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Comparing different vibration tests proposed for li-ion batteries with vibration measurement in an electric vehicle

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Abstract

Li-ion batteries are the most popular type of batteries in electric, EV, and hybrid vehicles, HV. During their life time the batteries will be subjected to vibrations and therefore vibration testing is demanded by several standards. Testing on different size levels of the batteries, i.e. cell, module or pack, are proposed. Depending on the standard random vibration tests or tests with sinusoidal excitation are required. To compare these standards with the measurements, Fatigue Damage Spectrum, FDS, and Shock Response Spectrum, SRS, have been used. The FDS is a tool to analyze and compare different types of vibration tests and vibration measurements with respect to the fatigue damage that the vibration will cause on a mechanic structure. The SRS is used to estimate the risk for functional disturbances in electric equipment subjected to shock and vibrations. The comparison shows that the FDS and SRS for different vibration tests proposed for li-ion batteries vary strongly. Both levels and frequency ranges differ. One of the compared standards prescribes testing only in the vertical direction. The measurement done in this study was done during rather hard driving on a test track, this means high but not unrealistic measured acceleration responses. For one of the measured responses, the risk for fatigue during service could be higher than the risk at the tests. The low frequency content of a test can be important as the measurements show higher low frequency content than in many of the standardized tests. But even the high frequency content of the test must be considered as batteries normally are equipped with a large number of small electrical devices with high critical frequencies. Only one of the standards requires a separate test of such devices.

Keywords: li-ion battery, vibration test, standard, field measurement

1 Introduction

Lithium-ion batteries are widely used today as they offer relatively high power per kilo. By combining many battery cells they can be used as a power source in electrical vehicles. Vehicles are exposed to environmental stresses during their life time and the batteries must then sustain and operate at these stresses.

Environmental testing [1] and [2] includes humidity tests, temperature tests, shock and vibration tests. The main reason for doing a vibration test is to verify that the battery is working properly in the vehicle, but also important for transportation purposes [3]. Vibration can cause fatigue damage of

different kinds, but also functional disturbances. In the worst case scenario, the cells can burst.
Different standard organizations have proposed different standards for vibration testing of Li-ion batteries. In this paper six such standardized vibration tests have been considered and compared with vibration measurements in electric vehicles.

2 Vibration and shock testing for the automotive industry

Vibration testing is very common in the automotive industry. Both whole cars and components are tested. A car is a large structure and therefore it has low resonance frequencies and the damage is mainly caused by the low frequency content of the vibration spectrum. On the other hand a component is a small structure and its critical frequencies are often found in the high frequency part of the spectrum. This is the reason why car chassis often are tested at low frequencies and components at high frequencies. Battery packs have large dimension but include also a lot of small electrical components. Therefore a test of a battery pack is something between a chassis test and a component test. Vibration testing can be done by sinusoidal or random excitation.

2.1 Sinusoidal excitation

This type of testing is the oldest one. Today random excitation is more common and in many cases more realistic. Sinusoidal excitation of a resonance frequency implies response of the test object at a high level. If the real excitation is random, the high response level at the sinusoidal test can be unrealistic. Sinusoidal qualification testing can be done either at the resonance frequencies of the test objects or as a sine sweep test covering the whole interesting frequency range.
Sinusoidal testing is suitable if the real vibration is narrow-banded, to compare vibration resistance of different constructions or as a time forced test.

2.2 Random excitation

Random excitation is most common today. If the real vibration is broad-banded, this type of excitation is most realistic. The amplification at resonances is not as large as at sinusoidal excitation, but in most cases more similar to amplification at real service. A test object with complicated geometry will often have several resonance frequencies and failure can be caused by interaction between these frequencies. With random excitation at the test all possible resonance frequencies are excited at the same time while at a sinusoidal test only one frequency at time is excited.

2.3 Shock testing

Vibrations in a vehicle are continuous and occurring during a long time. But a vehicle or equipment inside a vehicle are also subjected to transient stresses. Transients occur for example when the car is driving on the curb or into a pot hole. Even collisions cause events with high acceleration levels during a short period.
Shock testing is often done with half sine pulses with a specified duration and maximum level, but other pulse shapes can also be used. For electric components shock testing with half sine shaped pulses with duration 5-10ms and acceleration levels 20-50g are common. For crash testing trapezoidal pulses with durations up to 100ms and levels between 10 and 30g are often used.
The dynamic amplification due to a shock pulse is less than two times, i.e. lower than at both sinusoidal and random excitation.

