Ground (Hooper and Marco, 2014).

Vibration measurements were obtained using tri-axial accelerometers allocated on the battery pack to evaluate the vibration characteristics of the commercial vehicles and to derive a representative test profile that can emulate the total vibration energy in 100,000 miles. The row vibration data was post-processed with a nCode software to produce the representative power spectral density (PSD) plots in x, y, and z direction (Hooper and Marco, 2014). For example, Fig. 8 shows the plot of the PSD in z direction.

In conclusion, the comparison between the standards proposed for

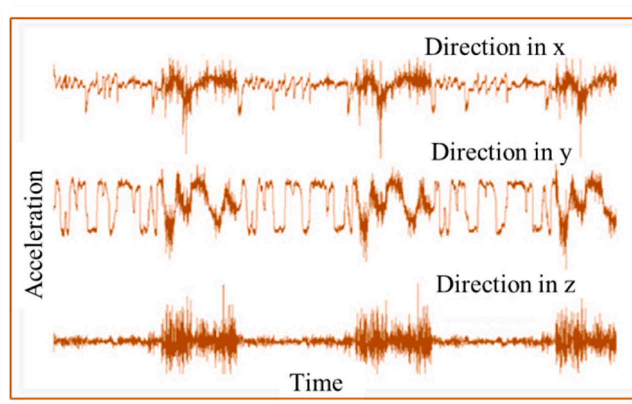

Fig. 7. Acceleration measurements taken in a MINI driven on different roads (freeway, highway, roads in town) (Martin et al., 2011).

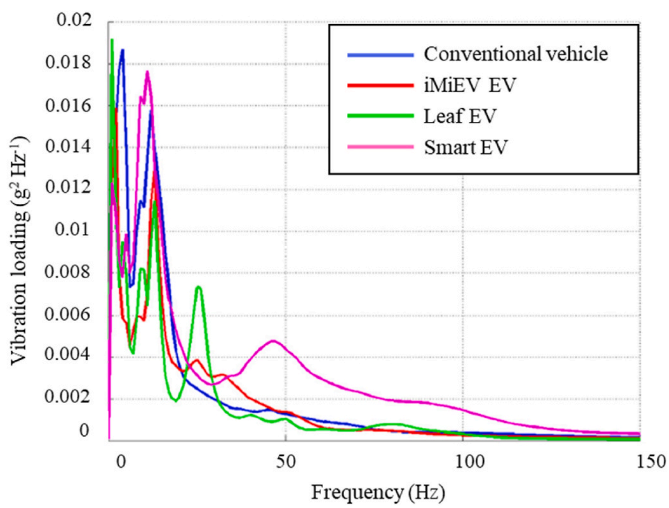

Fig. 8. City course road-surface PSD vibration profile plots z-axes (up and down) (Hooper and Marco, 2014).

lithium-ion batteries varies substantially with respect to vibration measurements. These standards are derived from traditional internal combustion power trains (Kjell and Lang, 2014). Consequently, battery pack design as per standards requirements can be over-engineered adding cost and weight which is not beneficial for the vehicle's integration.

4.7. Battery performance under mechanical pressure

Most of the materials of lithium-ion cells induce phase transition upon charge and discharge. During this process, changes of the active materials lead to swelling in unconstrained cells (Barker, 1999; Majima et al., 1999) or experience high stresses in a constrained cell by the module frame or casing (Mohan et al., 2014). During the operation, the increased volume in the cell can induce mechanical damage, mechanical fracture, and structural degradation causing irreversible capacity loss (Zhang, 2011). The constant chemical reactions cause irreversible expansion of the cell increasing its size and stress during the storage or during its use time (Niu et al., 2019).

In battery technology, the current, voltage, and temperature are considered to identify the state of health or capacity fading in cells to establish performance (Berecibar et al., 2016). However, it is complicated to evaluate the performance during real-time using computational models because, in driving scenarios, the voltage accumulates errors over time (Niu et al., 2019). Niu et al., implemented an experimental method to study the fundamental relation between the state of health, voltage, and stress (Niu et al., 2019) as shown in Fig. 9.

In the experiment, loads of 3 Kg, 5 kg, and 7 Kg, were applied to the battery at a 0.5C discharge rate, 1.3 A and 2.5 V. When the initial stress was less than 1 kg, a sharp decline in the capacity and increase in the stress was noticed, proving a negative correlation between both. However, when the stress reached to 4 kg, the correlation was hardly noticeable but after values greater than 4 kg the stress no longer affects the performance. Nevertheless, the capacity increased rapidly when the applied load exceeded to 10 kg (Niu et al., 2019). Fig. 10 shows a slight increase in real-time stress when the applied load was in between 2.7 kg and 10 kg.

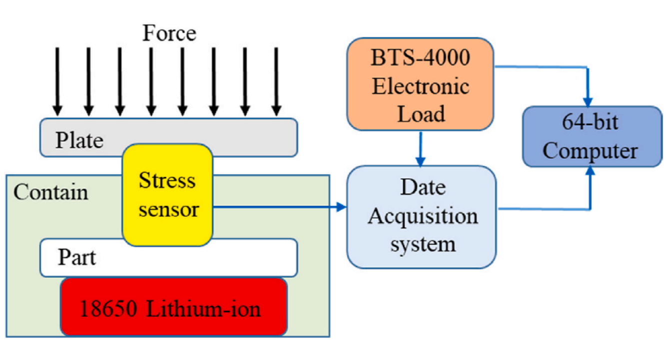

Fig. 9. Battery compression test (Niu et al., 2019).

More recently, Müller et al., studied the effects of pressure on the electrochemical performance and aging in lithium-ion cells. A graphite/NMC622 stacked Lithium-ion battery cell was considered for the experiments (Müller et al., 2019). It was revealed that the applied pressure increases the ionic pore resistance in the anode and cathode due to the decrease of the pore volume, which in essence, improves the electrical contact in the cell. However, different C-rate were applied in the cycling, revealed high reversible capacity losses due to reduced ion mobility in the electrode (Müller et al., 2019). In Fig. 11: The charge transfer resistance (*Rct*), pore resistance (*Rp*), electron transport resistance (*Rel*), and the ionic electrolyte resistance in the separator (*RSol*).

4.8. Damage characterization of the battery cell under impact loading

In battery technology, it is vital to understand the behaviour of the cells under different extreme load conditions in response to their electrical performance to optimize the collision safety design and develop reliable prediction models (Deng et al., 2020; Sahraei et al., 2012). Lithium-ion batteries are used in transportation as well as consumer electronics. Nonetheless, in electrified vehicles, the speed and acceleration cause the local forces and deformations, that in extreme conditions such as a vehicle crash, can result in local damage or even in a short circuit, smock, and fire in the cell (Jia et al., 2019; Sahraei et al., 2014). As a result, loads on extreme events need to be accounted to evaluate performance and safety in the battery pack.

Sahraei et al., conducted experiments in pouch cells to observe their mechanical behaviour with indentation loads. Fig. 12 (a) presents different punch sizes for local indentation. They observed that a short circuit appears with a local peak in force, a drop in the voltage, and an increase in temperature. In compression, the pouch cells withstand very high values, so then, uniform flat compression did not present a risk of short circuit in real life operations (Sahraei et al., 2014). However, in cylindrical cells, the compression force can crush the cell (Wierzbicki and Sahraei, 2013).

