Vibration Research
SEES Seminar 6th and 7th April Kista, Sweden

VIBRATION RESEARCH

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THE INNOVATOR IN SOUND & VIBRATION TECHNOLOGY

Welcome
SEES Meeting Kista, Sweden 2022

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VIBRATION RESEARCH

FROM FIELD MEASUREMENTS TO TEST PROCEDURES

HOW I CAN DO IT AND WHAT ARE THE HURDLES AND RESTRICTIONS?

THE INNOVATOR IN SOUND & VIBRATION TECHNOLOGY

VIBRATION RESEARCH

FROM FIELD MEASUREMENTS TO TEST PROCEDURES

HOW I CAN DO IT AND WHAT ARE THE HURDLES AND RESTRICTIONS?

Holger Boller
General Manager –
Vibration Research Europe GmbH

SOME SHORT WORDS ABOUT VIBRATION RESEARCH

Vibration Research formed as a private company in 1995 with 50 employees in development, research and production.
We have more as 5.000 installed Vibration Control systems worldwide for a Global Customer Base

Pioneered many vibration testing techniques

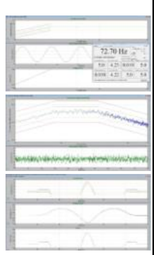
- First to perform long time history replication on ED shakers - We call it F.D.R. Field Data Replication
- Introduced Kurtosis Control - More Realistic Random Test
- Introduced FDS - Fatigue Damage Spectrum - Transfer, Compare and Accelerate Tests
- Introduced iDOF - Instant Degrees of Freedom - Smoother Response Curves in Random
- Introduced STAG - Sine Tracking Analysis and Generation - Easy Generation of SoR Test

FROM FIELD MEASUREMENTS TO TEST PROCEDURES

Actual Situation

- Simulation of mechanical stress is included in the design, development and qualification of products
- Use of mathematically generated time signals
- The test profiles follows a derivation of parameterized models
- Good correspondence between seen failures in the field and in the laboratory simulation

Our Problem is, that none of the signals thus generated is identical to the mechanical load in the field.
We can´t reproduce and justify all the upcoming failures from the field application and we generate new failures on our test bench which we never seen in the field.
So we have the wish to do a "little" bit more or we want to be with our test procedures closer to the reality.
The magic word is Test Tailoring.



FROM FIELD MEASUREMENTS TO TEST PROCEDURES

CONTENTS

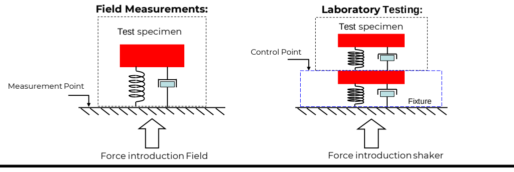
- How can we reproduce the measured different complex time signals in an easy way?
- How can we generate PSD profiles from the measured time signals in a realistic and reproducible way?
- How can we compare the generated fatigue damage between the Time signal and the generated RANDOM signal?
- How can we compare existing different Test Procedures?

Vibration Research Europe GmbH
Marker Höh 16 D 96524 Föritztal

☎ +49 (0) 36764 81 6363
✉ Holger@VibrationResearch.de
www.VibrationResearch.de

DIFFERENCE BETWEEN FIELD MEASUREMENTS AND SHAKER TEST

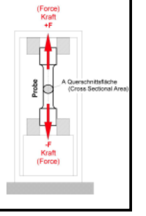
- The aim of the measurement in the field is to determine the vibration load.
- Acceleration is measured at the fixture of the test specimen, as a result of coupling to the base structure and its dynamic property.
- Shaker and fixture influence the force application through their internal impedance and have an influence on the test results.



DIFFERENCE BETWEEN MATERIAL AND VIBRATION TESTS

The Material Test with vibrating load´s investigates the Life Time of a component.

