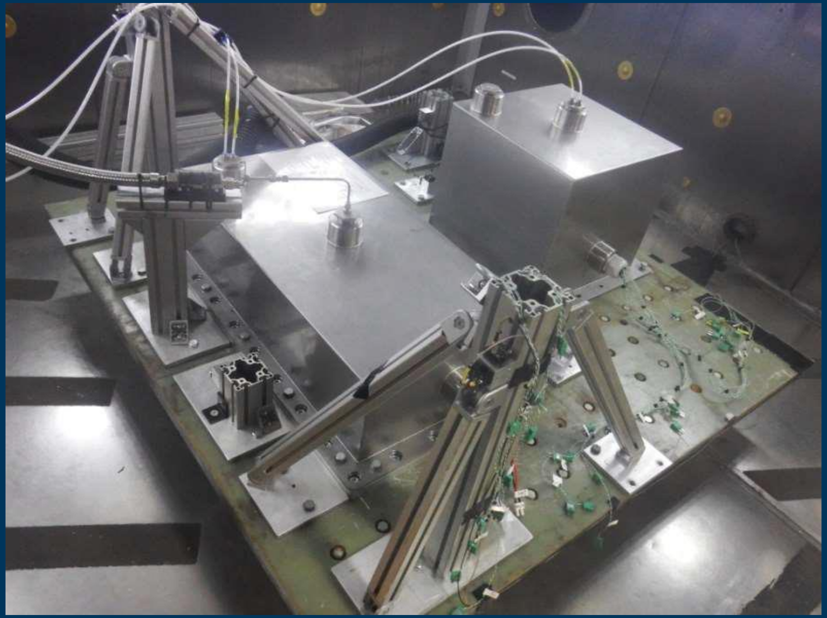
Virtual Seminar Series – Tuesday 2, 9, 16 November



Vibration Durability Testing and its Effect on Electric Vehicle Batteries

Presented by Dr. Jim Hooper
Principal Engineer – Electric Vehicle Projects
WMG, University of Warwick

Tuesday, November 16, 2021

Vibration Durability Testing and its Effect on Electric Vehicle Batteries

Abstract

Within this presentation, Dr. Jim Hooper will illustrate that vibration, that is representative of 100,000 miles of service can have a direct impact on the electrical and mechanical performance of electric vehicle battery cells and packs. The presentation will cover the work undertaken by WMG in vibration durability and will highlight test methodology that can be employed by engineers to quantify the vibration robustness of their battery packs. It will illustrate different electrical and mechanical characteristics that need to be considered in the assessment of battery cells, modules and packs and provide examples of tests that have been conducted on Tesla Model S battery modules.

About the presenter, Dr. Jim Hooper, Warwick Manufacturing Group, University of Warwick

Dr. Jim Hooper (Principal Engineer – Electric Vehicle Projects) – has over 15 years' leading and delivering engineer test and development projects across both industry and academia at vehicle, system, and subsystem level within a range of different sectors, including marine, off highway, automotive, aerospace and military. Jim has an engineering doctorate in High Voltage (HV) Battery Durability and Noise Vibration and Harshness (NVH) Evaluation, which defined the vibration experienced by an EV battery assembly over a typical UK / European 100,000 mile life and undertook studies to investigate ways in which battery cells and modules degrade when subjected to random vibration profiles which replicated a given vehicle life.

Vibration Durability Testing and its Effect on Electric Vehicle Batteries

16th November 2021

Dr Jim Hooper

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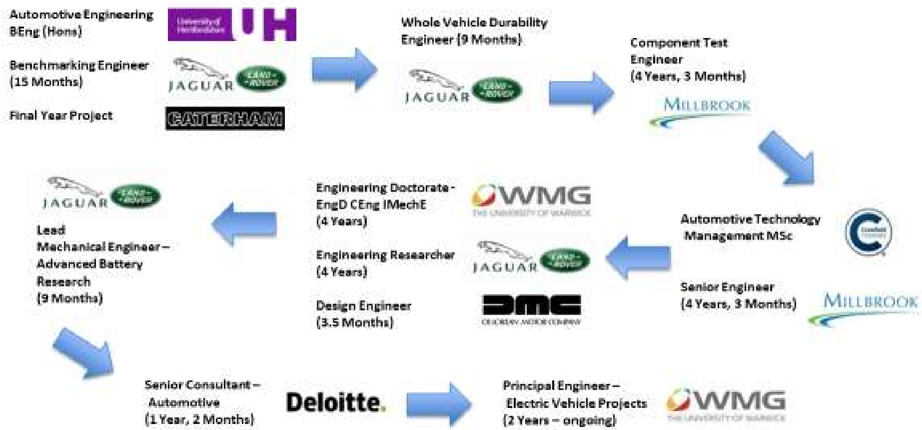
Introduction – Dr Jim Hooper

- Over 15 Years experience in vehicle testing, development and research - 10 Years experience of working with EV manufacturers
- Engineering Doctorate researching the durability of electric vehicle batteries with respect to vibration
- Have supported the delivery of >30 vehicle projects