3 Vibration analysis

Sinusoidal vibration is characterized by the frequency and the amplitude. Random excitation is more complicated and more complex analysis methods have to be used. This can be done by calculating the Power Spectral Density, PSD, or the Fatigue Damage Spectrum, FDS. Shocks can be analysed in the time-plane or by calculating the SRS.

3.1 Power Spectral Density, PSD

Most random vibration tests are specified by a Power Spectral Density. In old days the PSD was calculated by applying the random signal to a lot of parallel narrow-band filters and calculating the mean value of the squared signal for each of the filtered signals. These mean levels plotted vs. the centre frequencies of the corresponding narrow-band filter frequencies are equal to the PSD. Today a PSD is calculated by Fast Fourier Transform, FFT, technique, but the old way to do a PSD analyse tells a lot of what a PSD really is.
In a strict mathematic way a PSD can only be calculated for a stationary signal. A real vibration consists of several parts where the levels vary, depending on the type of road the car is driving on. A PSD calculated for the total signal will not show the short periods with high levels. A lot of PSDs

for sequences from different type of driving must therefore be calculated.
Most random vibration tests are specified by a PSD, that is the tests are assumed to be stationary. The PSD is well defined mathematically, but it's not directly related to the damage on a test object caused by a vibration. Of course a test with a higher PSD level during a certain time will cause more damage than a test with a lower PSD level during the same time, but the degree of damage cannot be seen directly from the PSD.

3.2 Fatigue Damage Spectrum, FDS

The simplest model of a dynamic system is the Single Degree of Freedom, SDOF, system. The system consists of a mass, a spring and a viscous damper, see Figure 1. When the ground is excited by the motion *x(t)* the mass starts to oscillate. Even if the excitation, *x(t),* is broad-banded, the response will be narrow-banded and determined by the resonance frequency of the SDOF system. The oscillation can be described either as the relative motion of the spring, *z(t)* or as the absolute motion of the mass, *y(t)*. Fatigue is caused by relative motion in the structure and therefore it is best related to the relative motion *z(t)*. By doing a cycle counting of the obtained motion *z(t)*, the damage due to the excitation *x(t)* can be estimated. If such cycle counting is done for SDOF systems with different resonance frequencies and the resulting damage plotted as a function of the resonance frequency, the Fatigue Damage Response Spectrum, FDS, is obtained [4].
When calculating the FDS the relative damping of the SDOF system must be specified in order to get the amplitude of the response, in this paper it's assumed to be 5%. Further, it's assumed that the fatigue damage varies exponentially with the stress. This life-strength relationship is then described by the Basquin equation.

$$C = S^b N_f \qquad (1)$$

Where N_f is the life-length, and the stress, *S*, is obtained from

$$S = Kz(t) \qquad (2)$$

In the calculations the value of the Basquin coefficient, *b*, is set to 4. This is a material parameter and can vary between 3 and 10.Values of the stiffness of the system, *K*, and the Basquin coefficient *C* are set to 1000 and 1, respectively. But these values will only affect the level of the FDS and as long as only comparisons between FDS for different tests or measurements are done, these values are not important.

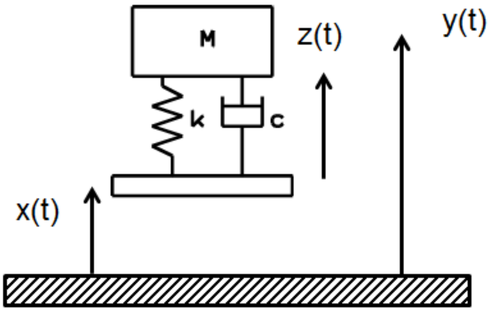

Figure 1 SDOF system on an accelerating ground. The ground is excited by the acceleration *x(t).* The response as relative motion is *z(t)* and absolute motion of the mass is *y(t).*

In contrast to a PSD the FDS is directly related to damage (if the damage mechanism is fatigue) and it can be calculated for all types of signals. That is random vibration tests with a single spectrum, random vibration tests consisting of subtests with different spectra and tests with sinusoidal excitation could be compared with respect to the damage the test will cause. The comparison is valid as long as the fatigue model assumed in the analysis is correct. Damage in real life is more complicated and therefore 'engineering judgment' must be used when using the FDS.