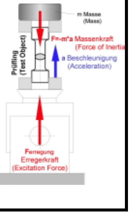
- **The Load is set to be**
  - equal to Excitation Force F [N] on the test object!
- **Correct, because**
  - Well defined state of tension
  - Low excitation frequency
- **One axis state of stress**
  - Tensile/compression stress: $\sigma = F/A$
  - Strain: $\varepsilon = \sigma/E$
  - Strain is a relative length variation: $\varepsilon = \Delta l/l$
  - Absolute length variation (Elongation) $\Delta l = \varepsilon * l$



DIFFERENCE BETWEEN MATERIAL AND VIBRATION TESTS

The Vibration Test verifies the Functional Time of the test object.

- **The Load is set to be**
  - equal the Excitation Acceleration on the test object!
- **Not absolutely correct, because**
  - Any state of stress
  - Test frequencies in the resonances and anti-resonances
- **Different stress locations in complex structures:**
  - Stress measurements with strain gauges in test object.
- **Dividing in substructures and do separate tests:**
  - If possible use of the original fixtures of the test object with their original stiffness
  - Shaker simulates mostly an infinite stiff restraint!

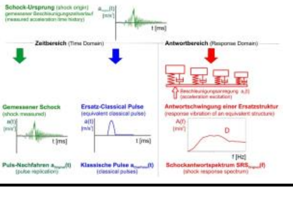


FROM THE FIELD MEASUREMENT TO THE SHAKER TEST

CREATE A TEST PROFILE FROM TIME HISTORY DATA

Possibilities for shorter time signals

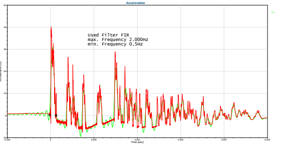
- *Method 1: Simulation of the time signals 1 : 1 on the shaker*
- Method 2: Definition of a classical pulse
- Method 3: Definition of a SRS shock test

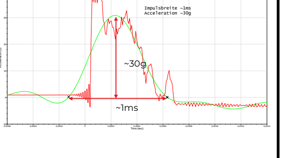


CREATE A TEST PROFILE FROM TIME HISTORY DATA

Definition of a classical pulse

- Here we can use a HP and LP filter to "eliminate" lower or higher frequency contents
- In some cases the maximum PEAK amplitude must be adjusted after the use of the LP filter.





Vibration Research Europe GmbH
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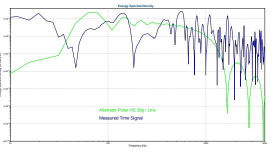
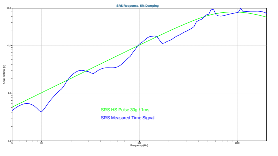
☎ +49 (0) 36764 81 6363
✉ Holger@VibrationResearch.de
www.VibrationResearch.de

CREATE A TEST PROFILE FROM TIME HISTORY DATA

Definition of a classical pulse

- The energy density spectrum can be used later to compare the alternate pulse with the original pulse in terms of the energy supply.





$$ESD(f) = PSD(f) \cdot T_{FFT} \left[\frac{\left(\frac{m}{s^2}\right)^2 \cdot s}{Hz}\right]$$

CREATE A TEST PROFILE FROM TIME HISTORY DATA

Definition of a classical pulse
Results and summary of the investigations

	Transient Signal	Classical HS Pulse	Classical HS Pulse
Frequency Content	~4.000Hz	10Hz - 2.500Hz	10Hz - 1.000Hz
Pulse Width		1ms	1ms
Excitation	~30g_{PEAK}	~30g_{PEAK}	~30g_{PEAK}
Response Ch2	~75g_{PEAK}	~66g_{PEAK}	~57g_{PEAK}

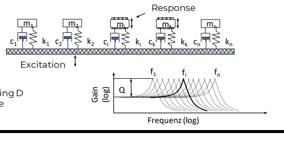
- The critical point is the definition of the used HP and LP filter so define the Classical Pulse.
- The definition only of the waveform, amplitude and pulse width is not sufficient.
- The frequency content is an important parameter. If the lower and upper frequencies do not match the real field load, the DUT may be over stressed or under stressed.