  Interesting ones include:

  - Tesla Roadster
  - Fisker Karma
  - Lotus Evora
  - Chevrolet Volt
  - McLaren MP-4-12C
  - Jaguar i-PACE
  - Wrightbus Routemaster
  - Triumph TE-1



Contents

- Research Background / Need
- Study 1 – Vibration Environment of EV Batteries
- Study 2 - Effect of Vibration on EV Batteries
- Conclusions

Research Background / Need

- Many barriers affecting the successful adoption and development of Electric Vehicles (EV's).
- Ensuring that EV batteries are durable enough so that they last the life of the product or maintain customer satisfactory performance over a warranted life (such as 10 years or 100,000 miles of customer usage).
- Published vibration data only relates to vibration abuse/robustness or legislative testing, and does not represent a "vehicle life" (such as 10 years operation or 100,000 miles driving).
- Potential that current EV cells are being assembled into battery packs in a manner which does not consider their durability behaviour – resulting in significant warranty risk.

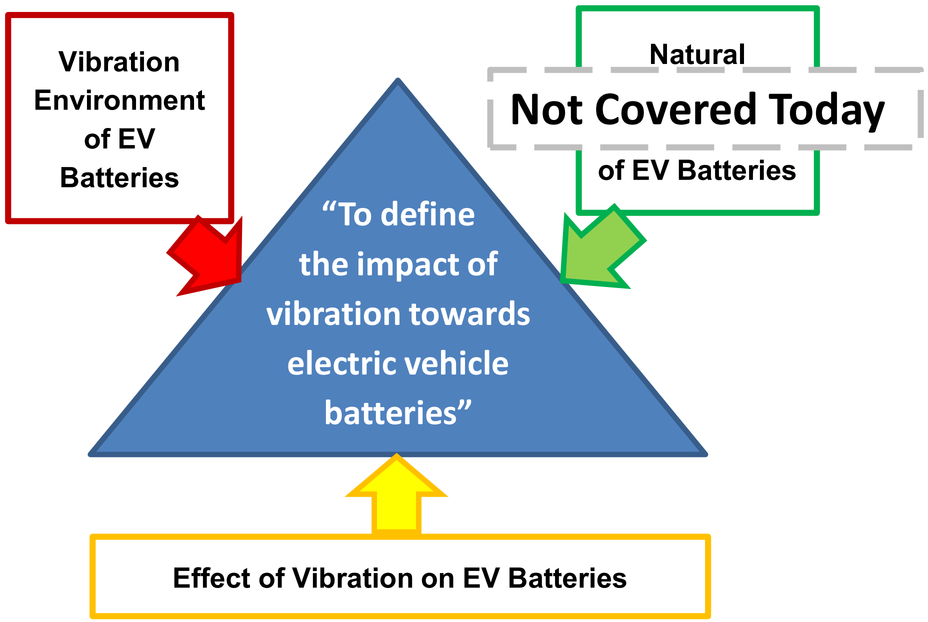
Research Objective

- **“To define the impact of vibration towards electric vehicle batteries”**

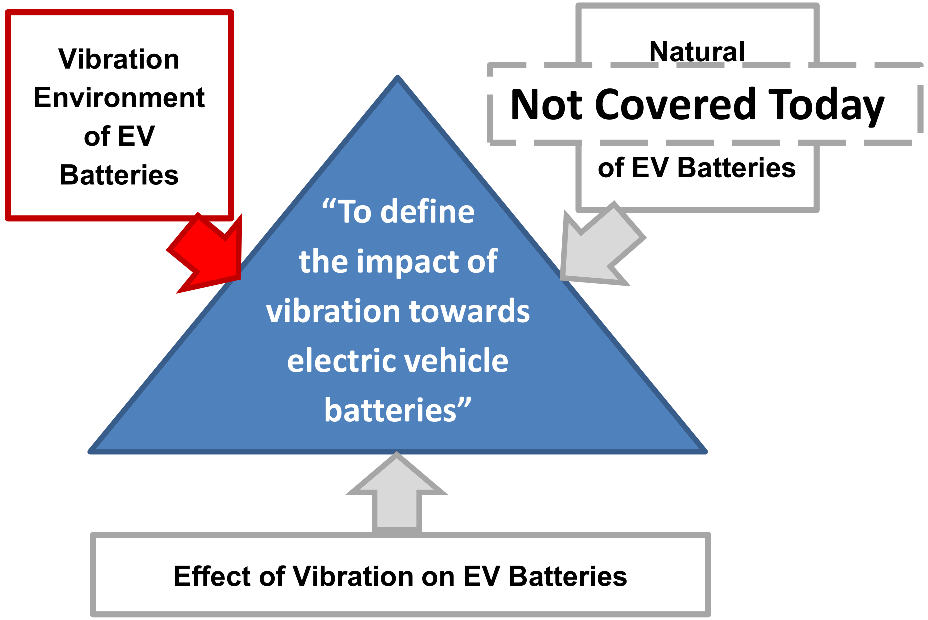
- To provide knowledge and evidence that allows manufacturers to understand the **mechanical durability and performance** of automotive electric vehicle battery assemblies and their sub components, with respect to vibration.

