Journal of Power Sources 557 (2023) 232541

Contents lists available at ScienceDirect

Journal of Power Sources

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

Defining a vibration test profile for assessing the durability of electric motorcycle battery assemblies

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HIGHLIGHTS

- Representative electric motorcycle (EM) random road vibration profiles are derived.
- The derived PSDs are suitable for testing frame mounted batteries.
- The profiles apply vibration from 5 to 200Hz ensuring application on shaker systems.
- PSD shows greater magnitudes for the EM compared to an EV in the X and Z axes.

ARTICLE INFO

Keywords:
Reliability
Data acquisition
EM (electric motorcycle)
Battery
Vibration
Durability

ABSTRACT

There has been little published research critically examining the vibration loading that battery assemblies within large sized electric two wheelers (ETWs) experience during their lifetime. Much of the existing research has been focused on assessing the battery packs of electric passenger vehicles, which have a different dynamic response to their two wheeled counterparts. Existing automotive procedures, therefore, cannot be applied to these modes of transport. It is important therefore that the magnitude and frequency of the vibration inputs that the ETW battery will be exposed to during the vehicle's life is understood.

For the first time, this study describes a methodology to derive random power spectral density (PSD) profiles that are representative of 60,000 miles of UK customer electric motorcycle (EM) usage for a vehicle operating in the large traditional motorcycle class. The derived PSDs are suitable for testing frame mounted batteries for mechanical durability using modern shaker table facilities and are derived utilising vibration measurements from a contemporary EM (Harley Davidson Livewire). In addition, it compares the measurements from a current production EM to that of profiles derived from passenger electric vehicles (EVs) published within existing studies to highlight the key differences between vibration environments experienced by batteries within passenger EVs and EMs.

1. Introduction

Since the millennium, decarbonising the tailpipe emissions of passenger vehicles has become an area of significant focus for manufacturers of motor vehicles. Governments around the world have been introducing legislation mandating the development of carbon dioxide (CO_2) reducing technologies, such as writing into law the banning of the sale of petrol and diesel engine vehicles, tax incentives for zero emission vehicles or the introduction of local ultra-low emissions zones (ULEZ) in major cities [1,2]. Vehicle electrification is a technology pathway being adopted by original equipment manufacturers (OEMs) to either reduce or eliminate tailpipe emissions. Whilst the passenger vehicle segment has been selling Electric Vehicles (EVs), which employ a rechargeable energy storage system (RESS), for over a decade, electric two wheelers (ETWs) are also starting to increase in popularity with consumers across all two wheeled vehicle sectors, with existing manufacturers (such Harley Davidson [3]) and new entrants (such as Zero, Energica, and Lightning [4–6]) are all offering battery electric motorcycles in the traditional two-wheeler segment. In regions such as China, policies

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https://doi.org/10.1016/j.jpowsour.2022.232541
Received 29 June 2022; Received in revised form 25 November 2022; Accepted 14 December 2022
Available online 20 December 2022
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Nomenclature

BS	British Standard
BW	Band Width
cc	Cubic Centimetres
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DFT	Discrete Fourier Transform
EAPC	Electrically Assisted Pedal Cycle
EM	Electric Motorcycle
ETW	Electric Two Wheelers
EV	Electric Vehicle
FDS	Fatigue Damage Spectrum
FFT	Fast Fourier Transform
Gn	Gravity = 9.81 m/s^2
g_n^2/Hz	Average power seen in a 1 Hz bandwidth within a PSD
Grms	Gravity Root Mean Square - Defines the overall energy or acceleration level of random vibration profile (PSD)
HBK	Hottinger Baldwin Kjaer GmbH
HC	Hydrocarbons
Hz	Hertz
ICE	Internal Combustion Engine
ICM	Internal Combustion Motorcycle
ISO	International Organization for Standardization
kg	Kilogram
kWh	Kilo Watt Hours
mm	Millimetre
NOx	Nitrogen Oxides
OEM	Original Equipment Manufacturer
PSD	Power Spectral Density
RESS	Rechargeable Energy Storage System
SAE	Society of Automotive Engineers
SOC	State of Charge
SRS	Shock Response Spectrum
ULEZ	Ultra-Low Emissions Zone

incentivising ETWs have been introduced in a bid to combat localised air pollution and to reduce congestion. Concerns over declining urban air quality and ever-increasing congestion has seen gasoline-powered two-wheelers being banned in 148 Chinese cities [7]. Policy intervention such as the introduction of performance standards that classified Electrically Assisted Pedal Cycles (EAPC) as bicycles (if these weighed less than 40 kg and had a maximum speed of 20 km/h) and priority access over internal combustion engine (ICE) transport with cities have encouraged the transition to ETWs in this region. An indication of the impact that these policy changes have had on the local air quality is presented in a study undertaken by Cherry et al. [8], where the average emissions per person for an EM was compared to that from public transport by bus. Within this study it was found that the difference in average emissions of NOx and particulate matter (major causes of health effects) of an average EM in China, compared to a passenger journey by bus was approximately 90% and 60% lower respectively, whilst CO_2 and carbon monoxide (CO) were 54.9% and 25.1% lower [8].

In studies undertaken by Refs. [7,9,10] it has been identified that conventionally powered gasoline two-wheelers contribute substantially to the transport related emissions of hydrocarbons and carbon monoxides. Within both studies, when compared to electric two wheelers, traditional Internal Combustion Motorcycles (ICMs) showed higher life-cycle emissions of particulates, CO, hydrocarbons (HC), and nitrogen oxides (NOx). In research published in Ref. [11] the benefits of large EMs (comparable to $>$ 600 cc motorcycles) with respect to CO_2 emissions have been corroborated using data for the UK's grid energy mix for 2019–2020 [11]. Within this study the levels of CO_2 saving were evaluated by considering different EM user groups and charging systems. From this study it was found that, depending on the home charging strategy and use case, a direct replacement of an ICM with an EM results in a CO_2 saving of approximately 68–92% per annum, depending on user behaviour and charging method used, when compared to a 2021 Euro 5 compliant 1200 cubic centimetre (cc) gasoline motorcycle [11].