Proposal: Observation of the frequency range from the SINUS or RANDOM test.

CREATE A TEST PROFILE FROM TIME HISTORY DATA

Definition of a SRS pulse - Theory

- A mathematical model is used - bank of single-mass oscillators (SDOF model).
- The Q-factor is the same for each single-mass oscillator (SDOF structure).
- SRS spectrum is not a spectrum of a Fourier transformation, the time signal cannot be reconstructed!
- SRS response does not describe the vibration response of the test object, but its excitation!
- In practice, there are many methods for calculating the necessary time signal to fulfil the SRS.
- The different used algorithm produce different time signals, especially at low and high frequencies.



$f_i = \frac{1}{2\pi}\sqrt{\frac{k_i}{m_i}}$

$Q = \frac{1}{2D} = \frac{\sqrt{k_i \cdot m_i}}{c_i}$

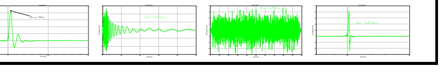
= constant

The Q factor or the damping D is the same for each of the single-mass oscillators.

CREATE A TEST PROFILE FROM TIME HISTORY DATA

Definition of a SRS pulse
Results and summary of the investigations

	Original Transient Signal	SRS Synthese Damped Sine	SRS Synthese Wavelet	SRS Synthese Random	SRS Synthese Pyro-Shock
Frequency Content	≈ 1.000Hz	5 - 1.500Hz	5 - 1.500Hz	5 - 1.500Hz	5 - 1.500Hz
Signal Length $te_{effectiv}$	3,0ms	≈ 540ms	≈ 270ms	≈ 950ms	≈ 3,7ms
Excitation	≈ 42g_{PEAK}	≈ 20g_{PEAK}	≈ 14g_{PEAK}	≈ 18g_{PEAK}	≈ 41g_{PEAK}
Response Ch2	≈ 66g_{PEAK}	≈ 66g_{PEAK}	≈ 68g_{PEAK}	≈ 67g_{PEAK}	≈ 52g_{PEAK}



CREATE A TEST PROFILE FROM TIME HISTORY DATA

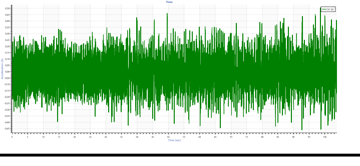
Definition of a SRS pulse
Results and summary of the investigations for different Synthesis Time Functions

- If the SRS spectrum $SRS_{Field}(f)$ is calculated for the time signal $a_{Field}(t)$ with the known Q-factor of the structural resonance, the same PEAK response amplitude is obtained in the SRS test as with direct excitation with $a_{Field}(t)$.
- Accordingly, it should hold that the response to $a_{Synthesis}(t)$ is load equivalent to that from $a_{Field}(t)$ only if the damping D for $SRS_{Field}(f)$ matches that of the structure at hand.
- The form of the time signal $a_{Synthesis}(t)$ - in particular also its duration of the impact T_{impact} in comparison to $T_{effective}$ - determines the input acceleration and therefore the size of the necessary shaker (see the table before).
- Comparable signal lengths of $a_{Field}(t)$ and $a_{Synthesis}(t)$ give comparable excitation levels
- Do not synthesize pyro-shocks if you have an earthquake application!