- **It has a focus towards “durability testing”** – a validation method which has been correlated to a pre-determined service life (e.g. 100,000 miles or 10 years)

Research Aims



Study 1 - Vibration Environment of EV Batteries



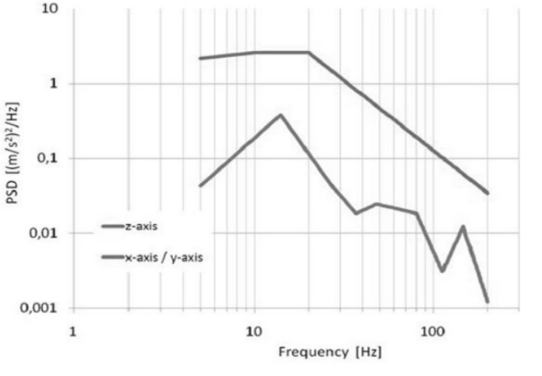
Study 1 - 4 Limitations of Previous Research

- Unrepresentative measurement data - data acquired from internal combustion cars / measured a single vehicle type.

- Used vibration measurements from a single road surface measurement and not a mixture of customer driving environments.

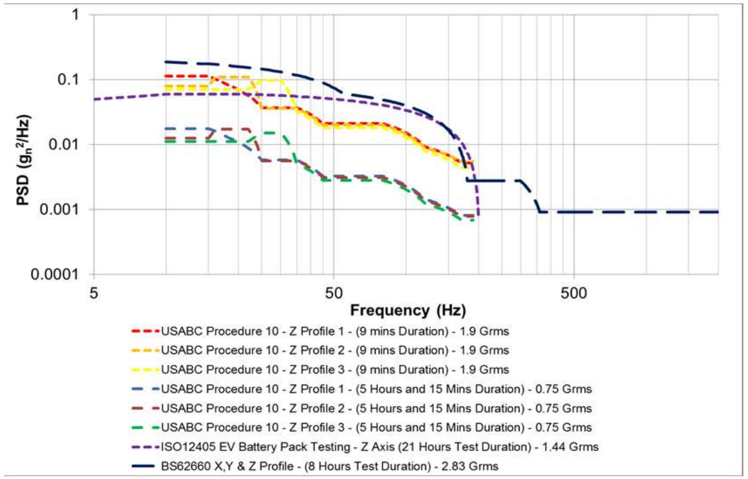
- Used profiles not correlated to a known durability life – 100,000 miles.

- Ignore horizontal and longitudinal axis vibration or applied a simplified load case.



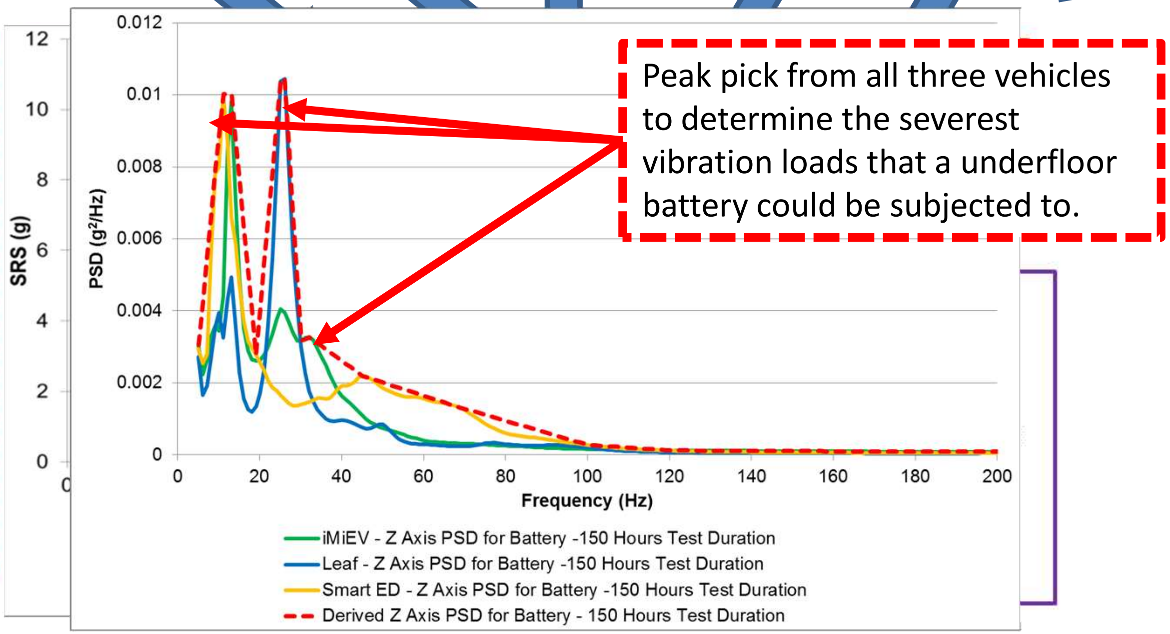
Objective of Study 1

- To develop a set of random vibration profiles that are representative of 100,000 miles of UK customer usage of a chassis mounted battery within an Battery Electric Vehicle (BEV) using actual BEV measurements that could be used by manufacturers to assess the durability of their products.