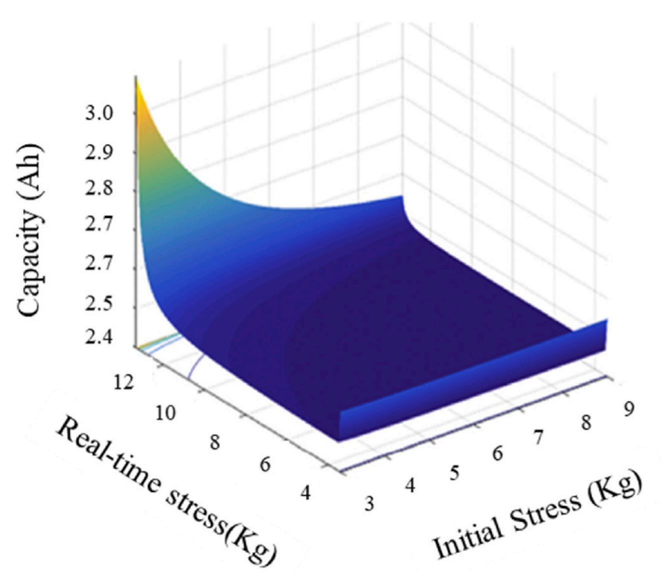

Fig. 10. Interaction effects of the inputs on the capacity (Niu et al., 2019).

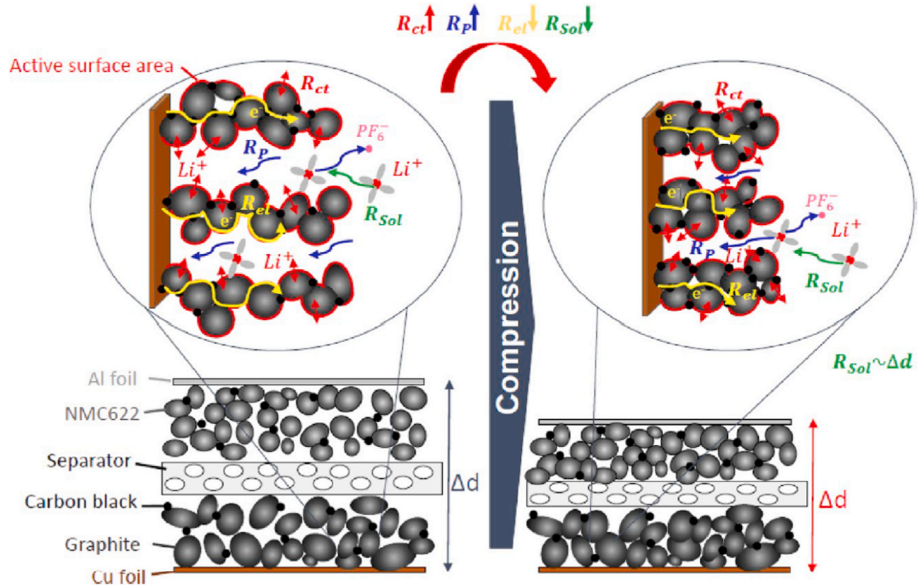

Fig. 11. Evaluation of the polarization mechanisms in compressed cell electrodes (Müller et al., 2019).

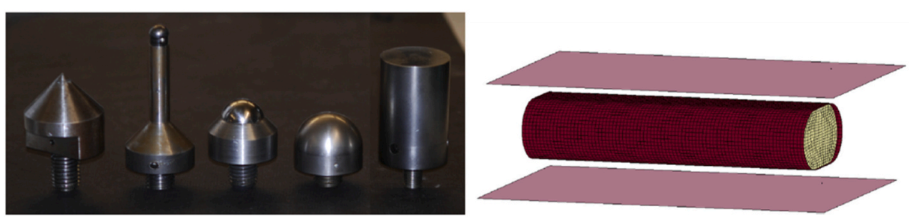

Fig. 12. (a) Punch sizes used for local indentation (Sahraei et al., 2014); (b) FE model of cell compression (Wierzbicki and Sahraei, 2013).

Wierzbicki et al., conducted experiments and used the principle of virtual work to understand the load transfer mechanism inside the cell. In the experiment, they allocated two flat plates parallel to the cell and applied a high load until the jelly roll crashed (Wierzbicki and Sahraei, 2013). The experimental data and calculations were then used to create a fine element model as shown in that usefully predict the average response of the jellyroll to crush between flat plate forces and other various types of loading as shown in Fig. 12 (b) (Wierzbicki and Sahraei, 2013).

Dengat et al., conducted impact tests in a pouch cell to study the response during various impact scenarios as shown in Fig. 13 (a). In each test, the cell was hit by an indent dropped from a certain height (Deng et al., 2020). The experiments utilized a pouch cells from where the voltage, temperature, loading force, and cell penetration were observed to characterize the response in the cell (Deng et al., 2020). The empirical and numerical results concluded that cell impact behaviors depend on various factors such as the platen type, indenter type, and the SOC of the cell. Using the test condition, a simulation was also created to compare the experimental results with the simulation as shown in Fig. 13. The model capture features of cell impact behavior such as the onset of short circuit, mechanical failure, and temperature growth (Deng et al., 2020).

In this study, the limitation of the test and simulations were given by the direction of the impact load and the module. In a real car collision, the crash can occur in any direction of the battery pack. In contrast, the experiments only considered one direction in a single cell and didn't account for the embedded condition of the cell in the model (Deng et al., 2020). The challenges for the study, were given by the variety of the cells, the multiple thin layers with different materials properties, and the physical processes that occur simultaneously during the deformation of the cell.

Damage characterization under impact loading is not yet useful to predict the failure and to describe the causal mechanism (Niu et al., 2019). For a computational intelligent assessment, Niu et al., created a methodology based on "impact test experimental campaign, sensor signals acquisition and processing, damage characterization test, and intelligent decision support system" as shown in Fig. 14. In the process,

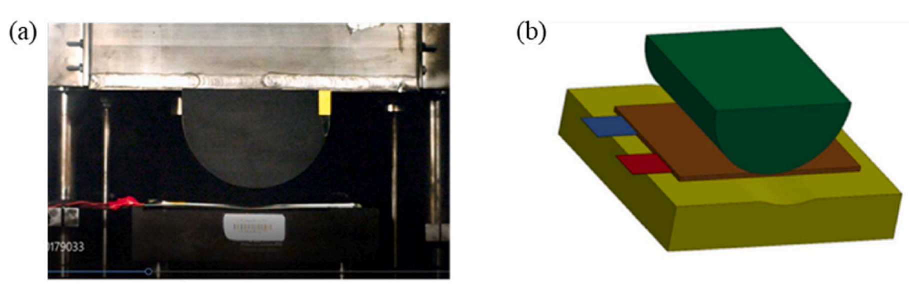

Fig. 13. (a) Experimental impact testing; (b) Model settings for impact simulations with a semi-cylindrical indenter (Deng et al., 2020).