In addition to emissions savings, the analysis presented in Refs. [7,9,10] the tank-to-wheel electricity consumption of electric two-wheelers was found to be 7.0 $\pm$ 3.0 kW h 100 km^{-1} for EMs making them one of the most energy efficient powered vehicles for individual road transportation [7]. To facilitate a comparison, the tank-to-wheel energy use of conventionally powered two-wheelers ranges from 25 $\pm$ 9 kW h 100 km^{-1} for mopeds to 41 $\pm$ 13 kW h 100 km^{-1} for motorcycles. Weiss et al. concluded that the replacement of conventionally-powered two-wheelers with electric variants could result in tank-to-wheel energy savings of approximately 50–90% [7].

In 2020, approximately 1% of all vehicles sold within the large motorcycle sector in the UK (approximately 933 units) were electric [12–14]. Furthermore, companies such as Triumph, BSA and Honda have also announced research projects in this area and have expressed a desire to offer commercial products in the near future [15–17]. However, EMs still face significant barriers within the marketplace when compared to incumbent ICM technology. One of these barriers is ensuring that the RESS lasts the life of the product or maintains customer satisfactory performance over a warrantied life (such as 10 years or 60, 000 miles of customer usage). The value of 60,000 miles is derived from the vehicle having a life of 15 years and covering approximately 4000 miles a year. As highlighted within [18–22], poorly integrated automotive components or assemblies, when subjected to vibration can result in a significantly reduced service life or the occurrence of catastrophic structural failure through fatigue cracking or the work hardening of materials [20,23,24].

Across many transport modes, many researchers routinely investigate electro-thermal ageing factors for RESS but the effects of mechanical factors regarding road induced mechanical excitation and vibration are very rarely included. Thus, there is a clear gap in knowledge of the effect of road-induced vibration on electric motorcycles; no off-the-shelf standards exist for EM, or indeed for powertrain components of ICM. Indeed, such is the lack of research in this area, that the effects of road induced vibration on electric passenger car vehicles are not comprehensively understood.

This paper presents, for the first time, a study where an EM-specific vibration profile is developed. It defines the initial methodology employed to develop the profile, which is derived from riding the vehicle over known durability surfaces at the UTAC Millbrook Proving Ground in the UK and measuring the frequency response of the battery assembly. The derived profile can be employed by EM manufacturers to assess their products for vibration durability via the use of either a hydraulic or electromagnetic shaker table system. To assist the development of future standards, this study also compares the derived vibration profiles to vibration experienced by battery assemblies within passenger EVs to illustrate the key differences in operational environment for these components within these two different vehicle sectors, highlighting the need to ensure that separate standards are developed for assessing the durability of the RESS within these products.

This paper is structured as follows. Section 2 defines the existing research in the area of vibration experience by EV batteries and the effect it has on battery assemblies. In addition it presents the gap in knowledge regarding the vibration frequencies experienced by EM RESS. Section 3 defines the method employed within this study to define an EM vibration profile that represents a 60,000-mile life, whilst the results from this study and how they compare to EV vibration are presented in section 4. Further work and conclusions are presented in sections 5 and 6 respectively.

2. Related research - vibration experienced and the effect of vibration on electric vehicle batteries

Vibration has been shown to influence the lifetime performance of lithium-ion cells. In a study undertaken by Brand et al., two different cell formats (pouch cell and 18650 cylindrical cell) were evaluated over a six month period using swept sine vibration and shock profiles from the UN38.3 Test 3 and Test 4 standard [25]. During these tests, the cells were visually inspected for mechanical failure to ensure that they were not leaking or damaged. Additionally, all cells' electrical properties were assessed and were scanned via microcomputer tomography to ensure that they were not damaged before or after testing. This study found that different cell formats had different degradation characteristics [25]. Pouch cells showed no degradation or failure when evaluated in accordance with UN38.3 shock and vibration testing, whilst the cylindrical cells evaluated in the Y-direction displayed mandrel loosening during the shock and long-term vibration tests (no vibration analysis was undertaken in the X-axis as for the cylindrical cells this was considered equivalent to the Y-axis). In addition, cylindrical cells stressed in the vertical direction (Z direction) also experienced degradation [25]. The cell orientation for this experiment is presented in Fig. 1.

Images collected before and after the tests revealed that the current interrupt device (CID), was damaged from long term vibration [25]. Internal damage was also observed on testing undertaken by Berg et al. in a study which evaluated 18 different 18650 cylindrical cells in accordance with SAE J2380 and an upscaled profile, defined by the authors as "severe" [26]. Although there was no significant change in electrical performance, Berg et al., found that the negative current collector tabs of certain cell designs were mechanically damaged [26]. Somerville et al. identified the electrochemical mechanism causing vibration-induced performance degradation in Li-ion cells via X-ray photoelectron spectroscopy on NMC cells during vibration tests [27]. They discovered that under vibration, the selectively formed surface film during normal usage is removed and is then replaced by the surface film caused by electrolyte decomposition, resulting in an increased capacity loss, and increased cell impedance [27]. In a series of vibration studies investigating the effect of vibration that was representative of 100,000 miles on 18650 cylindrical cells by Hooper et al. [28–30] up to a 257% increase of internal resistance was observed in some samples depending on cell chemistry and cell manufacturer [29]. Whilst all these studies have highlighted that vibration can influence the life of lithium-ion battery cells, the testing employed vibration profiles that had been developed from passenger EV data and not electric two wheelers. Regarding testing that has investigated the effect of vibration on the life of EM RESS and their subcomponents, no significant literature or data is available.

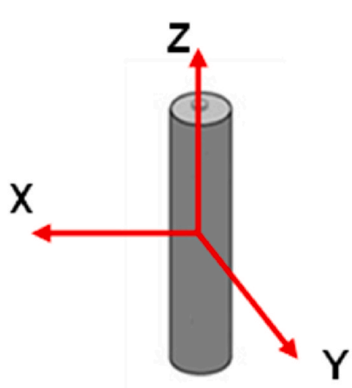

Fig. 1. Cell axis orientation.