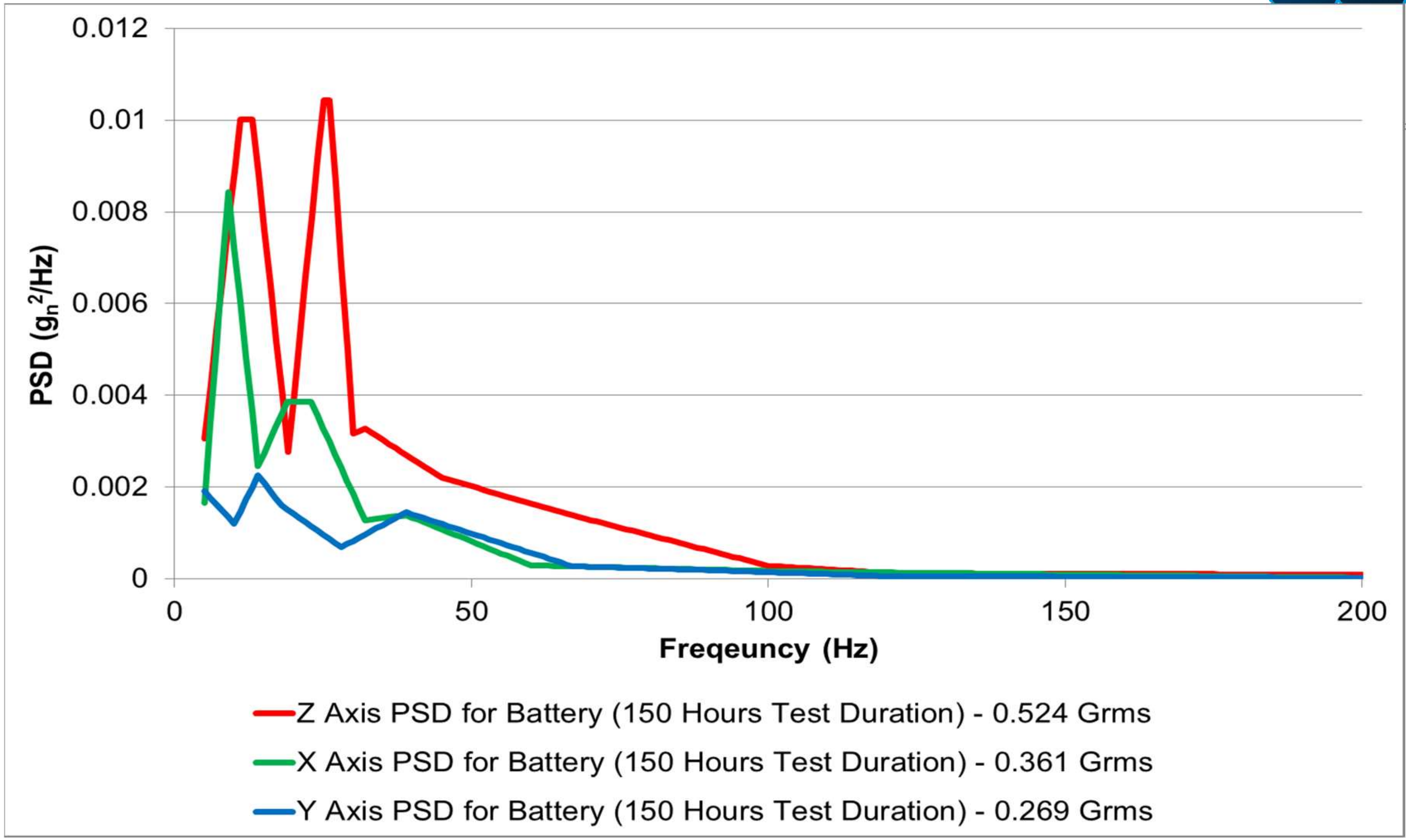


Method of Vibration Profile Derivation

1. Define customer usage and subsequent durability requirements
2. Collect representative road surface measurements in the time domain
3. Sequencing of data to 100,000 miles representative of UK BEV use
4. Convert to frequency domain (via FFT)
5. Determine test frequency range
6. Optimise test duration
7. Derived test profile



Vibration Profiles Developed from BEV Data



Conclusions from Study 1

- Devised a methodology and a set of recommendations for synthesising and developing vibration standards.

- Synthesised a set of vehicle representative vibration profiles from EV vibration measurements that replicate 100,000 miles UK BEV road usage in 150 hours for each axis from multiple surface measurements and several A and C segment vehicles.