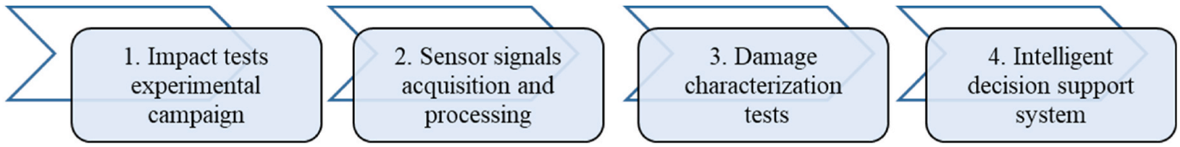

Fig. 14. Impact loading damage characterization framework for battery cell (Niu et al., 2019).

voltage, current, and impact forces were measured to identify significant features for signal characterization. The battery was inspected for damage categorization and quantification. The data was later introduced in patterns to provide the damaged entity of the cell (Niu et al., 2019).

4.9. Abuse condition of battery packs

In an accident, the vehicle collision exposes the battery pack to excessive forces dealing to destructive deformation and displacements. As a result, the mechanical abuse conditions are given by the crunch and penetration of the battery pack (Feng et al., 2018).

Amount mechanical abuse, there are different factors that influence the safety design of the battery pack. In small lightweight vehicle, the mass distribution of the battery pack is significant with respect of the total weight of the vehicle, hence, the centre of gravity and the moment of inertia of the vehicle depends on the position of the battery affecting the crash pulse in a collision. Considering the crash response, in a vehicle accident, the battery mass layout is a relevant safety performance for the battery pack (Zhang et al., 2015).

The mechanical behaviour of cell components is been investigated in different cells and modules. Lai et al., conducted tensile tests in a prismatic cell module component to characterize the tensile behaviour of the module's specimens. The tensile behaviour estimation test, based on the rule of mixture, demonstrated that the anode sheets have almost no load carrying capacity (Lai et al., 2014). The tensile properties in components are also conducted in pouch cell batteries. Choi et al., Study the effects of temperature and strain rate on pouch cells using an environmental chamber (Choi et al., 2013).

The characterization of plasticity and fracture behaviour of shell casing was studied by Zhang et al. The experiments, which compered the bending stress in the casing, jellyroll and the entire cell, demonstrated that the casing protect, and provided strength and fracture resistance in different mechanical loading scenarios, hence, the shell casing in cylindrical cells is an integral part of characterizing the mechanical loading (Zhang and Wierzbicki, 2015).

The purpose of understanding the behaviour in lithium-ion cells under mechanical abuse is to encounter a representative model which allow the prediction of any failure that induce short circuit. For example, the deformation behaviour due to mechanical abuse loading for a pouch and prismatic cells was investigated and modelled by Saharaei et al., (Sahraei et al., 2012). The FE model predict deformations and the onsets of short circuits under mechanical loads. Further investigation in short circuits initiation is described by Grave et al., his research presented the cell deformation and criteria for stress-based fracture to predict the location and load state for internal short circuit in a cylindrical cell (Greve and Fehrenbach, 2012).

Xia et al., demonstrated that pinch-torsion loads introduce the shear stress that increase the maximum first principal strain that introduce failure in the polymer tension zone of the separator. The failure is revelled in the early stage of torsion creating a small internal-short-circuit. Rooted on the experiment results, a FE models were developed to predict the deformation in the separator under pinch-torsion and pure pinch loading to predict short-circuits in pouch cells (Xia et al., 2014).

5. Mechanical performance with multi-objective design parameters

Safety, reliability, and performance are the major challenges for the electrification of the road transportation sector and are vital to ensure confidence to implement the use of electromobility in our society (Arora and Kapoor, 2018; Ruiz et al., 2018). In electric vehicles, the enclosure supports and protects the battery and its internal components, hence, it is a crucial part to maintain safety in the vehicle (Chen et al., 2019). A bad design of the enclosure could generate noise, cracking, or damage (Mohammadian and Zhang, 2015; Zhu et al., 2015) which can stop the normal operation of the battery and in some cases can trigger catastrophic events.

For an optimum mechanical design and structural performance, the mechanical structural parts require to have the ability to withstand vibrations, stresses, and deformations experienced in the vehicle due to the harsh road surface conditions (Bao and Zhao, 2018). High deformations of the battery pack can cause fire and explosion due to a short circuit. For this reason, the safety of the battery pack is also related to the performance of the mechanical parts. By reducing the weight, the efficiency of the battery can be improved in terms of life cycle and range, at the same time, the battery has to preserve high strength and resistance to vibrations (Shui et al., 2018).

The complexity of the structure and the different variables in a battery, demands the use of computational models to study battery performance. However, the traditional numerical methods such as FE analysis, require a lot of processing time. The computational burden for battery design optimization, can be avoided by the adoption of multi-objective optimization algorithms (Li, 2020). For example, the optimization of the strength and weight functions can be solved together faster to fulfil the optimum strength and weight despite both objectives are opposite.

Shui et al., proposed a four-phase design optimization methodology considering the performance improvements of mass, frequency and deformation. In this study, the loads of the battery pack were the gravity force acting in the vertical direction and the battery was fixed in all directions in the lifting lugs. For the natural frequency evaluation, vibration loads were induced at a frequency in between 7 and 200Hz. The design variable are in Fig. 15, where EW is the battery case wall thickness, EB is the bottom thickness, bb is the module bottom thickness, bwl is the long bottom thickness of the module and bww is the wide wall thickness of the module (Shui et al., 2018).

With the objective function method, a multi-objective optimization problem was reduced to a single-objective optimization problem. In equation 4-1, D is the weight of maximum deformation, M is the minimum mass and F is the maximum frequency, where k_1, k_2, and k_3 are the set values of the weight. The maximum deformation is considered the most important function. The variable of weight of the design values are given by x_1, x_2, x_3, x_4, x_5 and x_6 (Shui et al., 2018).

$$F(x_1, x_2, x_3, x_4, x_5, x_6) = k_1 D(x_1, x_2, x_3, x_4, x_5, x_6) + k_2 M(x_1, x_2, x_3, x_4, x_5, x_6) + k_3 f(x_1, x_2, x_3, x_4, x_5, x_6) \quad (7)$$

Zhang et al., applied multi objective optimization in a battery pack casing to minimise the maximum equivalent stress and maximise the resonant frequency utilizing different materials. Based on performance standards, the model proved that the carbon nanotube material (CNT) was the best material for design. Experiments showed the mechanical

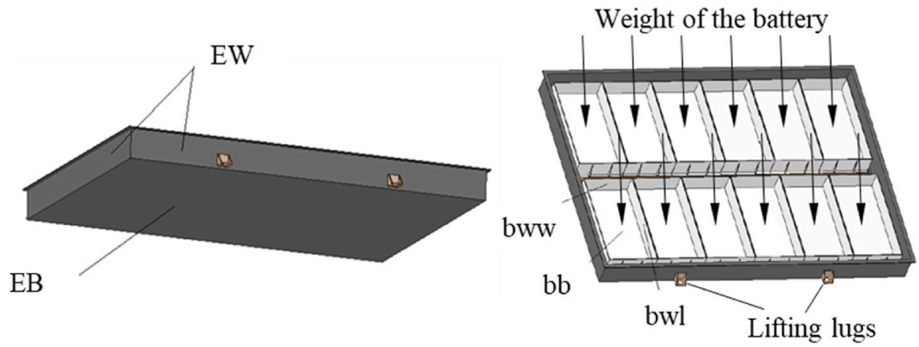

Fig. 15. Design variables, constrains and loads for the battery pack enclosure (Shui et al., 2018).

performance of the optimum design and validated the simulation model (Zhang et al., 2020). The parameters for the optimization design are illustrated in Fig. 16.