In recent years there have been several studies which have investigated the vibration experienced by RESS in vehicles. The study conducted by Hooper et al. defined the vibration experienced by the RESS within three commercially available EVs (the Nissan Leaf, the Smart ED and the Mitsubishi iMiEV) when subjected to multiple durability surfaces at UTAC Millbrook Proving Ground UK [31]. For each vehicle, the measured road surfaces were sequenced to represent the vibration energy that the battery pack may be exposed to during a representative 10-year service life resulting in a Power Spectral Density (PSD) for each vehicle [31,32]. The generated PSD were compared to two current "random vibration tests" of Society of Automotive Engineers (SAE) J2380 and British Standard (BS) 62660. This study identified that both standards were too aggressive when compared to the measured data [31, 32]. The data from this study was investigated further by Hooper et al., within [32] where the profiles from these vehicles were used to develop a vibration profile suitable for a wide range of EV RESS. This data was also compared to existing test standards, such as [8]. This study found that most random vibration tests currently available to engineers for conducting vibration testing on RESS are overly compressed with respect to test duration resulting in excessive shock loading, which may hide fatigue issues that may not propagate due to the over accelerated nature of the test. In addition, it was found that the potential fatigue damage within International Organization for Standardization (ISO) 12405 is not representative of a vehicle life of 100,000 miles durability [32]. Similar conclusions were found from a study undertaken by Ref. [33] where different vibration standards were compared against vibration measurements from a Volvo C30 Electric vehicle via assessing the shock response spectrum (SRS) and fatigue damage spectrum (FDS) of the recorded vibration data against the SRS and FDS of current RESS vibration standards. This study concluded that it is important that vibration standards and tests conduct evaluations in all three directions and consider frequencies below 10 Hz [33]. Kjell et al. highlighted that test standards that applied vibration via sinusoidal excitation have high response levels and therefore have a greater risk for low cycle fatigue or produce functional disturbances that are higher than during real service [33]. In addition this study identified that a high test time-compression factor (such as trying to replicate 10,000 miles in under an hour of testing) can cause other damage mechanisms during a test than seen during real service life [33].

Regarding studies investigating motorcycle and ETW battery vibration, there are limited publications in this area. Studies which have investigated vibration within these transport modes have traditionally focused on the vibration exposure to the riders, to support vehicle refinement and comfort studies. There are several academic papers that cover a range of two wheelers and identify the vibration levels experienced and compare these to ISO2631. In a study undertaken by Debowski et al., the effect of mass parameters on the torsional vibration frequencies in the steering system of a motorcycle is presented [34]. In a paper by Khan et al., vibration in a 70 cc ICE motorcycle that is induced by engine and transmitted to body, seat, handle and then to the human body is measured and analysed [35]. Whilst the study conducted by Khan et al. presents data that could be useful to help improve the design of motorcycle seating, the limitation with this study is that it relied on using uncalibrated accelerometers within a range of different mobile phones that were installed on the rider and motorcycle [35]. Also, the sampling rate of the data is undefined meaning that the results presented could be impacted by signal aliasing [35], also due to the poor mechanical fastening of the measurement devices employed by the study, the accuracy of the measurements is impacted and thus the study defined is not repeatable. In a study undertaken by Mulla et al., the vibration experienced at the seat and handlebar locations on a contemporary electric moped was investigated. It was concluded that the vibration level perceived in an electric moped is far lower than that of its conventional counterpart and higher resonant modes are not perceived by the driver which improves driver comfort, whereas in a conventional scooter the lower resonating frequencies causes high discomfort for the rider due to frequencies within the human perception range [36]. Whilst this is not focused on component durability testing, it does highlight the difference in vibration behaviour of ICMs and ETW. In addition, a study undertaken by Adamek et al. has shown that for the same operating conditions, the vibration in passenger cars was significantly lower than that of an ICM [37].

In addition to identifying the vibration experienced by the rider, there has been some work published which has investigated the natural frequency characteristics of an ICM frame. Within a study undertaken by Bocciolone et al. the natural frequency and mode shapes of a small ICM frame were determined both experimentally and in simulation. They were able to identify modes up to 1,000 Hz [38]. The frame exhibited modes at 205 Hz, 421 Hz and 462 Hz. Modal damping of 0.05%, 0.06% and 0.02% were also reported [38].

A noteworthy study in this area is by Kurniawan et al., who measured the vibration experienced by packages that were transported by different conventional motorcycles and tricycles within Thailand and Indonesia [39]. Whilst this study is not focused on frame mounted components, it does give an indication of the frequencies and loads that would be experienced onboard as the study employs a suitable data logger system and accelerometers rigidly fixed to the test vehicles. It also presents PSD of the frequency content experienced in cargo carrying locations of these vehicles from 0 to 100 Hz. In addition, the study considers different delivery routes and operational environments and is one of the most comprehensive studies available within the area of vibration loads experienced by two wheelers. The study identifies that cargo mounted on the rear of a two-wheeler motorcycle in Indonesia will experience peak accelerations at approximately 6 Hz, 28 Hz, 50 and 80 Hz in the vertical axis, when in service [39]. Whilst in the longitudinal and lateral, peak accelerations are observed at 6Hz, 28 Hz 35 Hz and 80 Hz [39]. The study also presents a composite PSD for evaluating delivery package robustness for a range of different two and three wheeled vehicles based on the operation within Thailand and Indonesia. The challenge with this study is that it employs ICE motorcycles and Tuk-Tuks. Because it has a focus towards final mile delivery, the profiles are not developed with a long-term durability focus.

In summary, this literature review was unable to identify any specific study that has investigated the effect of vibration on RESS or their components that are destined for use within EMs. Regarding studies that have specifically focused on the durability of EMs in general, there is limited research in this area. Whilst in recent years there have been studies evaluating the vibration durability of battery cells, they have exclusively employed profiles derived from EV data or are related to a four-wheel passenger vehicle application, which have derived vibration profiles from EVs.

Thus there is an opportunity to address this research gap and to record data from contemporary EMs and to convert these road load measurements to a profile suitable for evaluating battery cells, modules, and packs destined for ETWs, whilst ensuring this profile is representative of a given service life. The methodology described in this paper addresses this research gap.