- Replicate the X, Y and Z-axis vibration loading witnessed by an EV pack (and its sub components).

Study 2 - Effect of Vibration on EV Batteries

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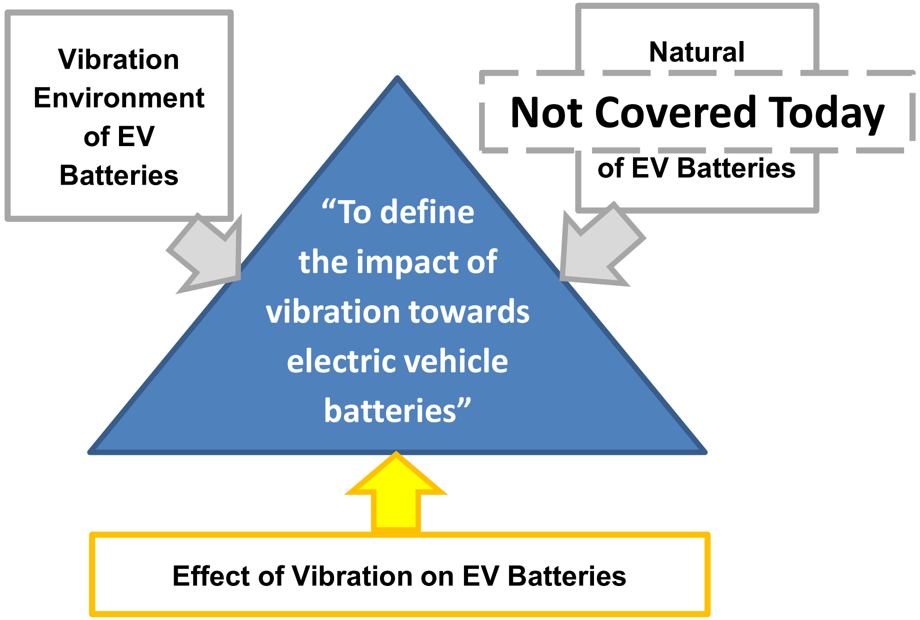

Study 2 – 4 Limitations of Previous Research

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- No testing has been correlated to vehicle mileage or life – all robustness or abuse.
- Test method often undefined or poorly executed. Test sample numbers and chemistry often undefined.
- Limited or no electrical / mechanical characterisation of test samples pre / post testing.
- Test fixtures poor or not defined – significant part of any vibration test.

Study 2 - Objective

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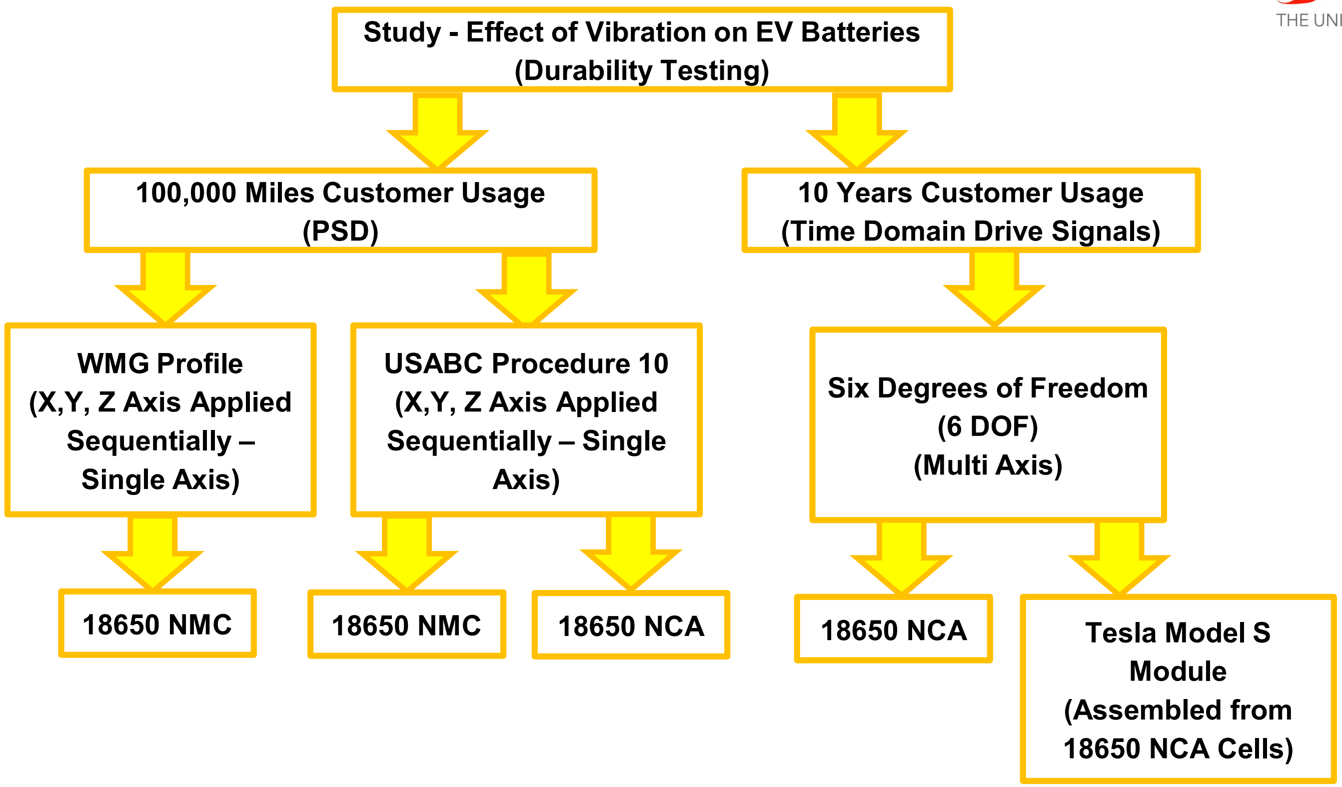
- To determine if Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Nickel Cobalt Aluminium Oxide (NCA) 18650 battery cells and a current productionised Tesla Model S battery module can be electrochemically and mechanically aged by mechanical induced vibration representative of a durability life of a vehicle (100,000 / 10 Years) using single axis and multi-axis vibration durability techniques and shaker systems.