CREATE A TEST PROFILE FROM TIME HISTORY DATA

Possibilities for longer time signals

- *Method 1: Field Data Replication*
- Method 2: Peak Hold PSD
- Method 3: Average PSD
- Method 4: Define the Test Amplitude
- Method 5: PSD Profile with the same Fatigue

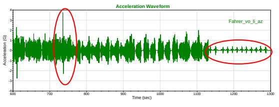


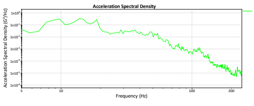
Vibration Research Europe GmbH
Marker Höh 16 D 96524 Föritztal
☎ +49 (0) 36764 81 6363
🖂 Holger@VibrationResearch.de
www.VibrationResearch.de

HANDLING OF THE TIME SIGNAL

PEAK HOLD - FFT based on peaks, from each time block

- Extracts the peaks from the blocks of data
- Max Values from each Time Block are used to create the PSD Spectrum
- Consideration of the requirements from EN 60068-2-64 - 5 frequency lines in the resonance bandwidth gives you the minimum space between each FFT line
- Critical for time signals with short events (pulses)
- Generates normally the worst case scenario with too much mechanical stress

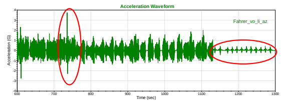


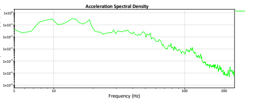


HANDLING OF THE TIME SIGNAL

AVERAGE - FFT of each block of data is averaged together

- Creates a uniform average - power of the test
- Critical for time signals with highly variable RMS value
- Consideration of the requirements from EN 60068-2-64 - 5 frequency lines in the resonance bandwidth gives you the minimum space between each FFT line
- This method "lose" short events
- Depending on the length of each Event and Level this method create in the most cases too less mechanical stress

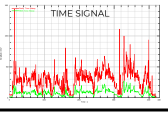


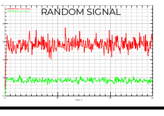


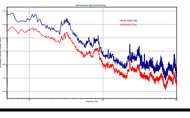
CREATE A TEST PROFILE FROM TIME HISTORY DATA

Comparison between PEAK HOLD PSD, AVERAGE PSD and TIME SIGNAL
Results and summary of the investigations

Signal	g_{RMS}	g_{PEAK}	v_{RMS}	v_{PEAK}	d_{PEAK}	KURTOSIS
TIME SIGNAL	0,44	-3,9 / 4,7	0,05	-0,25 / 0,27	-6,2 / 7,4	~6
PEAK HOLD PSD	1,86	-11,1 / 11,1	0,21	-1,3 / 1,3	-36,6 / 25,7	~6
AVERAGE PSD	0,44	-2,6 / 2,6	0,05	-0,39 / 0,31	-7,9 / 7,2	~6



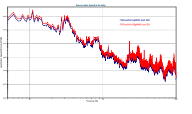




HANDLING OF THE TIME SIGNAL

Increasing the Test Amplitude

$$T_t = \left(\frac{\sigma_e}{\sigma_t}\right)^b T_e \quad \text{or} \quad \sigma_t = \sigma_e * \sqrt[b]{T_e / T_t}$$



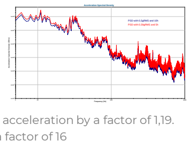
σ_t RMS Value of the acceleration amplitude of the test profile
σ_e RMS Value of the acceleration amplitude from the field
b is a "empirical value" typically between 4 and 8, depending on the type of the specimen material, and failure mechanisms.

In the MIL 810 is proposed for electronic components of the factor of 4.

HANDLING OF THE TIME SIGNAL

Increasing the Test Amplitude

$$T_t = \left(\frac{\sigma_e}{\sigma_t}\right)^b T_e \quad \text{or} \quad \sigma_t = \sigma_e * \sqrt[b]{T_e / T_t}$$



From the equation we get:

- Halving the test time is achieved by increasing the acceleration by a factor of 1,19.
- Doubling the amplitude reduces the test time by a factor of 16
- An increase by a factor of 4 means - 5 years in the field will be tested in a period of one week in the laboratory.

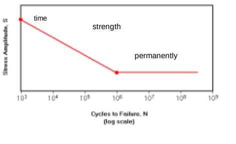
You must stop immediately with this kind of calculation when you can see failure during your vibration test which you never seen in the reality.

