Using Fatigue Damage Spectrum for Accelerated Testing with Correlation to End-Use Environment

Todays Presenter: John Van Baren

We will begin shortly!

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Global Technical Integration Engineer,
General Motors Company

John VanBaren, PE
President, Vibration Research Corporation

Biographies

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Thomas Achatz is a licensed professional engineer with over 25 years engineering experience. He is widely recognized in the automotive industry as a leader in applying all facets of risk management, reliability, and statistical methods to expedite development and validation of automotive components. Mr. Achatz holds graduate degrees in Mechanical Engineering from The University of Michigan and Management of Technology from Rensselaer Polytechnic Institute. He is currently employed as a Global Technical Integration Engineer in the Hybrid Power Electronics group at General Motors Company in Milford, MI.

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John Van Baren is the president of Vibration Research Corporation, Jenison Michigan, which he founded in 1995. He is a graduate of Calvin College, and the University of Michigan Engineering School. Van Baren is a registered professional engineer in the state of Michigan. His experience includes 25 years in R&D of various capacities in the vibration world. Van Baren has designed shaker systems, shaker amplifiers and shaker controllers. He was a pioneer in the application of time-history replication on electro-dynamic shakers, and also the introduction of "Kurtosion" to the vibration world. He continues to guide the company forward as a leader and innovator in the field of vibration testing.

VIBRATION RESEARCH

Today's Goals

- ***Question #1:***
  - *What random profile is needed (and for how much time) to accurately simulate the end-use environment over the life-cycle of my product?*
- ***Question #2:***
  - *My product operates in many different vibration environments, how can I confidently combine them into one accelerated test?*
- ***Question #3:***
  - *How can I use the FDS to accelerate my test?*

VIBRATION RESEARCH

Background

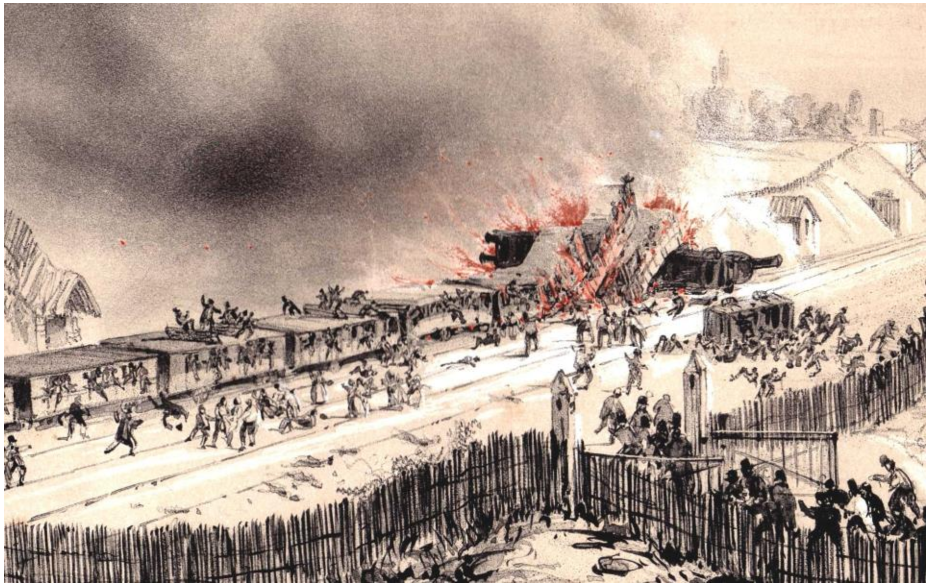
- *What is Fatigue Damage?*
  - *How does a UUT experience damage?*
    1) *Exceeding characteristic instantaneous stress limits*
    2) *Long-term damage due to fatigue*
- *How can we shorten tests, or the time required to acquire data for a test?*
  - *Apply an equivalent amount of fatigue damage, leaving you free to adjust the time that the test runs.*
- *In theory, a specific amount of damage leads to failure.*

Example of fatigue:

1842 Versailles train disaster

Drawing of a fatigue failure in an axle by Joseph Glynn, 1843
Main article: Versailles rail accident
Following the King's fete celebrations at the Palace of Versailles, a train returning to Paris crashed in May 1842 at Meudon after the leading locomotive broke an axle. The carriages behind piled into the wrecked engines and caught fire. At least 55 passengers were killed trapped in the carriages, including the explorer Jules Dumont d'Urville. This accident is known in France as the "Catastrophe ferroviaire de Meudon". The accident was witnessed by the British locomotive engineer Joseph Locke and widely reported in Britain. It was discussed extensively by engineers, who sought an explanation.