3. Method development of a random vibration profile representative of 60,000 miles durability

In order to understand a component's response to a vibration input the limits of this input must be specified. Within the field of vibration testing, there are two primary types of vibration inputs: "random" and "swept sine". A swept sine test excites individual frequencies within a particular range (e.g. 5–200 Hz). However, a random test will apply a broad band of frequencies to the component and influences many frequencies simultaneously. In order to make this signal repeatable the signal can be controlled based on pre-determined criteria.

Because random vibration excites a defined band of frequencies, resonant frequencies within the item under evaluation are excited regularly and together, subsequently causing interactions which typically would not occur within a sine vibration test [20,32]. Random vibration testing is also more representative of road-surface-induced vibration phenomena on wheeled vehicles and subsequently is more desirable for accelerated life testing of chassis mounted components [20, 32]. Random vibration profiles are generated via applying a fast Fourier transform (FFT) to the measured vibration signal to convert it from the time domain to the frequency domain.

To reproduce a random signal on a shaker table it is necessary to define parameters that are applicable and representative of the operational environment of the item and replicates the vibration energy within the frequencies representative of the service condition. Random test profiles are defined as amplitude against frequency which will has an upper and lower frequency restriction (e.g. 5 Hz–190 Hz) and are presented in the form of a PSD. In the case of random vibration profiles, because the acceleration is applied over a spectrum of many frequencies, the level is expressed as the quantity of g rms^2 in a 1 Hz bandwidth or $grms^2/Hz$ [32]. However, within test standards it is more commonly expressed as g_n^2/Hz. This unit of g_n^2/Hz describes the average power seen in a 1 Hz bandwidth, i.e. the PSD. The area below the curve is the energy content of the test profile and is a combination of an average level over the test bandwidth and represents the g rms or more commonly referred to as the Grms. The Grms can be calculated using Equation (1) where the bandwidth in Hz is defined by *BW* and the g_n^2/Hz value by *PSD*.

$$Total\ GRMS = \sqrt{BW \times PSD} \qquad \text{Equation 1}$$

The following section summarises the experimental method employed to measure the vibration experienced by the RESS within a current production EM when subject to road surfaces associated with typical customer usage. The stages associated with converting these vehicle measurements into a random vibration profile that can be replicated on either a hydraulic or electromagnetic shaker system are described in Fig. 2 and the following sections. This can then be used to validate if the vehicle's battery assembly is satisfactory for the duration that is the equivalent of a given mileage. It utilises the methodology that is defined in Ref. [32] for an EV, but defines within sections 3.1 and 3.2 the extensions to the process necessary to replicate a profile suitable for an EM. The commercially available Hottinger Baldwin Kjaer GmbH (HBK) n'Code software was employed within this study to process the PSD plots for each of the X, Y and Z axes, and the associated FDS and SRS data. The theory behind the software and developing random vibration profiles that are representative of a given durability life is discussed in greater detail within [32,40–43].

3.1. Collecting representative road surface data

The vibration characteristics of a Harley Davidson Livewire were evaluated over the durability surfaces available at the UTAC Millbrook Proving Ground, in Bedfordshire in the UK. The details of the test vehicle are presented in Table 1. This vehicle was chosen because it is one of the most popular large sized EMs on the market. At this stage a single EM was selected to demonstrate the methodology and contribution of the work; further EM will be added in the future to validate the generality of the approach. The EM was instrumented with two tri-axial accelerometers mounted at an upper and lower position on the battery housing. These positions are presented in Fig. 3. The accelerometers used were MEMS Tri-axial ASC model number 5411LN with 100 g_n range, which were mounted to the desired location of the vehicle via a mounting base and HBK X60 adhesive. Data was collected at a sample rate of 2,000 Hz (which was 2.5 times the maximum desired post-processed data frequency, which was 800 Hz) by Ipetronik M-SENS 8 analogue measurement modules. The data was recorded using the SAE J670e vehicle axis convention shown in Fig. 4. It must be noted that the battery on the test bike was rigidly mounted to the frame with no obvious isolation mounts

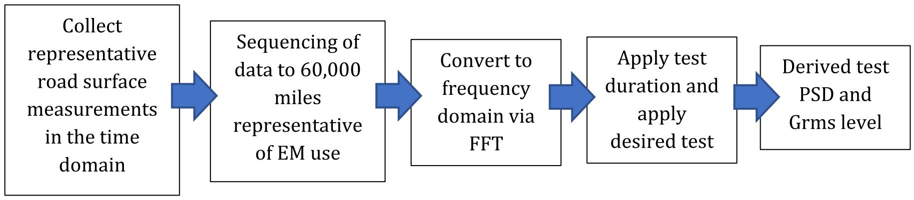

Fig. 2. Process for developing random vibration profile for an EM

Table 1
Test vehicle details and specification [3].

Motorcycle	Harley Davidson Livewire
Model Year	2021
Test Vehicle Registration	AF21KUA
Weight (kg)	210 Kg (Dry)
Dimensions (mm)	780 mm
Seat Height (Unladen)	2,135 mm
Length	1,490 mm
Wheelbase	
Useable Battery Capacity (kWh)	13.6 kWh

employed.

The EM was assessed using a rider who was 178 cm tall and weighed approximately 80 kg ± 5 kg including protective clothing, with the tyres inflated to the manufacturer's recommended pressures. The EM was charged to 100% state of charge (SOC) at the start of the measurement activity and was left to rest at an ambient temperature of 18 °C ± 3 °C for at least 8 h prior to testing. One limitation associated with this study is that measurements from within the EM's battery assembly was not possible. However, for developing a suitable test profile to validate the battery using a shaker system, external measurements of the battery casing are appropriate as closed loop control accelerometers for the shaker system are typically installed to the test items exterior surface or the shaker table armature.

The vibration experienced by the battery assembly within the EM was recorded over several predetermined surfaces at UTAC Millbrook Proving Ground. A description of these surfaces is provided in Table 2.