3.3 Shock Response Spectrum, SRS

The FDS is a suitable analysis method as long as the damage mechanism is fatigue. This is the case in many applications, especially for damage on mechanical structures. But if the damage mechanism is functional disturbance of electrical equipment, the damage is often caused by the maximum response of the oscillating object. Very similar to the FDS a Shock Response Spectrum, SRS, can be calculated. Instead of doing cycle counting on the relative motion *z(t)*, in Figure 1, the absolute maximum response of the mass *y(t)* is determined and plotted as a function of the resonance frequencies. Sometimes the SRS is named Extreme Response Spectrum, ERS. The relative damping used in the SRS calculations was 5%. For a test with a sinusoidal signal the maximum response was calculated by multiplying the excitation amplitude with the Q-factor.

$$Q = \frac{1}{2\rho} \qquad (3)$$

Where ρ is the relative damping of the SDOF system. For the random tests the maximum response was calculated by multiplying the calculated Root Mean Square value of the SDOF system responses by a factor three. Theoretically the maximum response can be higher. But the control system of a vibrator clips the signal, and in most cases '3σ-clipping' is used, where σ is the Root Mean Square, RMS, value of the excitation. For the measured signals the maximum response was just the one calculated by the analyze.

4 Review of standards for vibration testing

Six standards for vibration testing of Li-ion batteries have been used in the comparison. A review of different standards for testing Li-ion batteries is found in [5]. A summary follows below

4.1 IEC 62660-2

IEC 62660-2, [6] is a standard for reliability and abuse testing of Li-ion cells. The vibration test in this standard is the general vibration test for environmental testing of electrical and electronic equipment in road vehicles given in ISO16750-3, [7]. The severity for sprung mass in a passenger car is chosen for the IEC test. Three uniaxial random vibration tests in the frequency range 10-2,000 Hz are prescribed.

4.2 ISO 12405-1:2011

The ISO 12405-1:2011, [8], is a general standard for testing Li-ion battery systems containing electric performance tests, reliability tests and abuse tests. Vibration tests on two levels are suggested; one test for electric and electronic devices identical to ISO 16750-3 (or IEC 62660-2) and one test for battery and pack systems. The latter test is done as three uniaxial random tests at 5-200 Hz. During the vibration test the temperature should be varied between -40°C, ambient temperature and +75°C.

4.3 SAE J2380

SAE J2380, [9], [10] and [11] contains shock and vibration tests for modules and packs. It's a random test in the frequency range 10-190Hz. In the vertical direction three subtests with different spectra are proposed. Each of these spectra covers a part of the low frequency range of the spectrum. No separate test of electric devices is defined. During the different subtests the batteries should be charged to different levels.

4.4 USABC Electric Vehicle Battery Test Procedures Manual

The USABC Electric Vehicle Battery Test Procedure Manual, [10], [11] and [12] is issued by the United States Council for Automotive Research (USCAR). This is a collaborative technology organisation between different car manufactures. According to this test procedure the vibration test of batteries can either be performed as a random test or as a sinusoidal test. The random vibration test is identical to the test described in SAE J2380. The sinusoidal test starts with excitation with 2000 cycles at a fixed frequency between 10 and 30Hz. The amplitude should be 5g in the vertical direction and 3.5g in the horizontal directions. After that test 60 sweep tests 10-190-10Hz during 8h should be done. The amplitude of the sweep in the vertical direction should be 3g at 10Hz and decrease to 0.75g at 190Hz. In the horizontal directions the level should decrease from 2.5 to 0.75g.

4.5 ECE R100

ECE R100, [13], is a regulation from the United Nations with tests for construction and functional safety of batteries for electric vehicles. Issue 2 of this regulation will be official valid during 2013. A vibration test for a complete pack or subsystem is specified. The test will be done as a sine sweep test in the vertical direction. The frequency range is 7 to 50Hz. Up to 18 Hz the level should be 1g and then decreasing and from 30Hz the level should be 0.2g

4.6 UN Transportation Testing (UN / DOT 38.3)

The UN procedure; Transportation Testing (UN/DOT 38.3) for Lithium Batteries, [14], contains requirement to ensure the safety of lithium batteries during shipping. Unlike the other standards in this review the test is simulating a transport and not vibrations in an electric vehicle. But vibrations occurring during a road transport and usage can be similar and therefore the standard is mentioned here. A sine sweep test between 7 and 200 Hz is stated. The level between 7 and 18Hz should be 1g and then increase and from 50Hz it should be 8g. The test should be done in three directions. The purpose of the standard is to ensure a safe transport and not to verify the function of electric devices mounted on the batteries.