Overview of Study



Test Method

Electrical Characterisation

Pre Test

- EIS
- 1C Capacity Discharge
- Pulse Power
- OCV
- Photographs

Conditioned to Desired Test Charge State

Mechanical Characterisation

Pre Test

Natural Frequency Measurement / Modal Analysis

Application of Vibration

Single Axis (Random PSD)
USABC Procedure 10
WMG / MBK Test Profiles

6DOF – (Time Domain)
Smart ED Proving Ground Measurements Sequenced to MBK Structural Durability Procedure

Mechanical Characterisation

Post Test

Natural Frequency Measurement / Modal Analysis

Electrical Characterisation

Post Test

- EIS
- 1C Capacity Discharge
- Pulse Power
- OCV
- Photographs

Test Fixtures

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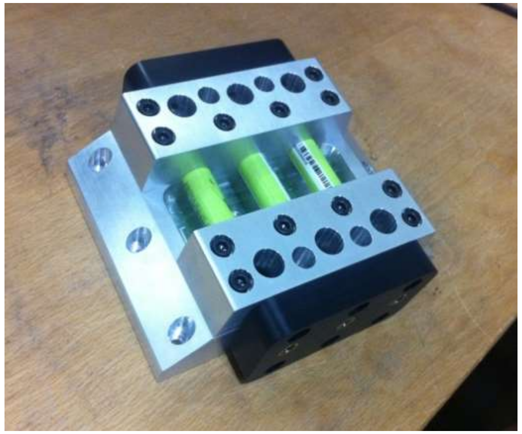
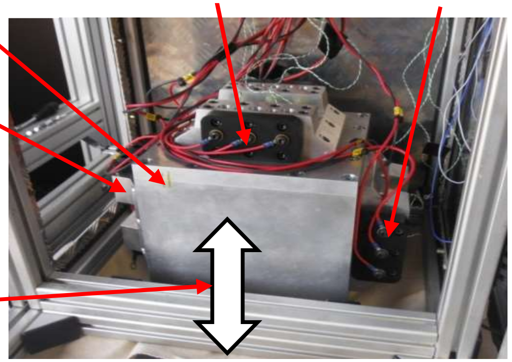
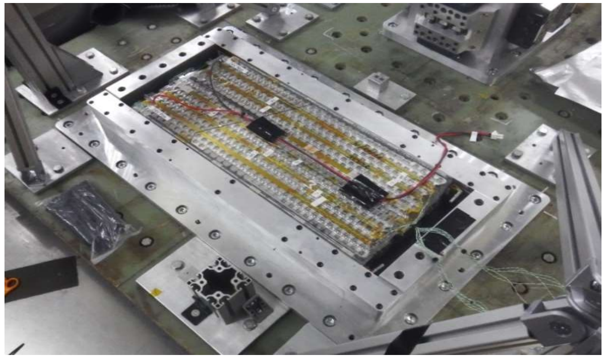