3.2. Sequencing of data to 60,000 miles EM use

In order to generate a representative real world vibration profile a variety of surfaces and operational environments must be included, and these must be sequenced together in an appropriate way to form 60,000 miles of representative usage. In this case the representative usage was for a vehicle ridden in a European market. This procedure was based on the Millbrook structural durability schedule [45], however the weighting of surfaces was adapted based on a motorcycle use case for typical UK operation using data presented in Ref. [46]. While this procedure represents an internal organisational standard, it has evolved over 20 years of experience and is currently employed by several leading OEMs [31]. It is also based on collected customer usage data and has been correlated with real world use. The surface weighting as adjusted for an EM for each surface classification is illustrated in Table 3.

3.3. Conversion to frequency domain via FFT

Once the time domain data has been sequenced to represent 60,000 miles of European EM usage, as shown in Table 4, the measured data needs to be transferred from the time domain to the frequency domain so that a PSD profile suitable for a shaker system application can be generated. This is achieved via the use of a discrete Fourier transform (DFT) [47] as illustrated in Equation (2).

$$x_k = \sum_{n=0}^{N-1} x_n \, e^{\frac{2\pi i}{N}} \, kn \qquad 2$$

where x_n represents a complex time-domain data set, x_k a complex frequency-domain data set and N, the size of the data sets (which are assumed to be equal). The notation used in the DFT sees two indices: n and k [46]

3.4. Application of test duration and desired test frequency

For experimental efficiency, it is desirable to compress the test duration of random vibration durability tests by increasing the Grms level of the synthesised PSD so that the same FDS can be achieved in less time. To determine if a profile is too aggressive through excessive test time compression, the severity of the peak loading applied to the system

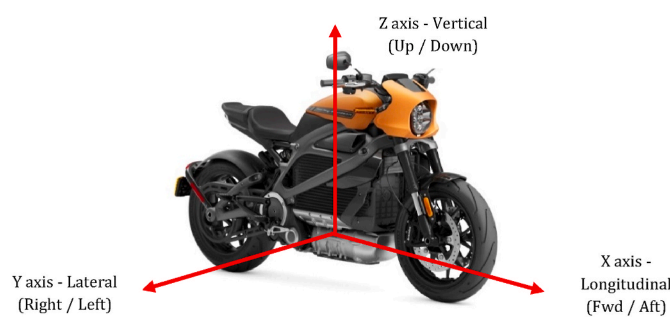

Fig. 4. SAE J670e Vehicle axis convention [3,44].

Fig. 3. Harley Davidson Livewire test bike – accelerometer positions highlighted.

Table 2
UTAC millbrook durability surface descriptions [32,45].

Road Surface	Road Surface Classification	Road Surface Description
Belgian Pave	Urban	Industry-standard surface for evaluating a vehicle's noise, vibration and harshness durability. 1.45 km of Edinburgh block granite paving
Cats Eyes 30mph	Rural	44 cats' eyes along a 90 m length of track
Cats Eyes 50mph	Rural	44 cats' eyes along a 90 m length of track
City Course	Urban	Level asphalt paved surface with multiple tight turns, speed humps, and posted speed limits typical of an urban driving environment
Handling Circuit	Rural	A concrete paved 6 m wide track with varying camber, typical of rural roads
Hill route (Loop 1)	Rural	A simulated alpine road which has numerous ascents, descents and bends with changing camber and transmissions sets
HSC	Motorway	A circular constant radius banked concrete paved track constructed to simulate motorway driving conditions
Mile Straight (PT)	Motorway	Long, precisely levelled surface with fast approach and departure lanes
Mile Straight (WOT)	Motorway	Long, precisely levelled surface with fast approach and departure lanes
Potholes	Urban	Two large potholes, made from cast iron and placed into a concrete surface
Random Waves	Urban	Undulating surface out of phase, inducing maximum suspension travel and high amplitude low frequency input to vehicle structure
Sine Wave	Urban	Sine waves out of phase, for high frequency input to the vehicle structure
Sine Wave Medium	Urban	Sine waves out of phase, for high frequency input to the vehicle structure

Table 3
Surface weighting for vibration profile development based on UK motorcycle usage trends [45,46].

Surface Classification	Original Millbrook Structural Durability Surface Classification Weighting (%)	Surface Weightings for Motorcycles - UK Report 2016
Urban	45	37.31
Rural	31	43.43
Motorway	24	19.26

can be checked through commercial software (n'Code 2021) This compares the SRS of the synthesised PSD to that of the combined SRS of each measured surface to ensure that the shock loading is not outside that of the original measurements. Within this study 30 h per axis was chosen so that 1 h was representative of 2,000 miles of durability loading in the desired test axis. This means that the test can be scaled based on expected mileage in the future. Fig. 5 shows an SRS of each of 30-h test duration compared to the SRS analysis of the pre sequenced data in g_n (as shown by the red dashed line in Fig. 5). From this data it can been seen that the 30-h test duration is well within the SRS of the baseline SRS.

A significant decision for application of a vibration test profile is the chosen frequency range under assessment. The frequency range is typically defined by the capabilities of the shaker facilities and the frequency band where the peak energy occurs within the measured data. 5–200 Hz was chosen for the EM test profiles within this study. A maximum frequency of 200 Hz was chosen to ensure that it could be replicated on hydraulic shakers (which typically display performance run off above 250–300 Hz) [29,48] whilst a 5 Hz starting point was chosen so that the profile could be conducted on electromagnetic shaker facilities which typically cannot replicate frequencies below 5Hz (due to the lower displacement associated with these facilities) [20]. Reviewing PSDs of the test data highlighted that most of the vibration energy occurred between 7 and 30 Hz for the Z axis, whilst most of the vibration energy for the X and Y axes occurred between 5 to 42 and 5–200 Hz respectively. However, it is worth observing that both the X and Y axes show high energy input at frequencies below 1Hz due to the roll and pitching motions associated with a two wheeled vehicle which differ significantly to the levels witnessed by a battery assembly in a four wheeled passenger vehicle. However, due to the low frequency, the level of damage that these sub 1Hz vibrations cause is assumed to be minimal and therefore can be excluded from the profile. Fig. 6 shows the synthesised PSDs for the X, Y and Z axes of the battery assembly for a test that would replicate 60,000 miles of European customer durability in 30 h of vibration in each axis.

Table 4
Surfaces recorded and the number of repeats for each surface to generate vibration profile.