HANDLING OF THE TIME SIGNAL

Theory of the Fatigue Damage calculation S-N Curve (S for stress, N for cycles):

Miner's Rule: $N_i = c * S_i^{-b}$

- N = Number of stress cycles to failure
- S = peak amplitude of cyclical stress
- b = fatigue parameter



Calculation of damage: $D = \frac{1}{c} \sum_i n_i S_i^b \quad D = \sum_i \frac{n_i}{N_i}$

- c is experimentally found to be between 0.7 and 2.2. Usually for design purposes, c is assumed to be 1.

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = c$$

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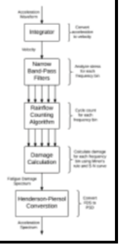
HANDLING OF THE TIME SIGNAL

RANDOM PSD Profile and Test Time with the same Fatigue
Theory of the FDS calculation

- Velocity is desired because Henderson-Piersol equations utilize velocity - Velocity has a direct relationship to stress
- So the acceleration waveform is converted into a velocity waveform
- Stress waveform is narrow-band filtered and the defined Q value is used
- Q value determines filter bandwidth
- Cycle counting and damage calculation ensure in each frequency-bin to determine damage contributions over a spectrum of frequencies.
- Spectrum spacing determines number of points in spectrum (number of frequency bins)



HANDLING OF THE TIME SIGNAL

RANDOM PSD Profile and Test Time with the same Fatigue
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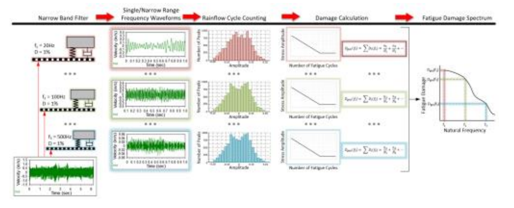
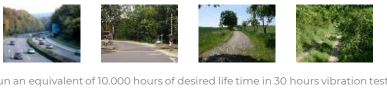


HANDLING OF THE TIME SIGNAL

RANDOM PSD Profile and Test Time with the same Fatigue

- We have 4 different time signals and would like to make a random test that recreates the same fatigue.

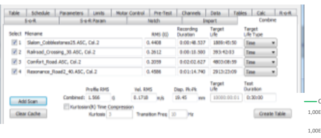


- We want to run an equivalent of 10.000 hours of desired life time in 30 hours vibration test
  - select a 'b' and 'Q' value for your data and product.
  - "b" is calculated with: $N_i = c * S_i^{-b}$
  - "Q" or quality factor is used in narrow band pass filter calculations, and will affect the smoothness of the Fatigue damage

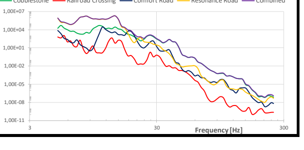
If you are not sure then MIL-Std 810 suggests b = 8 and Q = 50.
(see pg. 288 of MIL-STD 810G)

HANDLING OF THE TIME SIGNAL

RANDOM PSD Profile and Test Time with the same Fatigue



Signal	Proportion
Cobblestone	19%
Railroad Crossing	4%
Comfort Road	48%
Resonance Road	29%



HANDLING OF THE TIME SIGNAL

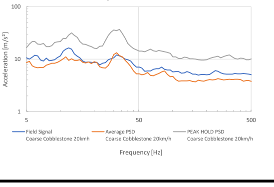
RANDOM PSD Profile and Test Time with the same Fatigue