Table 1: Survey of standards for vibration tests of Li-ion batteries for electric and hybrid vehicles

Name	**IEC 62660-2**	**ISO 12405-1**		**SAE J2380**
Headline	*Secondary lithium-ion cells for the propulsion of electric road vehicles*	*Electrically propelled road vehicles – Test specification for lithium-ion traction battery systems Part 1- High power applications*		*Vibration testing of electric vehicle batteries*
Object *Cell/Module/Pack/ Electronics*	Cell	Electronic devices on the batteries Same as **IEC 62660-2**	Pack (including electronics)	Pack / Module
Directions	Three directions	Three directions	Three directions	Three directions
Vibration mode *Sinus/Random*	Random	Random	Random	Random
Frequencies *(Hz)*	10-2000	10-2000	5-200	10-200
Acceleration *(g)*	3 (rms)	3 (rms)	1.44 (rms)	1,9-0,75(rms)
Time/axis *(hour)*	8	8	21	>13.6
State of Charge (SOC) before test	100 % (EV), 80 % (HEV)	N/A	50 % after two standard cycles	100 %, 80 % and 40 %

Table 2: Survey of standards for vibration tests of Li-ion batteries for electric and hybrid vehicles

Name	**USABC**		**ECE R100**	**UN 38.3**
Headline	***Electric Vehicle Battery Test Procedures Manual***		*Regulation No. 100-2*	*38.3 Lithium Battery Testing Requirements*
Object *Cell/Module/Pack/ Electronics*	Pack/Module/Cell Same as **SAE J2380**	Pack/Module/Cell	Module/Cell	Pack/Module/Cell
Directions	Three directions	Three directions	Vertical	Three directions
Vibration mode *Sinus/Random*	Random	Sine	Sine	Sine
Frequencies *(Hz)*	10-200	10-200	7-50	7-200
Acceleration *(g)*	1,9-0,75(rms)	5-0,75	1-0,2	1-8
Time/axis *(hour)*	>13.6	6	3	3

State of Charge (SOC) before test	100 %, 80 % and 40 %	> 50 %	0% and 100%

5 Description of the measurements

Measurements of vibrations in the field were conducted on a Volvo C30 Electric. The aim of the measurements was to investigate and compare vibration spectra obtained at different locations in an electric car. In order to measure high, but realistic spectra the car was driven on a rumble strip test track, see Figure 2. This driving should be the most extreme a car is subjected to, with exception for accidents, and occurs only during a limited fraction of the life cycle. The measuring points were chosen to measure spectra at locations where batteries are or could be placed.

Figure 2 The rumble strip test track built by special cobble stones with a diameter of 100 mm and a height of ~15 mm.

Besides the measurement on the test track measurements were also done during ordinary city driving. However, the measured data during this type of driving have very low levels and are not considered in this paper.

Three-axes piezoelectric accelerometers were used. Data were sampled to a PHOTON II, LDS Dactron data acquisition system. The sampling rate was 6kHz. This high sampling rate was chosen as some of the standards require testing up to 2kHz.

From the sampled data PSD, FDS and SRS were calculated. It was found most useful to analyse the FDS.

6 A comparison between the different standards

The different standards ask for different excitation (random, sine sweep or continuous sine) during different test times. In a strict mathematic way it's not possible to compare the standards. One way to compare the different standardized tests is to calculate the FDS and SRS. This way to compare different type of vibration tests and/or measurements is common and prosed in several handbooks and standards, for example MIL STD 810, [2]. The use of the method is demonstrated in [4]. The strength of comparing in this way is that the analysis methods are damage related. Of course it must be remembered that it's the damage is obtained from a very simple model of a test object, the SDOF system, and that only simple damage mechanisms are assumed; Fatigue without any fatigue limit for the FDS and maximum acceleration response for the SRS.

All tests with the exception of ECE R100, require testing in three directions. ECE R100 requires only testing in the vertical direction. IEC 62660-2 and UN 38.3 use the same severities in all directions, but the other standards require a higher level in the vertical direction.

ISO 12405 uses different spectra in the transverse and longitudinal directions. If the pack should be mounted below the passenger compartment a test at a reduced level in the transverse direction is proposed, see Figure 3.