Surface Relating	Surface in km	Classification of Surface	Repeats for 96,560 km (60,000 Miles) - Motorcycle Weighting	Distance for Surface (km) (Motorcycle Weighting)
Belgian Pave	1.45	Urban	2,039	2,956
Cats Eyes 30mph	0.16	Rural	3,526	564
Cats Eyes 50mph	0.16	Rural	3,526	564
City Course	1.29	Urban	22,324	28,798
Handling Circuit	4.51	Rural	1,287	5,806
Hill route (Loop 1)	1.77	Rural	19,775	35,002
HSC	5.95	Motorway	1,397	8,309
Mile Straight (PT)	1.29	Motorway	3,988	5,144
Mile Straight (WOT)	1.29	Motorway	3,988	5,144
Potholes	0.16	Urban	184	29
Random Waves	0.64	Urban	4,078	2,610
Sine Wave	0.16	Urban	4,091	655
Sine Wave Medium	0.16	Urban	6,117	979
Total (km)				**96,561**

3.5. Derived PSD for contemporary shaker tables

The peak values were selected to derive a simplified PSD that encompassed the greatest vibration witnessed by the battery from the two measurement locations. The derived profiles were defined by up to 24 break points to ensure that they could be uploaded into a wide range of commercial shaker system controllers. The subsequent synthesised vibration test profiles representative of 60,000 miles of durability for the X, Y and Z axes of an EM battery assembly are illustrated in Fig. 7 and defined in Table 5:.

4. Comparison of synthesised EM test profile to passenger EV profiles

The EM data recorded and synthesised in this study is compared to EV passenger profiles generated from previous research [32,40,41]. Both the EM and EV passenger profiles compared were derived from the same proving ground surfaces and were recorded under the same test conditions and speeds. In addition, they were sequenced in a similar

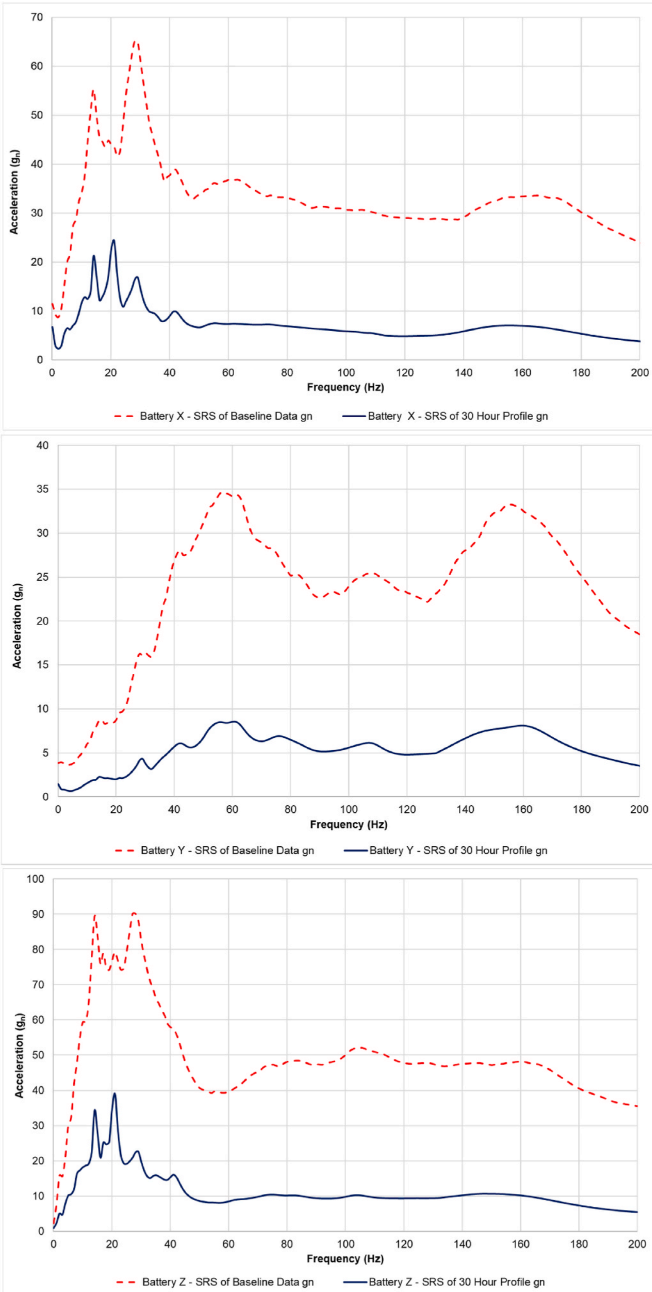

Fig. 5. SRS of battery baseline data versus SRS of battery 30 hour profile.

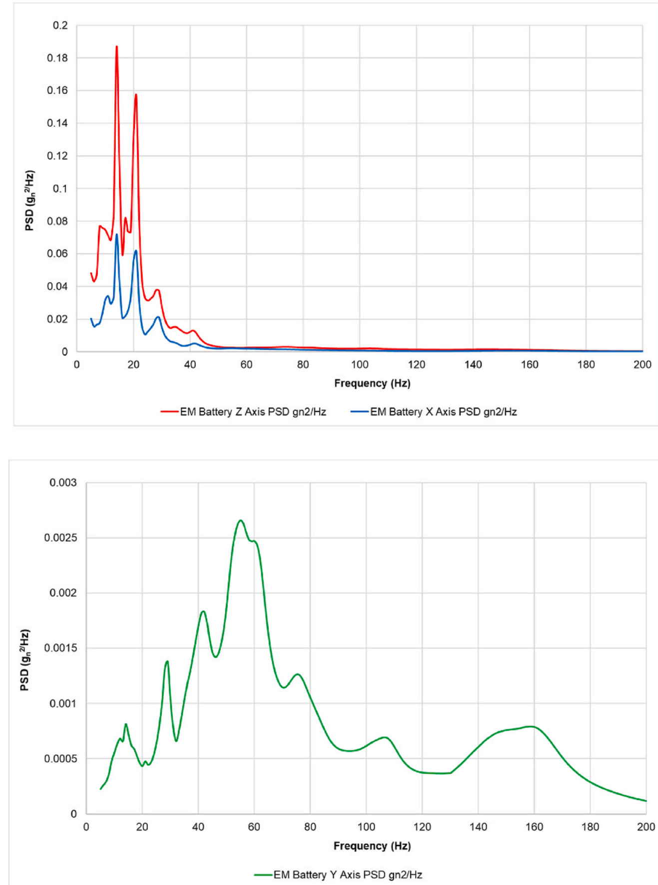

Fig. 6. Synthesised X, Y and Z axis PSDs for EM battery assembly vibration durability test- 30 hour test duration (Per axis).