Considering the objective of the optimization design, the formula of the multi-objective design is given in equations (4)–(2), where p1 represent the thickness of the floor, p2 and p3 represent the front and side thickness; p4, p5, p6, and p7 represents the lifting thickness respectively.

$$findx = [p1, p2, p3, p4, p5, p6, p7], \text{ min } p8, \text{ max } p9 \tag{8}$$

Shui et al., and Zhang et al., utilized FE Analysis software to conduct a static and dynamic analysis to obtain preliminary results of deformation and natural frequency. Then, considering the design variables, the optimization of the model design was conducted by applying generic algorithms and methods such as Central Composite Design (CCD) (Hang et al., 2011) and Latin Hypercube Sampling (LHS). For the analysis of the multi-objective model formulated, non-dominated sorted generic algorithm, NSGA II, was introduced to optimize the model base on the optimum combination of inputs.

5.1. Battery pack enclosure optimization with surrogate models

In a battery pack structural optimization, the topology and shape of components imply a multi-objective and a multi-constrain optimization problem. Clearly, the computational time using FEA is the main challenge during this work. The computational efficiency is improved with the implementation of metamodels or surrogate models (Xu et al., 2020). Lin et al., proposed a surrogate-based design optimization methodology to optimize the thickness of the battery pack with an air-cooling system. The definition of the optimization problem was assumed to be dependent on the mechanical performance of the structural design of the battery pack with lighter weight (Fang et al., 2013).

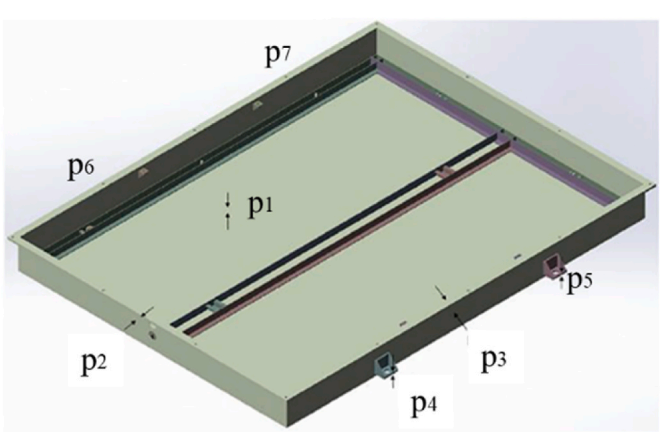

Fig. 16. Casing's Parameters of the Battery pack (Zhang et al., 2020).

In the analysis, the stress in the battery pack was assumed not be greater than the material tensile limit (380 MPa). The magnitude of the transient shock was equivalent to 40g in 6 ms acting along the *x* and *y* access. By applying FEA, the baseline design proved that the battery needed to be redesign because the maximum stress was above the tensile stress in both directions, approximately 402 MPA in the *x*-axis and 422 MPa.

Considering that the first order natural frequency needed to be as higher as possible to avoid resonance effects with the vehicle, the first natural frequency was maximized at the same time the structural mass was minimized maintaining the levels of the transient shock response indices in the *x* and *y* access. The optimization problem is shown in Eq. (9), subjected by Eq. (10). $F_m(x)$ is the total mass, $F_f(y)$ is the first order restrained natural frequency of the battery pack, $S_{(x)}$ and $S_{(y)}$ is the global maximum Von-Mises stress in the battery pack when a transient shock is applied in x-axes and y-axis. The design variables, in Fig. 17, are represented by *x* with a range between 0.5 mm and 1.5 mm (Lin et al., 2016).

$$Maximise\ \left[F_m(x) - F_f(x)\right] \tag{9}$$

$$Subjected\ to \left\{ \begin{array}{c} 0.5mm \leq x \leq 1.5mm \\ S_{(x)} \leq 380\ MPa \\ S_{(y)} \leq 380\ MPa \end{array} \right\} \tag{10}$$

Different surrogate methods were stablish to minimise the mass and the frequency: Polynomial Response Surface (PRS) (Montgomery, 2020), Kriging (KRG) (Hardy, 1971), and Radial Basis Function (RBF) (Sacks et al., 1989). To select the most accurate metamodels or surrogate modelling technique, it was necessary to evaluate sampling data at some training points. Consequently, based on the design experiment (DoE) approach, optimum Latin hypercube sampling (OLHS) was used to generate the initial training points (Park, 1994). The computational results of three numerical estimators, r-square, relative average absolute error (RAAE), and relative maximum absolute error (RMAE) (Jin et al., 2001), were applied to determine the accuracy of the surrogate models.

Particle swarm optimization (PSO) is commonly used to obtain

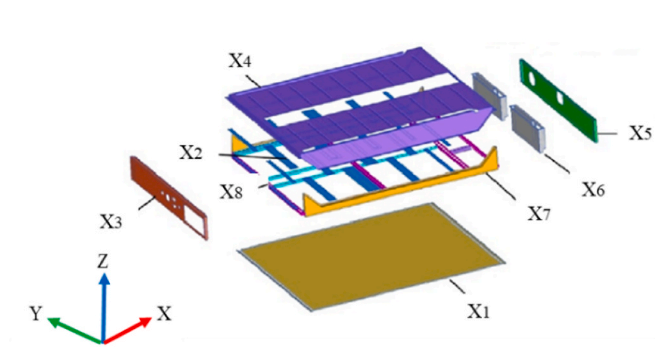

Fig. 17. Design variable in the battery pack (Lin et al., 2016).

optimal solutions. This algorithm considers initial random solutions for repeated iterations. Nevertheless, the multi-objective particle swarm optimization (MOPSO) algorithm, which is an improved algorithm of PSO (Coello et al., 2004), was utilized by Lin et al., to achieve fast convergence and attaining well distributed Pareto frontier. MOPSO is an effective tool in structural optimization, hence, a proposed optimization procedure is summarized in Fig. 18.

More recently, Xu et al., propose a new adaptive sampling method, based on the complex method (CM) considering the connection between the optimization process and the establishment of the surrogate model. In this work, the samples establish the surrogate model and form the complex shapes to help the optimization search. The propose method, based on a simple modelling process and small sampling size. Hence, the efficiency and accuracy of existing adaptive sampling methods improves and the computational cost for solving optimization problem is reduced (Xu et al., 2020).

For an engineering application, the model proposes the optimization of an air-cooled battery model considering the design variables, as shown in Fig. 19, where *d* represent the distant between the replacement point and the worse point. The battery module optimization model is expressed in Eq. (11).

$$\min f\,TD = f\,TD\,(d1,\ d2,\ d3,\ d4,\ v)$$

$$s{:}t.\ f\,V\,(d1,\ d2,\ d3,\ d4,\ v) \leq \varepsilon v$$

$$f\,TSD\,(d1,\ d2,\ d3,\ d4,\ v) \leq \varepsilon TSD \qquad (11)$$

$$1 \leq d1 \leq 4;\ 1 \leq d2 \leq 4$$

$$1 \leq d3 \leq 4;\ 1 \leq d4 \leq 4$$

$$0{:}002 \leq v \leq 0{:} \qquad 02$$

In the equation, the objective function *fTD* is the maximum temperature difference, *fV* is the volume of the battery pack, *fTSD* is the temperature standard deviation, *v.εv* is the flow rate in the air cooling. The initial design values of temperature *TSD* and volume *V* are given by *εTSD*. The surrogate models of *TD*, *V* and *TSD* are expressed in Eq. (12).