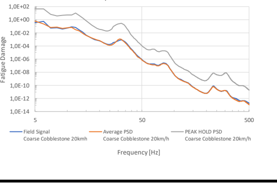
- This approach opens up enormous savings potential in terms of testing time.
- But, we have limits to the increase in energy supplied on the test bench, in the form of the maximum acceleration (force) and the expected response from the test specimen in real use.
- To have realistic limits, the Shock Response Spectrum (SRS) calculation, can be used to describe the realistic limits.
- Just like FDS, the SRS is calculated from the measurement data for each relevant event. However, unlike the FDS, the **SRS is not cumulative**.
- Therefore the individual repetition factors are irrelevant for the SRS. Even the SRS of the individual events are not cumulated.
- The envelope is built from all events. And this enveloping SRS sets the realistic limits which may not be exceeded during the test.
- The SRS is calculated from the accelerated test spectrum.
- The comparison of the two SRS shows if the generated test spectrum is within realistic limits as a result of the test time reduction (and therefore higher energy density).

HANDLING OF THE TIME SIGNAL

RANDOM PSD Profile - SRS and FDS Comparison

- Without any additional time compression





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☎ +49 (0) 36764 81 6363
✉ Holger@VibrationResearch.de
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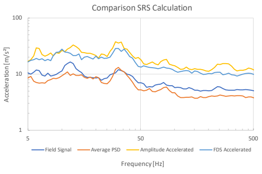
HANDLING OF THE TIME SIGNAL

RANDOM PSD Profile - SRS Comparison

- With additional time compression (2.000h real life and 20h Random Test)
- Acceleration Amplitude Method gives us a Amplification Factor of 3,16



HANDLING OF THE TIME SIGNAL

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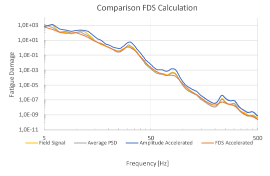
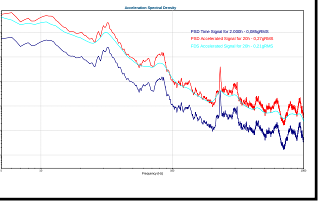




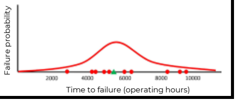
HANDLING OF THE TIME SIGNAL

Statistical Parameters

- In the real world, probabilistic effects occur that cause a deviation in the lifetime results.
- These effects are essentially due to variations in manufacturing quality, material quality and real stress.
- Definition of the used distribution function to described the failure probability.
- This kind of failure information can come directly from the investigated test device or from a similar device - as an example from a previous device.
- The requirement is that the damage mechanism is identical, at a comparable vibration stress.

For our example a test specification could be developed with this additional information as follows:

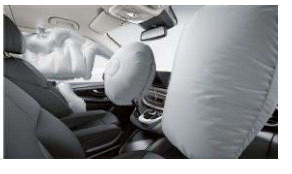
- with a system reliability of xx%
- with a safety factor of xx%
- for an required operating time of ~xx h
- necessary test samples

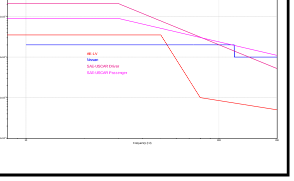


FROM FIELD MEASUREMENTS TO TEST PROCEDURES

CONTENTS

- How can we compare different existing Test Procedures?
- Comparison of different existing Test Specification for Air Bag modules

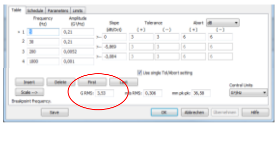


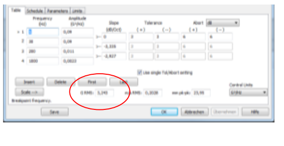


HANDLING OF THE TIME SIGNAL

Comparison of different Test Profiles

- RANDOM Profile 1
  - SAE/USCAR Driver - Test Time 22h
- RANDOM Profile 2
  - SAE/USCAR Passenger - Test Time 22h