manner. The EV profiles presented in Fig. 8 replicate 2,000 miles of durability for hour of test time. Therefore 30 h of testing per axis would replicate 60,000 miles. What is noticeable from this comparison of PSDs, is that the Z and X axis loading is significantly greater from 5 to 50 Hz for a battery which is mounted within the frame of a large sized EM when compared to the levels experienced by a battery that is mounted within an A or C segment passenger EV. For the Z axis, acceleration levels are approximately 8 times greater, whilst for the X axis, they are 4 times greater for an EM than an EV. This highlights that using established passenger vehicle standards for motorcycles for durability testing will under-evaluate the battery assembly with respect to vibration and could lead to a greater chance of in-service warranty failures. A noteworthy observation is that both the EM and EV Z-axis profiles show large peaks around 15–18 Hz suspension mode and 21–28 Hz suspension modes.

Reviewing the levels experienced by the Y-axis within both vehicle types, shows a difference in vibration loading with respect to peak frequency content. Within the EV, profile peaks occur in the Y axis at approximately 18 and 39 Hz, which are the result of body modes, whist the EM has a 55–61 Hz peak which is likely to be a torsional mode of the frame and battery moving together, due to the mass of the battery suspended in the frame causing motion at this frequency. Further visual analysis of the frame during a strip down of the EM post testing revealed that the frame was cast using very slender members to ensure maximum battery packaging volume, which are likely to cause a torsional moment. However further modal analysis of the frame and battery assembly is required to investigate this theory. The general differences in frequency content and energy levels in the Y-Axis are likely to the fact that a motorcycle has a different roll response to road excitation due to its two wheeled nature. It is important to note that centre of gravity is of greater concern for stability of EM than for EV since in an EM the battery pack forms a greater percentage of the vehicle mass compared to an EV and it is also mounted higher than for an EV battery. Also, the brand DNA of vehicles is often reflected in the ride/handling compromise where the optimum suspension stiffness for ride is less than that for optimum handing, so a compromise must be made. Too stiff suspension results in lower grip as the wheel cannot move fast enough to match the road, too soft and the bike will squat and dive. The natural frequency of the suspension is normally higher for more sporty products as handling is given greater priority. A touring motorcycle would target greater comfort, so likely have a suspension frequency closer to the optimum ride frequency.

5. Further work

Whilst this study has derived a vibration profile that can be employed by manufacturers and researchers to evaluate and assess the

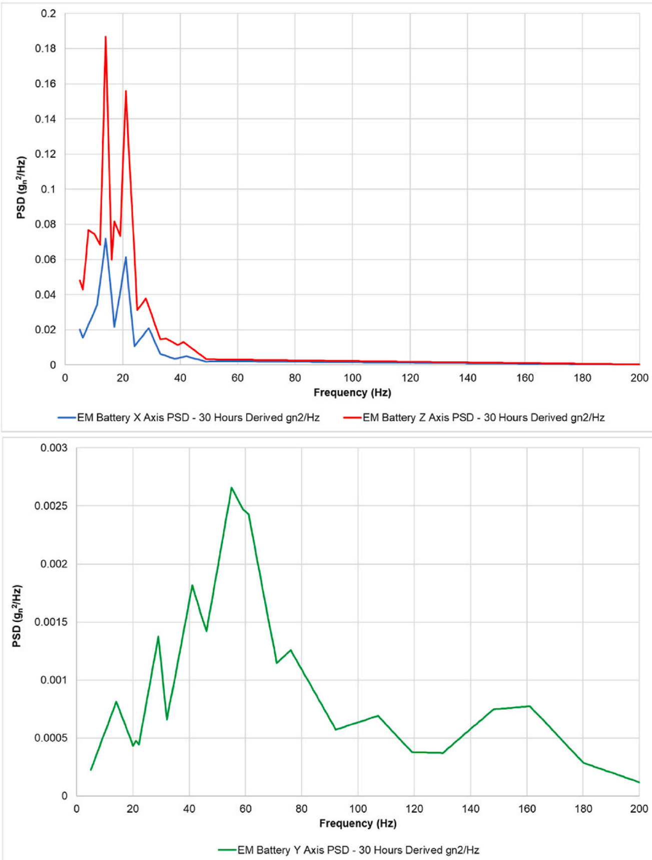

Fig. 7. Derived EM vibration profiles for X, Y and Z axes of the battery assembly – 30 hours in each axis replicates 60,000 miles of customer use for UK.

Table 5
Set points for derived EM vibration profiles for X, Y and Z axes of battery assembly for shaker controllers.

Frequency	EM Battery X Axis PSD	Frequency	EM Battery Y Axis PSD	Frequency	EM Battery Z Axis PSD
Hz	g_n^2/Hz	Hz	g_n^2/Hz	Hz	g_n^2/Hz
5	0.02018	5	0.0002251	5	0.04809
6	0.01549	12	0.0006821	6	0.043
11	0.0341	14	0.0008121	8	0.07677
14	0.072	20	0.0004337	10	0.07462
17	0.02171	21	0.0004755	12	0.06853
21	0.06127	22	0.0004449	14	0.1868
24	0.01065	29	0.001376	16	0.0598
29	0.02096	32	0.0006576	17	0.08164
33	0.006289	41	0.001816	19	0.07341
38	0.003508	46	0.001419	21	0.156
42	0.004899	55	0.002658	25	0.03131
49	0.001912	59	0.002468	28	0.03784
54	0.002116	61	0.002428	33	0.01445
200	0.0001403	71	0.001147	35	0.01511
		76	0.001257	39	0.01135
		92	0.000573	41	0.01298
		107	0.0006911	49	0.003239
		119	0.0003785	200	0.0002766
		130	0.0003711		
		148	0.0007471		
		161	0.0007743		
		180	0.0002859		
		200	0.0001177		

durability and mechanical aging performance of EM RESS and components, the derived profiles use surface weightings based on an ICE vehicle structural durability schedule, which has been adapted with EM