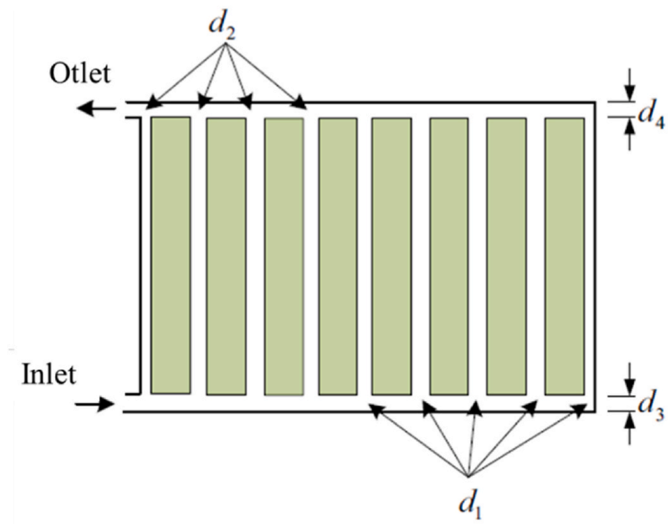

Fig. 19. Design variables of the battery model (Xu et al., 2020).

$$f\,V = f\,V\,(d1;\ d2;\ d3;\ d4;\ v)$$

$$f\,TD = f\,TD\,(d1;\ d2;\ d3;\ d4;\ v) \qquad (12)$$

$$f\,TSD = f\,TSD\,(d1;\ d2;\ d3;\ d4;\ v)$$

5.2. *Battery pack vibration evaluation with parametric reduced order models*

The modules of the battery pack are assembled by bolts or welds to keep the cells packed together and the prestress due to joining can influence the dynamic response of the structure. The models are often comprised of many cells arranged in a repeating layout forming a

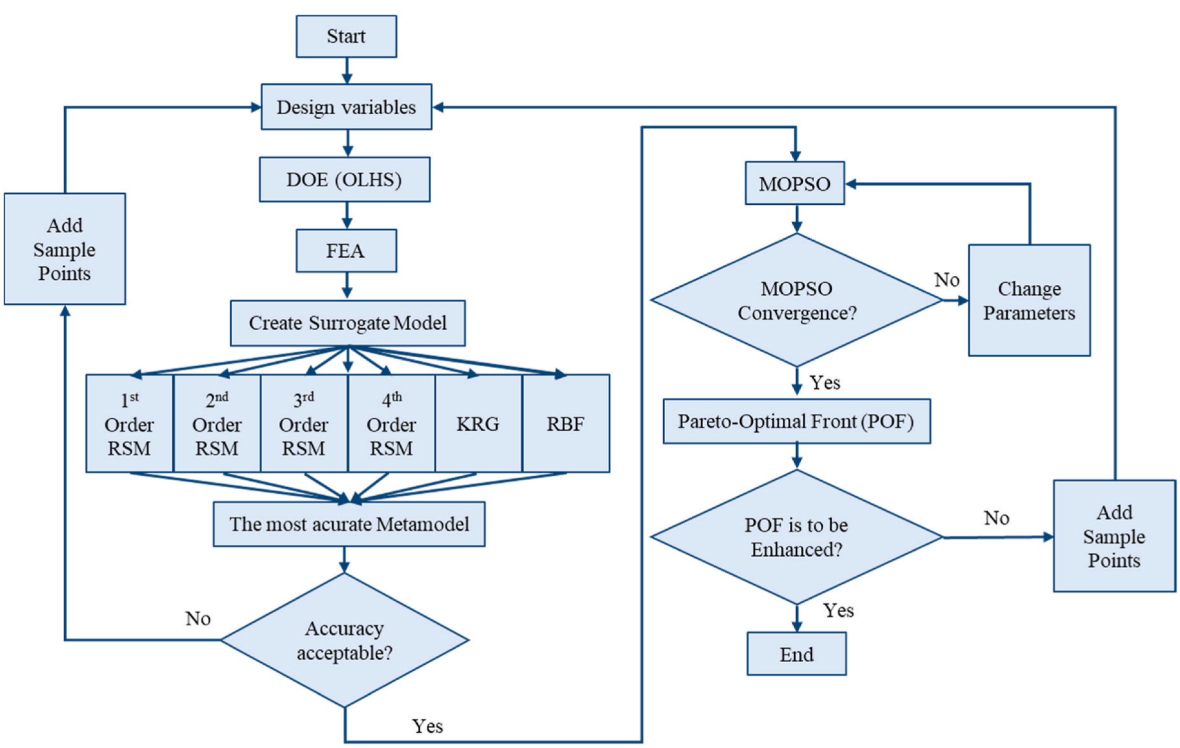

Fig. 18. MOPSO of the proposed flowchart procedure (Lin et al., 2016).

periodic structure which creates high modal density in many frequency bands (Batou, 2015; Coello et al., 2004; Ezvan et al., 2017) The random structural variation among the cells and the high modal density can create Anderson localization, where the vibration energy is concentrated in a small region of the structure. This localization phenomenon can trigger mechanical or electromechanical failure due to high local vibration amplitude and high stress levels in the module pack (Bendiksen, 2000; Hodges, 1982; Offer et al., 2012).

Hong et al., develop a numerical model to account probabilistic force response simulation to capture the effects of vibration caused by prestress and structural variations in a battery for HEVs. Statistical dynamic response calculations were needed to accurately account for the effects of random vibrations (Lu et al., 2018). However, statistical calculations were difficult to perform using liner methods as a result of nonlinearities in the parameters of each cell that directly influence the mode shapes of the pack.

A numerical method and a design oriented techniques such as parametric reduce order models (PROMs) (Balmès, 1996; Balmes et al., 2004) needs to be applied to reduce the processing time due to the reanalysis of complex structures. Hong et al., utilized a simple FE academic model comprised of 20 cells to demonstrate the structural dynamic characteristics of the battery as illustrated in Fig. 20.

The responses due to the prestress variation and dynamic loads shown in the full-order FE model were significantly different. Fig. 21 (a) presents the values of the force response at the centre node of the first cell at different values of prestress. The small random structural variations were modelled by variations of Young's modulus (*E*). The identical cells were mechanically coupled to the frame showing high modal density induced to the entire battery pack structure as shown in Fig. 21 (b) (Hong et al., 2014).

Monte Carlo simulation combines with finite element models (FEMs) is an alternative method of sample-based statistical analysis. As an alternative to overcome the computational time issues in conventional FEMs for structural dynamics analysis, component mode synthesis (CMS) (Hurty, 1965) is a reliable and established method. However, CMS has to be modified to account for parametric variability in the structure. CMS is a good approach to break down large structure models into much smaller components (Bendiksen, 2000; Hintz, 1975; Rubin, 1975; Shyu et al., 2000).