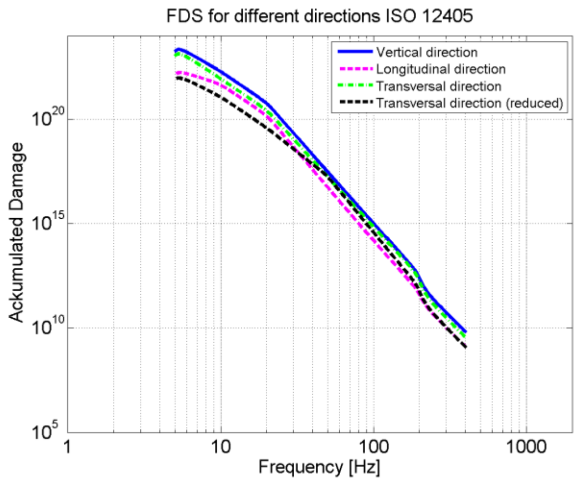

Figure 3 FDSa for the tests proposed by ISO 12405-1.

USABC uses the same severities in both horizontal directions, but has the choice between a sinusoidal test and a test with random excitation. As usual the test with sinusoidal excitation is the most severe one, see Figure 4. The sine test contains sinusoidal excitation 5g at a frequency between 10 and 30 Hz for 2000 cycles in the vertical direction. The spectra are calculated for such excitation at 10Hz.

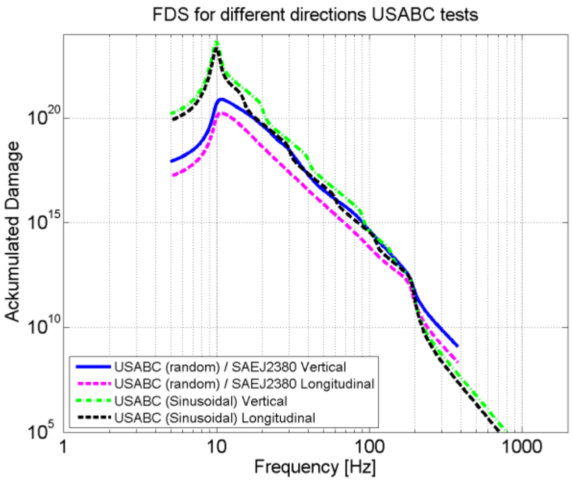

Figure 4 FDSa for the tests proposed by USABC.

The purpose of the tests differs; IEC 62660-2 is a test for testing cells. Cells have small dimensions and therefore higher critical frequencies can be expected. It's therefore natural that this test is more severe, especially for higher frequencies; see Figure 5 and Figure 6. The UN38.3 test has a very high level in the frequency range 50-200Hz. The transportation test is a robustness test, a battery subjected to this test will probably also pass the other tests. It's only for frequencies below 25Hz and above 200Hz that this test is not harder than any of the other tests. But if the batteries during the transport test are placed in anti-vibrating packing, this test cannot be used as a qualification test for batteries stationary mounted in a car.

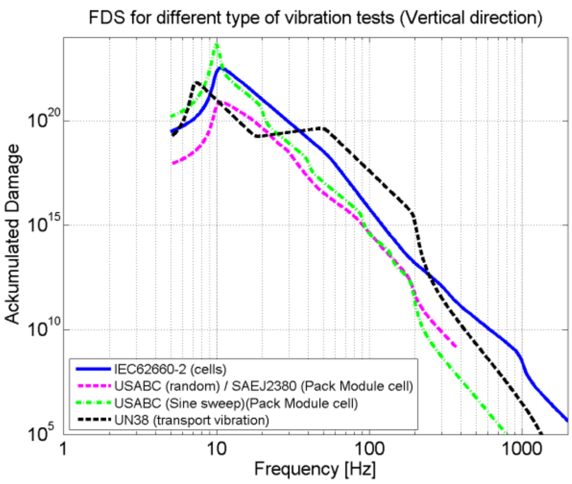

Figure 5 FDSa for tests for cells, packs and transport simulation.