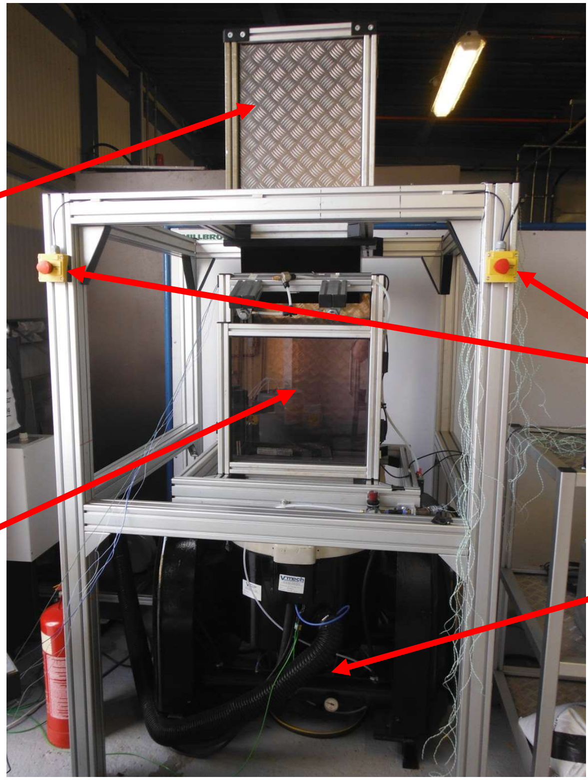


- All fixtures evaluated for resonances in accordance with BS EN 60068-2-6:2008 prior to use.



Test Set Up – Safety Equipment

Sand hopper and PLC release system (will release if cells achieve +60°C. Shaker will also shut down in event of fire or temperature over load)



Test chamber

Manual sand release / system shut down panic buttons

VP85 Shaker table

Test Set Up – Safety Equipment

Gas monitoring line

Gas nitrogen injection line

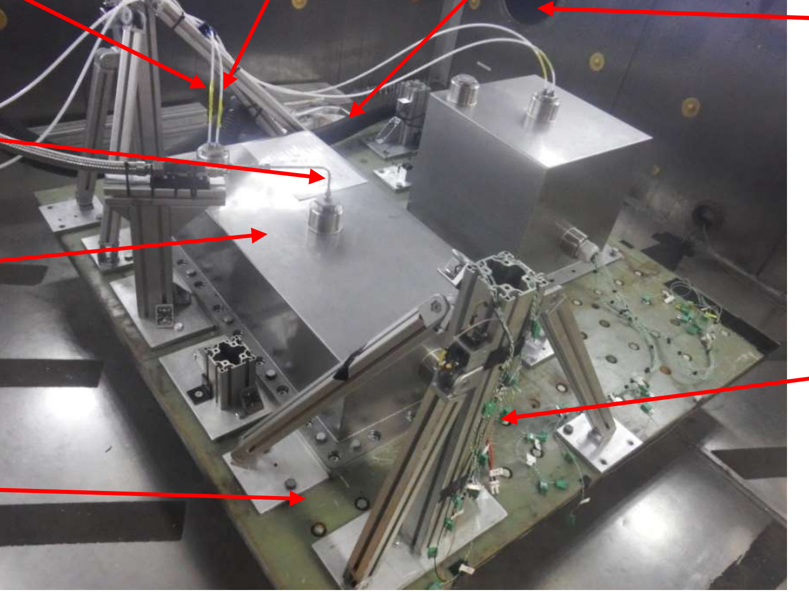
Forced gas extraction system hoses

Blast panel in chamber

Liquid nitrogen injection hose

Fire enclosure

G10 thermal barrier between shaker head expander and fixtures



Surface mount thermocouples attached to module monitoring for increase in temperatures

Application of Vibration – Single Axis Testing

SAE J2380
Vehicle Z Axis
(Vertical) Profile

Note – SAE J2380 is the same as USABC Procedure 10

Application of Vibration – Multi Axis Testing

Results – Cylindrical Cells

Electrical Characterisation	18650 Cell Chemistry and Test	Orientation in Pack / Control				Worst Performing Orientation
		Z	X	Y	Control	
Change in 1C Discharge Capacity (%)	NMC - SAEJ2380	-2.17	-3.92	-4.38	-0.16	Y
	NMC - WMG-MPG Profile	-2.69	-3.37	-1.38	-0.34	X
	NCA - SAEJ2380	-11.42	-11.45	-12.29	-11.33	Y
	NCA - 6DOF	-2.13	-2.13	-2.12	-4.13	Comparable
Pulse Power - Change in R_{DC} (mΩ)	NMC - SAEJ2380	57.65	64.09	67.80	3.86	Y
	NMC - WMG-MPG Profile	55.45	36.29	33.11	0.08	Z
	NCA - SAEJ2380	1.88	2.17	1.90	1.38	X
	NCA - 6DOF	2.87	2.75	2.52	1.02	Z
EIS Change in R_O (mΩ)	NMC - SAEJ2380	39.45*	80.97	100.20	4.77	Y
	NMC - WMG-MPG Profile	87.83	72.5	31.37	0.83	Z
	NCA - SAEJ2380	1.53	1.72	1.84	1.42	Y
	NCA - 6DOF	1.53	1.58	1.49	1.59	X
EIS Change in R_{CT} (mΩ)	NMC - SAEJ2380	-5.36	-6.09	-5.93	-9.30	Z (Least Improvement)
	NMC - WMG-MPG Profile	-6.74	-6.88	-7.51	-9.82	Z (Least Improvement)
	NCA - SAEJ2380	1.06	0.06	-0.04	1.42	Z
	NCA - 6DOF	-2.12	-0.59	-4.37	-5.17	X (Least Improvement)
OCV - Change in Voltage (V)	NMC - SAEJ2380	0.000	0.001	0.001	0.001	Comparable
	NMC - WMG-MPG Profile	0.007	0.004	0.006	0.003	Comparable
	NCA - SAEJ2380	0.000	0.000	0.000	0.000	Comparable
	NCA - 6DOF	-0.001	-0.001	0.000	0.000	Comparable