Lu et al., developed a new non-linear PROM to eliminate the CMS method to reduce the computational time required to create low order models. The new model captures the hardening and softening effects in battery materials, the linear effects of prestress and cell-to-cell variations, non-linear force responses of PROMs, and structural variations at different states of charge (SOC) (Lu et al., 2018). Consequently, the model captures global level structural variations, that consider stress variation in the entire battery pack, and the component level structural variations, which reflect variation in the state of charge or temperature variation between cell-to-cell.

The structural vibration in the model included the linear and nonlinear behaviour given by the prestress, as shown in Fig. 22 (a) and cell-to-cell variation as illustrated in Fig. 22 (b). The prestress changes the modulus of elasticity in the whole battery and some cells have different modulus of elasticity as represented in Fig. 22 (b). The linear behaviour of the model includes the prestress and cell-to-cell variation, and the nonlinearity part reflect the nonlinear behaviour of the cells (Lu et al., 2018).

6. Thermal loads in battery packs

The temperature affects the battery in operating and store conditions (Q. Wang et al., 2016b). For example, in operating conditions, the uneven temperature upon the module's cells can affect the electrochemical behaviour and create electrical unbalanced (Bandhauer et al., 2011). In resting and store conditions, the battery pack is sensitive to the ambient temperature and vulnerable to short circuits (Wu et al., 2019). For this reason, it is vital to implement an efficient cooling and heating system to improve the performance and protect the battery with in different range of temperatures (Balmès, 1996; Jaguemont and Van Mierlo, 2020).

6.1. Thermal performance of a battery

The performance of a battery is driven by the operating temperature and the voltage. Thereby, the battery performs well when temperature is in the specified range. Otherwise, the battery can have irreversible damage that can even cause thermal runaway (Q. Wang et al., 2016b/). For example, at temperatures below 20 °C, the battery charge process become sluggish, restricting the application in cold areas or winter season (Zhu et al., 2015) and temperature above 35 °C increase the battery degradation reducing the life time as shown in Fig. 23.

Very low temperatures can reduce the battery capacity and high temperatures can damage the active chemical components in the cells (Jaguemont et al., 2016). Consequently, the excess and the lack of heat cause problems to the battery. When the temperature increases the chemical reaction inside the cells also increase with higher capacity and power, so then, more heat dissipation needs to be removed to avoid thermal runaway (De Hoog et al., 2018). The problems arise when a localised deterioration uneven the temperature distribution or the battery exceeds the permissible levels during charge or discharge operation (Rao and Wang, 2011).

Lithium-ion batteries (LIBs) have been used in different applications including cell phones, laptops, electric vehicles and stationary energy

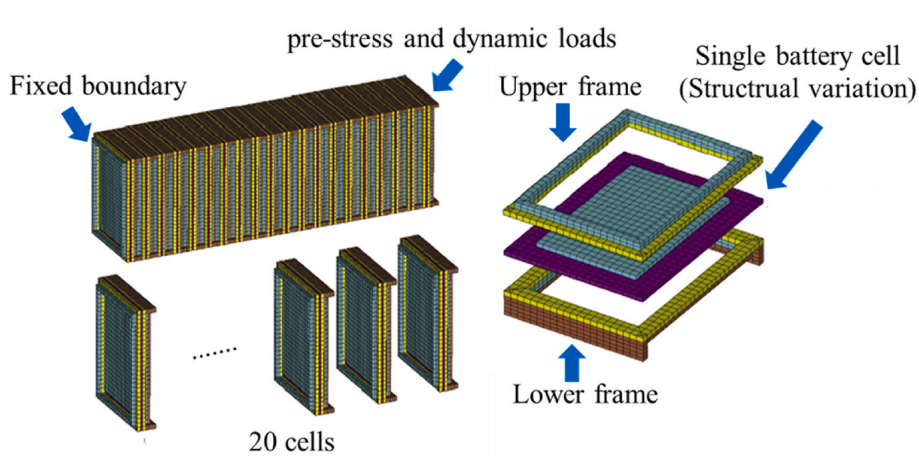

Fig. 20. The geometry of the academic battery pack with 20 pouch cells (Hong et al., 2014).

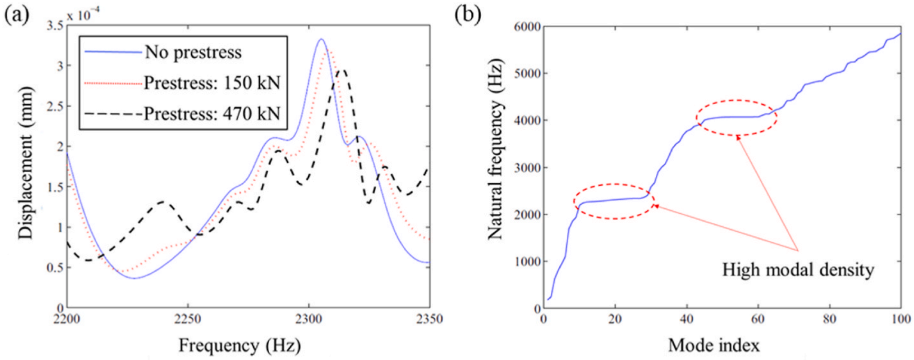

Fig. 21. Academic battery. (a) Force response at the centre node; (b) Natural frequencies without variations between cells and without prestress (Hong et al., 2014).

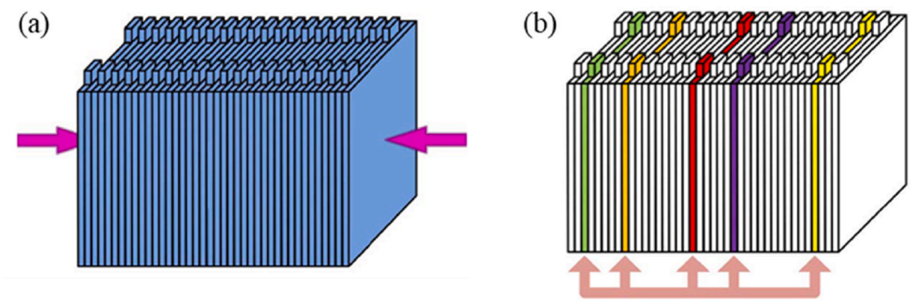

Fig. 22. Structural variations. (a) Prestress variation; (b) Cell-to-cell variations (Lu et al., 2018).

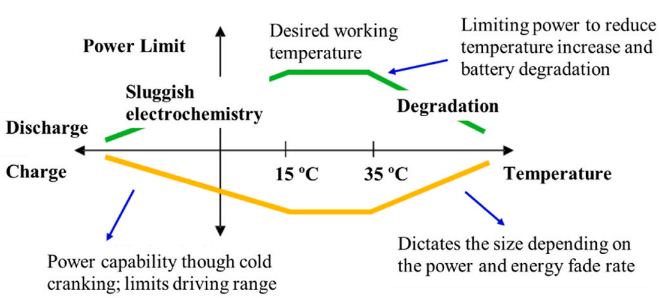

Fig. 23. Battery operating range (Q. Wang et al., 2016b).