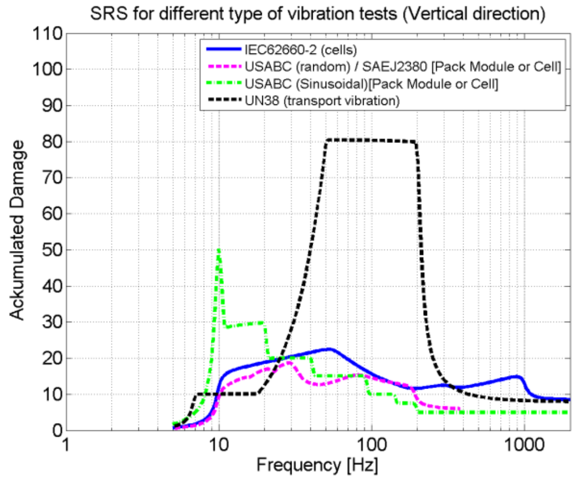

Figure 6 SRSa for tests for cells packs and transport simulation.

The USABC, ISO 12405 and ECE R100 are tests proposed for testing packs or modules stationary mounted in vehicles. FDSa and SRSa for these tests are shown in Figure 7 and Figure 8. The ECE R100 test is only done in the vertical direction and the level is much lower than the levels of the other tests. The ISO 12405 test for packs has a lower frequency range than the other tests, 5Hz instead of 10Hz. This means that the test can cause much more damage for a large pack with a low resonance frequency. The sinusoidal test according to USABC is very severe at the frequency where the continuous sine is run, in this paper it's assumed that that test is run at 10Hz. The ISO test has a high FDS but the SRS is low. The reason is that the spectrum level is moderate, but the test time is rather long (21h). During that time there will be a lot of oscillations (at a moderate level) introducing fatigue damage. The random USABC test has a duration of only 15 minutes at its highest level. A sinusoidal test has in most cases higher maximum responses than a random test and the duration of the USABC sinusoidal test is 6h.

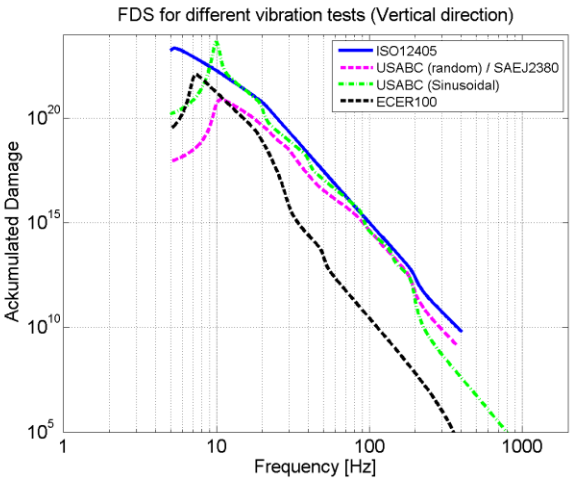

Figure 7 FDSa for different tests proposed for testing packs and/or modules.

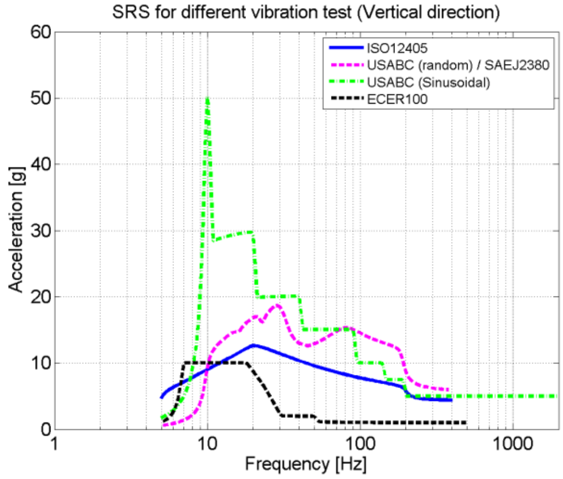

Figure 8 SRSa for different tests proposed for testing packs and/or modules

7 Comparing different standardized tests with measurements from the test track

Just to get an idea of the damage caused by one of the standardized tests and the damage that could be obtained at real service life it was assumed that a car can be subjected to a driving similar to that on the test track for at most 1h every week. If we assume that the life of a car is 15 year, the damage corresponding to 800h driving on the test track should be calculated and compare with the damage caused by the different standardized tests.

FDSa and SRSa of the measured signals were calculated. The levels of the FDSa were adjusted to correspond to 800h driving. Then these measured spectra were plotted and compared with the corresponding spectra for the standardized tests. The acceleration levels at the different measuring positions varied a lot. For some measuring positions the measurements were repeated and it was found that the variation between the individual measurements was small. Measurements in three directions were done, but in this paper only measurements in the vertical direction is presented.