Results – Tesla Module

Test	Pre-Test	Post Test	Change	Change in %
OCV (V)	24.91	24.88	-0.03	-0.12
1C Capacity Discharge (mA)	221.82	221.55	-0.27	-0.12
C/3 Discharge (mA)	223.65	222.05	-1.60	-0.72
DC Resistance (mΩ)	5.22	5.36	0.14	2.73

Mode	SOT Mode Z Axis (Hz)	EOT Mode Z Axis (Hz)	Change in Frequency	Percentage Change	Mode Shape
1	249.08	249.08	0.00	0.00	First Bending
2	262.26	262.63	0.38	0.14	First Torsion
3	387.16	393.52	6.36	1.64	Second Torsion

Conclusions from Study 2

- This study has conducted single and multi-axis vibration testing on NMC and NCA 18650 cells and a Tesla Model S module that was representative of 100,000 miles and 10 years of vehicle usage.

- Different cell chemistries within the same cell form (18650) display different degradation when subjected to vibration.

- NCA 18650 cells show a greater resistance to vibration aging than NMC cells.

- There is evidence within these studies that orientation can impact the rate of degradation caused by vibration, however this is dependant on chemistry.

Questions

Thank you to:

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List of Publications

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- **Hooper, J.,** Marco, J., Chouchelamane, G., Chevalier. J., Williams, D., Multi-axis Vibration Durability Testing of Lithium Ion 18650 NCA Cylindrical Cells. Journal of Energy Storage, 2018. 15: p 103-123
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- **Hooper, J.,** Marco, J., Chouchelamane, G., Lyness, C., and Taylor, J., Vibration Durability Testing of Nickel Cobalt Aluminium Oxide (NCA) Lithium-Ion 18650 Battery Cells. Energies, 2016. 9(281): p. 1-18.
- Bruen, T., **Hooper, J.,** Marco, J., Gama, M., and Chouchelamane, G., Analysis of a Battery Management System (BMS), Control Strategy for Vibration Aged Nickel, Manganese Cobalt Oxide (NMC) Lithium-Ion 18650, Battery Cells. Energies, 2016. 9(255): p. 1-20.
- **Hooper, J.** and Marco, J., Defining a Representative Vibration Durability Test for Electric Vehicle (EV) Rechargeable Energy Storage Systems (RESS), in Electric Vehicle Show 29 (EVS29). 2016, EVS29: Montreal, Canada. p. 1-6.
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- **Hooper, J.** and Marco, J., Experimental Modal Analysis of Lithium-ion Pouch Cells. Journal of Power Sources, 2015(285 (2015)): p. 247 to 259.
- **Hooper, J.** and Marco, J., Characterising the in-vehicle vibration inputs to the high voltage battery of an electric vehicle. Journal of Power Sources, 2014. 245: p. 510-519.
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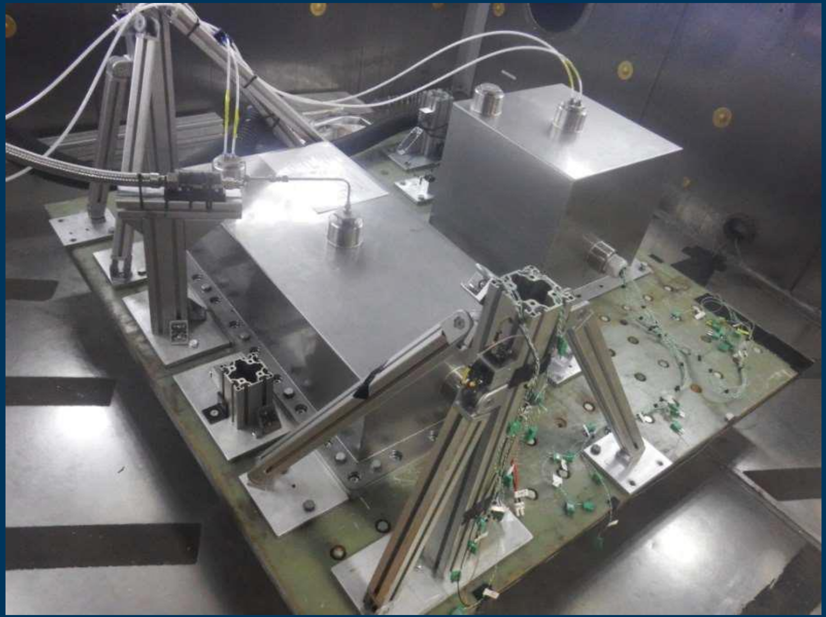

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