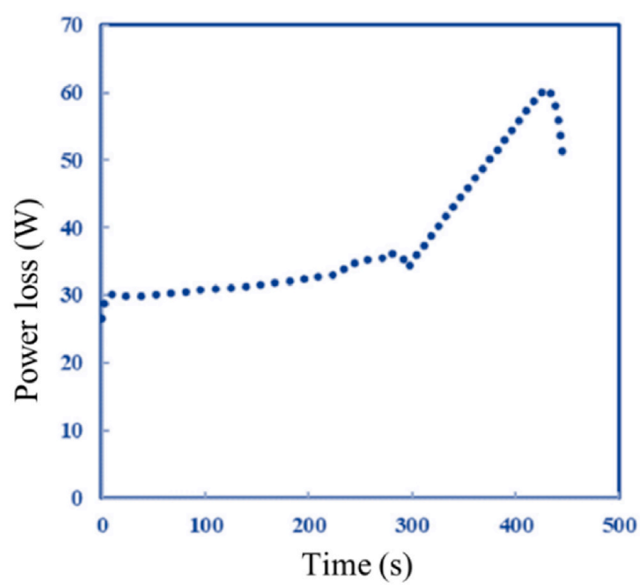

Fig. 24. Heat generation of an LTO cell under a fast-changing profile (Jaguemont et al., 2016).

storage wells due to their high energy density, range and charge-discharge ability. Even though, energy and power capabilities of LIBs decrease sharply at low operation temperatures (Jaguemont et al., 2016). Fig. 24 shows a temperature raise in a lithium titanium anode cell (LTO) under fast charging conditions at 8C and a current of 184 A with an average heat generation of 37.65 W (Jaguemont et al., 2016).

6.2. Traditional thermal management systems

In an Air-cooling passive system, the battery takes the air from the environment or the cabin, meanwhile, in an air-cooling active system the battery takes a pre-conditioned air from an air conditioner. Both systems require few elements to operate like fan, external power and heat (Jaguemont and Van Mierlo, 2020). Air cooling can be implemented in batteries with low energy density, however, high energy density such us Lithium-ion batteries demand a redesign of the cooling system (Pesaran et al., 1999).

In liquid cooling, the high heat transfer coefficient of the water and other fluids makes it more efficient that the air cooling, hence, liquid cooling can reduce significantly the battery temperature (Piller et al., 2001). Liquid-cooling management can be divided into three categories: immersing cooling, where the modules are directly immersed in the fluid. Direct cooling, where a direct surface of the battery is in contact with the heat transfer with the fluid and indirect cooling where other devices such as cooling plate, piping or a jacket is allocated nest to the cell (Jaguemont and Van Mierlo, 2020).

The refrigerant cooling systems is considered a sub-category of liquid-base cooling systems (Kim et al., 2019). Connecting the evaporator of the battery, parallel to the evaporator in the cooling loop, the heat of the battery is transferred to the evaporating refrigerant. The battery evaporator utilizes some portion of the compressor output that is reserved for the air conditioning to cool the battery (Dinçer et al., 2017).

A phase change material cooling utilizes a phase change material (PCM) to accumulate or emits heat. The material change from one state to another, absorbing or releasing large amount of heat. The material store or release heat when it is solidified or melted depending of the temperature (Siddique et al., 2018). Phase change material (PSM) is considered a low cost in automotive application, non-corrosive and with high latent heat (Bose and Amirtham, 2016). However, it has low thermal conductivity and suffer from leakage problems in its molten face (Zhang and Fang, 2006).

In the battery, the PCM is a solid material block moulded to allow the insertion of the battery. The cells are connected to the PCM with two plates to release the heat absorbed by the PCM. When the heat is generated in the battery by the charge or discharge process, the heat is transferred from the cell to the PCM due to conduction phenomenon. In the process, the PCM absorbs heat as sensible heat, then, absorbs a large amount of latent heat until the end of the phase maintaining constant temperature. This property of the PCM protect the cell for drastic thermal loads and temperature unevenness (Siddique et al., 2018).

6.2.1. *Thermal runaway*

The constant development of lithium-ion battery in energy density and longer-range demands materials that usually have lower thermal stability introducing a safety concerns in electric vehicles. Thermal runaway is caused when a chemical reaction occurs one after another. The temperature dramatically increase from external or internal heat due to an abnormal abuse (Feng et al., 2018). The abuse conditions can be mechanical such as crunch, nail penetration, drop and vibration, electrochemical abuse such as overcharge and over discharge and thermal abuse such as external heating from a fire (Wen et al., 2012).

The chain reaction in the thermal runaway induce smoke, fire and even explosion. Unfortunately, the thermal runaway can occur by abuse condition or by self-induced failure. It has been demonstrated that thermal runway is not only caused by internal short circuit but also by chemical crossover (Liu et al., 2018).

The most common abuse in lithium-ion batteries is the overcharge abuse. It induces high temperature, high pressure and high current that in most cases results in thermal runaway. Overcharge is caused by the malfunction of the cell charger where the electricity flow is forced after its limited designed capacity (Zhang et al., 2012).

Feng et al. proposed a method to decrease the hazard caused by the thermal runaway. The improvement of the anti-thermal runaway capability can be achieved by modifying the internal materials of the cathode, anode, separator and electrolyte. Low active materials can cut off the chain reaction. Each battery pack needs a thermal management system capable to dissipate the heat to avoid overtemperature and the BMS to ensure the safe operation where the detection measures have to be in place such as detection algorithm to warn the users of the coming fault. When the thermal runaway happen, secondary measure to reduce the fire propagation needs to be stablish to allow the driver to baccate the electric vehicle (Feng et al., 2018).

One of the most common problems that induce internal short circuits in the cells is the formation of dendritic lithium. In the surface of the anode, the dendrite lithium grows performing the polymer separator causing the connection between the positive and negative electrode, hence a short circuit is induced in the battery (Wen et al., 2012). Recently, extensive research has been conducted to understand the formation of lithium dendrites on anode surface to prevent short circuits and thermal runaway in lithium-ion batteries (Yamaki et al., 1998).

After experiments at different C charging rates, Orsine et al. concluded that there is a close relation in the formation of Li-dendrite with the current density. The faster is the charging current in the battery the bigger the growth of dendritic lithium (Orsini et al., 1998). Orsine et al. applied 1C and C/5 charging current in a 4.5 V battery. With an electron microscope, it was observed Li-dendritic proliferation at 1C charging rate.

The accumulation of overheat generation in the battery cause the thermal runaway. However, there are components in commercial batteries which can mitigate the risk. The positive temperature coefficient (PTC) devices are composed of thin conductive layers of polymer. When the temperature is high the PTC is overheated and increase its own resistance in order to restrict the current along the cells. After few time, the PTC reversibly recover the conductive properties as its temperate cool down (Wen et al., 2012).

Despite a lot of research explain the factors that influence the battery performance, integrity and safety. There are not evident to suggest, that a comprehensive study has been conducted to compile the temperature and vibration with and emphasis of a thermo-vibration couple loads. During the battery operation, vibration and temperature act together adversely affecting the power supply. However, if the loads are study independently, a realistic approach and results are misleading. Therefore, this review concludes that and experimental study about structural and power performance under thermo-vibration couple loads can be a novel contribution to academia.

In Table 1, a summary of the performance parameters discussed previously has been presented for the benefits of the reader which goes on to show the limitations and key findings, and relevant authors.