Figure 9 and Figure 10 show the measured spectra and the spectra for the ECE R100 test. Above 20Hz and below 5Hz the measured FDSa and SRSa are above the corresponding spectra for the test. A test is said to be conservative if it's more severe than real service. The ECE R100 test is only conservative if the resonance frequencies of the test object is between 5 and 20Hz.

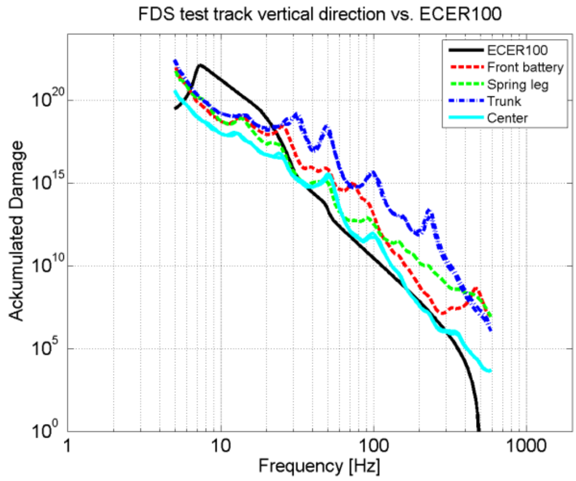

Figure 9 FDSa of measured acceleration signals and the FDS for the ECE R100 test

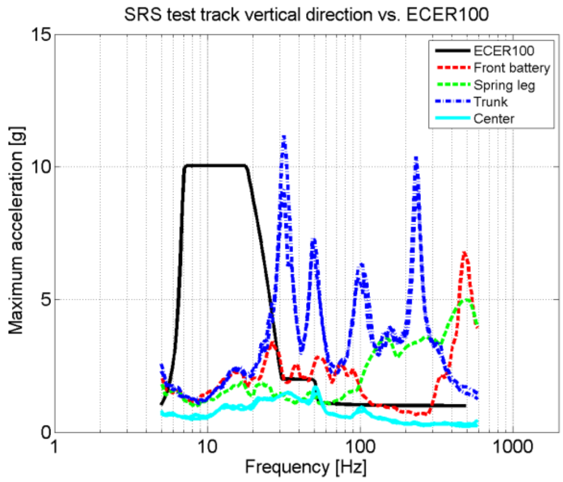

Figure 10 SRSa for the measured acceleration signals and SRS for the ECE R100 test

In Figure 11 and Figure 12 the measured spectra are compared with the test spectra for the USABC tests. One of the measured FDSa (Trunk) is above the test FDSa at three frequencies between 50 and 300Hz. For frequencies below 5Hz, the measured FDSa are also above the test FDSa. The SRSa for the measured signals are below the SRSa of the tests.

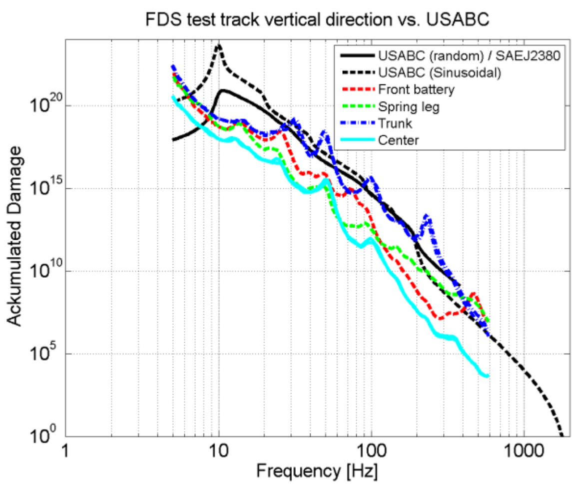

Figure 11 FDSa for the measured acceleration signals and FDSa for the USABC tests

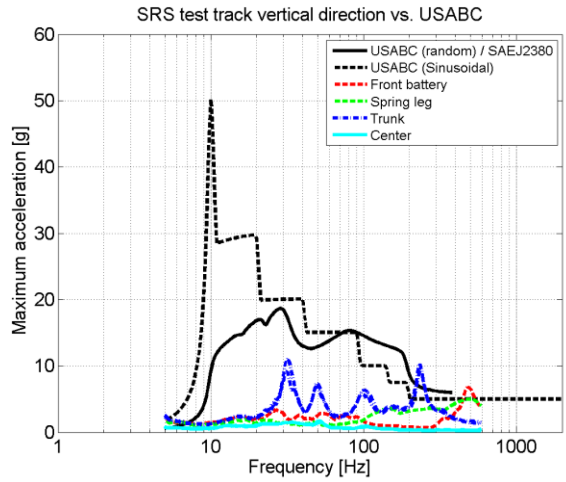

Figure 12 SRSa for the measured acceleration signals and SRSa for the USABC tests