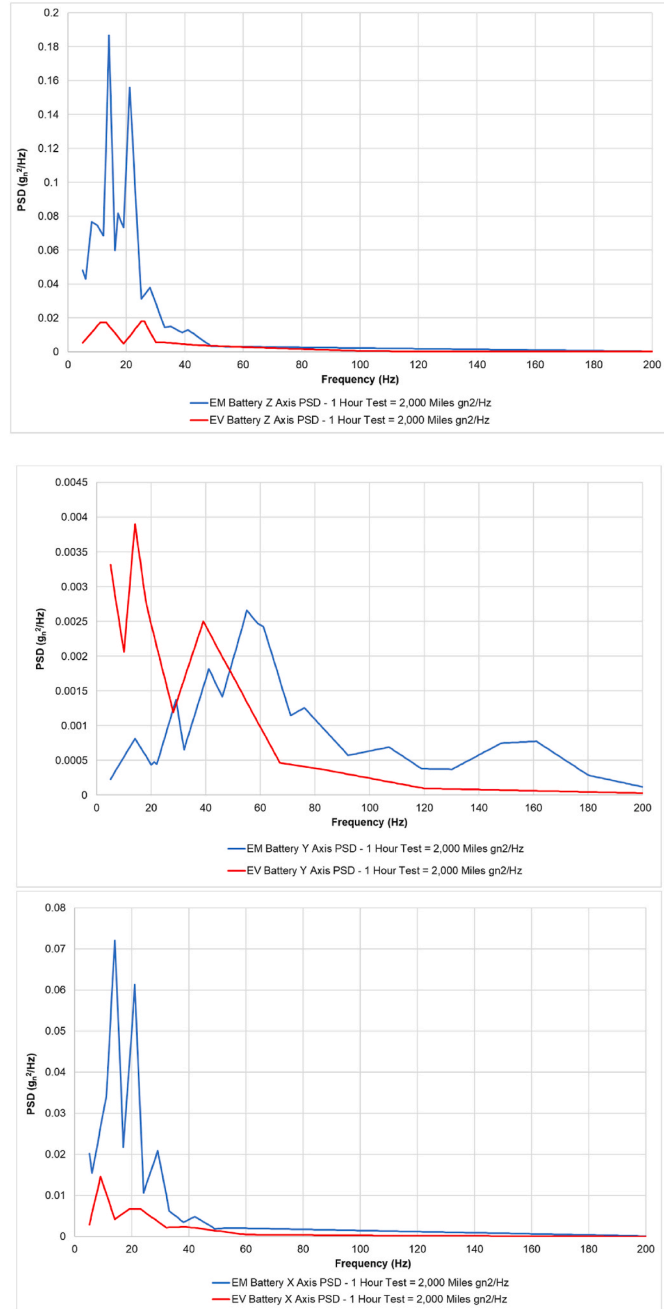

Fig. 8. Comparison of EM vibration profile against established EV profile for X, Y and Z axes of vehicles.

customer usage data. Greater accuracy could be achieved in the future undertaking a long-term monitoring project of EM to understand the customer use behaviour and the loads they are subjected to.

Further, this study has focused on European usage, and has not considered the implications of different markets on the durability requirements for RESS. Therefore, it would be beneficial if future surface weightings also considered regional variances regarding measured accelerations and customer usage.

The developed profile is based on data from a single EM. Whilst it shows that there is a significant difference between EVs and EMs and provides a basis for EM manufacturers who are conducting vibration durability tests, more data needs to be collected from a wide range of EM products to develop a generic motorbike durability test profile.

The derived profiles assumes that the transmission of the vibration from the external casing will be the same for the internal components, such as cells, bus bars and other interconnecting hardware. It is therefore recommended that a future study with both the external and internal parts of a battery instrumented is conducted and the difference in vibration loading and transmissibility of inputs can be determined. Instrumentation of the suspension, and a full motorcycle modal analysis could also be employed to investigate the motorcycle's vibration behaviour in more detail.

Finally, whilst the derived profiles have been trialled on commercial shaker table facilities at both WMG and UTAC, they should be applied to testing cells, module and packs to evaluate cell performance and degradation.

6. Conclusions

There has been little published research critically examining the mechanical integration of the HV battery system within a large ETW. However, if excessive vehicle warranty claims are to be avoided it is important that engineers tasked with the design of the battery installation properly understand the magnitude and frequency of the vibration inputs that the system will be exposed to during the vehicle's predicted life; this manuscript presents an initial contribution towards this goal.

This study describes for the first time the methodology for development of test profiles for testing the X, Y and Z axes of a RESS for a large EM product., where 30 h of vibration in each axis of the RESS is representative of 60,000 miles of European durability surfaces sequenced to EM Road usage.

The devised test profiles apply vibration from 5 Hz to 200 Hz ensuring that they can be replicated on a wide range of shaker systems whilst ensuring the device under test is excited within a suitable frequency range, representative of operation of a large EM product.

The PSD shows significantly greater magnitudes for the EM compared to that experienced by an EV in the X and Z Axes.

CRediT authorship contribution statement

James Michael Hooper: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Methodology, Validation, Data curation. **Darren Williams:** Resources, Investigation, Writing – original draft, Writing – review & editing, Software, Methodology, Validation, Data curation. **Kieran Roberts-Bee:** Writing – review & editing, Investigation. **Andrew McGordon:** Supervision, Writing – review & editing. **Phil Whiffin:** Funding acquisition, Project administration. **James Marco:** Conceptualization, Writing – review & editing, Supervision.

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

The data that has been used is confidential.

Acknowledgements

This work has been supported through the Advanced Propulsion Centre project (eBSA, project no. 75281).

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