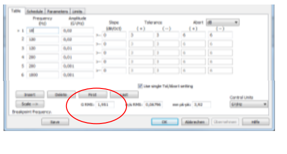


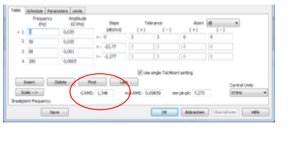


HANDLING OF THE TIME SIGNAL

Comparison of different Test Profiles

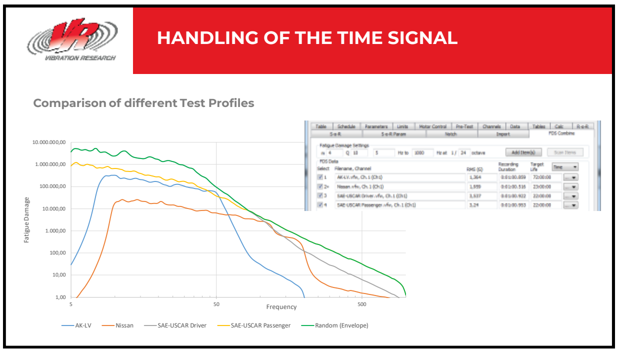
- RANDOM Profile 3
  - Nissan - Test Time 23h
- RANDOM Profile 3
  - AK-LV - Test Time 72h

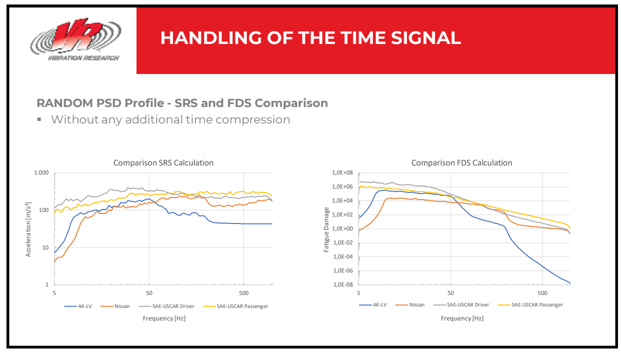


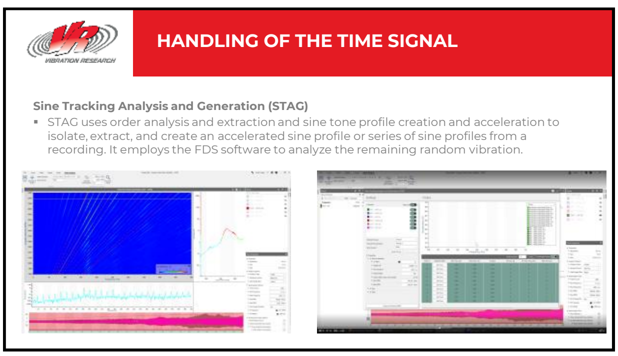


Vibration Research Europe GmbH
Marker Höh 16 D 96524 Föritztal

☎ +49 (0) 36764 81 6363
✉ Holger@VibrationResearch.de
www.VibrationResearch.de


HANDLING OF THE TIME SIGNAL
Comparison of different Test Profiles
Fatigue Damage
Frequency
AK-LV
Nissan
SAE-USCAR Driver
SAE-USCAR Passenger
Random (Envelope)


HANDLING OF THE TIME SIGNAL
RANDOM PSD Profile - SRS and FDS Comparison
Without any additional time compression
Comparison SRS Calculation
Comparison FDS Calculation
Acceleration [m/s²]
Fatigue Damage
Frequency [Hz]
AK-LV
Nissan
SAE-USCAR Driver
SAE-USCAR Passenger


HANDLING OF THE TIME SIGNAL
Sine Tracking Analysis and Generation (STAG)
STAG uses order analysis and extraction and sine tone profile creation and acceleration to isolate, extract, and create an accelerated sine profile or series of sine profiles from a recording. It employs the FDS software to analyze the remaining random vibration.


ANY QUESTIONS?
+49 (0)36764 816363 / +49 (0) 151 2202 4566
holger@vibrationresearch.de
Marker Höh 16
96524 Föritztal
VibrationResearch.com
You Tube
in