In Figure 13 and Figure 14 the measured spectra are compared with the spectra for ISO 1405.This test contains more low frequency content than the USABC tests, so the measured spectra at low frequencies are below the test spectra. But still the FDS for the trunk position is above the test spectrum. For frequencies above 200Hz the SRS of the test is for some frequencies lower than the measured SRSa.

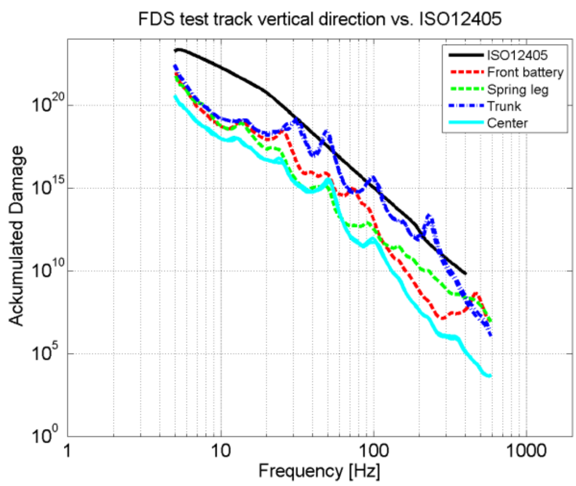

Figure 13 FDSa for the measured acceleration signals and the FDS for the ISO12405 test

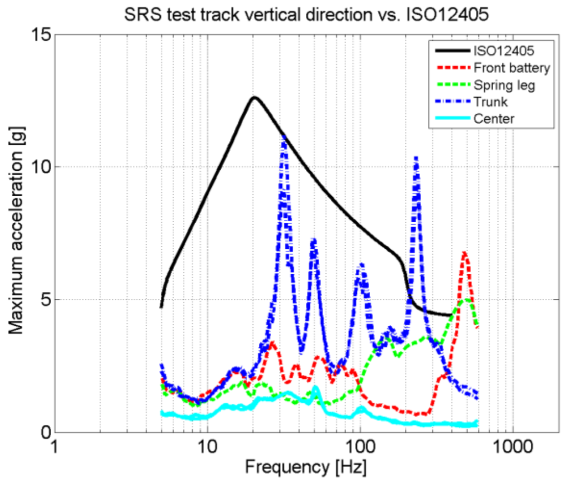

Figure 14 SRSa for the measured acceleration signals and the SRS for the ISO 1405 test

Especially for the USABC tests the SRSa are much higher than the measured spectra. The reason for this is that the time acceleration factor of the test is rather high. Fatigue damage is forced by exciting at a higher level than the real level.

8 Discussion

There are resonance peaks at one of the measured locations (trunk). These peaks cause the measured FDS to be higher than all FDSa for standardized tests.

The frequency range of the ECE R100 test is narrow and the level low. Therefore it's a risk that the test will not be conservative. It should also be mentioned that the test is only conducted in the vertical direction, but vibrations occur even in the horizontal directions.

The sine test proposed by USABC has much higher FDS and SRS than the random test in the medium-low frequency range corresponding to the frequency for the excitation with continuous sine. The SRSa of the standardized tests are much higher than the SRSa of the measured acceleration signals due to the time forcing. With high time forcing there is a risk that other damage mechanisms will occur during the test than during real service. In this case it can be functional disturbances or low cycle fatigue.

The ISO 12405 test is the only test which have frequency content lower than 10Hz. As a battery pack is large it can have low resonance frequencies and in that case it's important that they are excited at the test. The ISO standard is also the only standard which has a high frequency test for electronic devices.

9 Conclusions

- Testing in all three directions is important
- It can be important that testing is done at frequencies below 10Hz.
- Tests with sinusoidal excitation have high response levels and therefore the risk for low cycle fatigue or functional disturbances during these tests can be higher than during real service.
- A high time-forcing factor can cause other damage mechanisms during a test than during real service life.

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