7. Conclusions

A comprehensive review of the lithium-ion battery pack is presented to acknowledge the major factors that influence the structural performance and the electrical performance due to the working and environmental conditions. For example, vibrations from road roughness, acceleration, and sudden collision considerably affect the mechanical properties and electrical performance of lithium-ion batteries (Zhang et al., 2017) as well as induce fatigue damage and functional disturbances (Kjell and Lang, 2014). Despite, effort in research conducted in academia and industry with great demand in technology for design, little investigation has been conducted to critically evaluate the mechanical integration, safety, and performance considering the vibration and temperature as a thermo-mechanical couple load.

There are research evidences to conclude that mechanical properties on lithium-ion cells are affected by vibration energy due to vehicle life driving conditions (Bandhauer et al., 2011; Hooper et al., 2016). Therefore, it is vital to design a structure that accomplishes the mechanical requirements (Li et al., 2013) such as the ability to resist deformation and vibration shocks (Shui et al., 2018). For this reason, vibration test is applied in batteries for safety, durability, and performance to predict the functionality in the vehicle operation (Lang and Kjell, 2015; Pesaran, 2001). However, previous research acknowledges that different vibration tests proposed in standards and regulations for lithium-ion battery packs vary substantially in the levels of energy and frequency range (Kjell and Lang, 2014) so there is still a big challenge to emulate a test that represents the real working condition of electric vehicles.

Ambient temperature in store and operating conditions impact the overall battery pack performance. For example, at height temperatures, the battery can have irreversible damage that can even cause thermal runaway (Q. Wang et al., 2016b). Low temperatures decrease considerably the power capabilities and proliferate aging. The charge process becomes very slow when the temperature is below -20 °C, restricting the application in cold areas or in winter season (Pesaran et al., 1999; Zhu et al., 2015). Consequently, the cells and the modules need to operate at the desire temperate range to result in optimum battery performance and life (Pesaran et al., 1999). Nonetheless, heat has been an addressed challenge for battery performance in the past researches, only few publications combine other performance parameters to provide a more realistic output performance of the battery pack.

Uneven temperature distribution leads to different charge and discharge behaviours causing electrical unbalance in the modules which

Table 1
Performance parameters and limitations.

The performance parameters	Limitation and key findings	Authors
Durability: Desirable vehicle life	Vibration durability test by standard are not representative for EV applications. The standards for the tests of the battery packs have not been derived to emulate a given vehicle life, they intend to validate the fail-safe function of the battery	James Michael Hooper and James Marco
Stress condition: Cell precompression forces	Constantly chemical reactions cause irreversible expansion of the cell increasing their size and stress during the storage or during its use time. The stress condition influences the capacity of the cell.	Xiaodong Niu, Akhil Garg, Ankit Goyal, Alessandro Simeone, Nengsheng Bao Jian Zhang, Xiongbin Peng
Mechanical: Strain, bending, force displacement, creep and tolerance changes during charge and discharge	Mechanical characterization varies depending on the type of cell (cylindrical, prismatic and pouch) and therefore, the mechanical performance of the cell differs between cells and applications.	James Michael Hooper, James Marco, Gael Henri Chouchelamane and Christopher Lyness
Dynamic: Mechanical crush, penetration, impact resistance, mechanical shock	Crush, penetration and impact resistant are dynamic tests to evaluate the safety function of the cell during extreme conditions. The experimental data support the FE method in cells and assembly of cells to predict mechanical deformation and failure.	James Michael Hooper, James Marco, Gael Henri Chouchelamane and Christopher Lyness
Environmental: temperature and decompression	The temperature is a major factor which influence the life cycle and battery performance. Environmental temperature and pressure are wide to cover for research.	James Michael Hooper, James Marco, Gael Henri Chouchelamane and Christopher Lyness
Position: In-pack orientation	The orientation of the pack in the vehicle influence in the performance. The direction of mechanical load varies depending on the battery orientation.	James Michael Hooper, James Marco, Gael Henri Chouchelamane, Julie Sylvie Chevalier and Darren Williams
Battery shape: Cube or rectangular	The electrical, chemical, and mechanical analysis have to be gradually combined to understand the internal changes in the cell. However, chemical and mechanical interpretations are time limited.	Chang-O Yoon, Pyeng-Yeon Lee, Minho Jang, Kisoo Yooc and Jonghoon Kima
Cell balancing: Cell-to-cell variations	Cell variation increase the differential current flow and heat generation in the system. It is extremely difficult to quantify the cell ageing due to vibration loads.	James Michael Hooper, James Marco, Gael Henri, Chouchelamane and Christopher Lyness
Cell imbalance: Impedance, discharge rate	There are many problems with battery imbalance and many battery equalization methods. This variety undermine the equalization system for the battery. The capacity of the battery depends on the capacity of the weakest battery cell.	Javier Gallardo-Lozano, Enrique Romero-Cadaval, M. Isabel Milanes-Montero, Miguel A. Guerrero-Martinez
Extreme loads conditions: indentation load, compression loads, impact energy.	The direction of the impact load, the embedded cell condition in the model, the variety of cells, the multiple layers materials, multiple physical processes during the cell deformation are important to understand the battery response but are difficult to predict.	Indentation load: E. Sahraei et al., Impact energy: Deng et al. Compression load: Wierzbicki et al.,
Structural features in the battery pack enclosure: Deformation, Natural frequency and mass	The direction of the impact load, the embedded condition of the model, structural shape in structures and computational time are variables which make the prediction of mechanical performance challenging and can cause limitations.	Li Shui, Fangyuan Chen, Akhil Garg, Xiongbin Peng, Nengsheng Bao, Jian Zhang
Localization phenomena: Local vibration amplitudes and stress	FEA have millions of DOF so conducting statistical analysis is computationally expensive for high fidelity full-order models. A numerical method, PROM is applied to diminish considerably the processing time to study nonlinearities in structural variations.	Lu, Jauching, Kiran D'Souza, Matthew P. Castanier, and Bogdan I. Epureanu

reduces the performance of the battery pack. When a battery pack is integrated with the vehicle, it becomes a more complex system confronting many safety problems (Garg et al., 2016). The problems are at the macro level, which involves the enclosure in vibration, shocks and insulation. Other problems, demand an implication at the cell level such as capacity fading, impedance increase and self-discharging; suggesting that both, the macro and micro level are interrelated for battery performance (Lu et al., 2013).

The internal resistance of a lithium ion battery is small, and therefore it is likely to vary with vibration and temperature (Dubarry et al., 2014). The alterations in the resistance are compared to obtain valuable information for the calibration of the BMS, that would provide data for power performance evaluation (Park et al., 2020).

In battery design, electrochemistry, thermal management, and mechanical integrity are interrelated aspects (Sahraei et al., 2012). For this reason, performance evaluation in the overall battery output requires a comprehensive study in the cell, modules, thermal management, and enclosure. As a result, in this study, a comprehensive review of the battery pack and cell performance parameters is presented with the intention to acknowledge the major factors that influence the structural performance and the battery cell performance due to the working and environmental conditions.

Due to complex electrochemical reactions inside the cell, the performance quantification of the battery is always a challenge, a limitation to allocate instrumentation inside the cell, require sophisticated controls derived for empirical correlation based on the SOC and SOH (Dubarry et al., 2014). No one has reported the work about how the effects of vibration and temperature at a battery level are inter-related with the cell. Consequently, still, research needs to be conducted to understand the effects of thermo-mechanical couple loads on the battery power output for battery performance evaluation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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