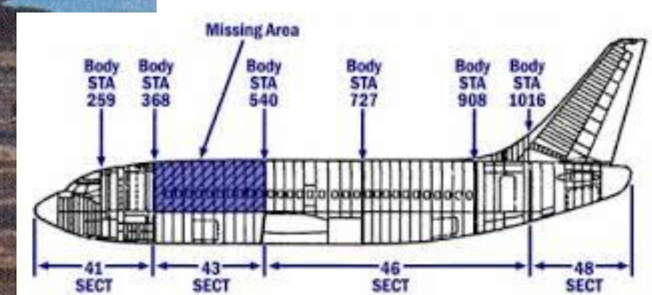
The derailment had been the result of a broken locomotive axle. Rankine's investigation of broken axles in Britain highlighted the importance of stress concentration, and the mechanism of crack growth with repeated loading. His and other papers suggesting a crack growth mechanism through repeated stressing, however, were ignored, and fatigue failures occurred at an ever increasing rate on the expanding railway system. Other spurious theories seemed to be more acceptable, such as the idea that the metal had somehow "crystallized". The notion was based on the crystalline appearance of the fast fracture region of the crack surface, but ignored the fact that the metal was already highly crystalline.



Example of fatigue

Aloha Airlines Flight 243

April 28, 1988 - Boeing 737



VIBRATION RESEARCH

Calculating Fatigue: S-N Curve, Miner's Rule

- *MIL-STD-810G[1] (Method 514.6, Annex A) states that:*
  - *"The most commonly used method for calculating a reduction in test duration is the Miner-Palmgren hypothesis that uses a fatigue-based power law relationship to relate exposure time and amplitude." This is the case in our fatigue-based import.*

- *A major assumption that usually accompanies the Palmgren-Miner linear damage hypothesis is that the slope of the S-N curve is approximately linear on a log-log plot. In the Henderson-Piersol[1] approximations that undergird much of this algorithm, this assumption is stated as:*

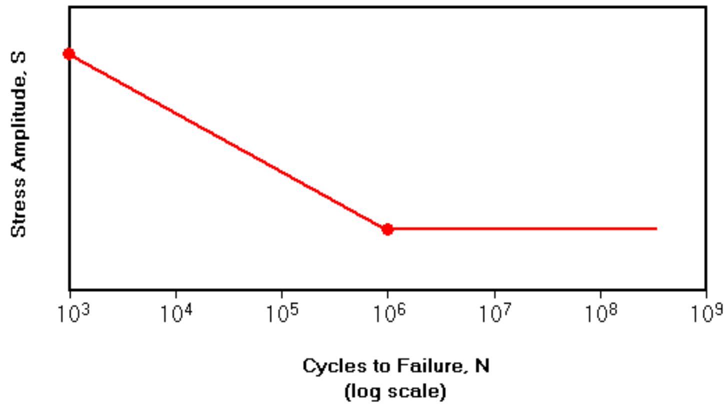
$$N = c \times S^{-b}$$

[1]Fatigue Damage Related Descriptor for Random Vibration Test Environments, Henderson/Piersol

VIBRATION RESEARCH

Calculating Fatigue: S-N Curve, Miner's Rule

- ***S-N Curve (S for stress, N for cycles):***



- ***Miner's Rule:***
    - $N = c \times S^{-b}$
    - ***C is experimentally found to be between 0.7 and 2.2. Usually for design purposes, C is assumed to be 1.***
    - $-b$ ***is related to the slope of the S-N curve***

Rainflow Counting Explained

- http://www.vibrationdata.com/tutorials/rainflow_counting.pdf

Rainflow Counting Explained – Page 1

RAINFLOW CYCLE COUNTING IN FATIGUE ANALYSIS
Revision A

By Tom Irvine
Email: tomirvine@aol.com

August 26, 2011

Introduction

The rainflow method is a method for counting fatigue cycles from a time history. The fatigue cycles are stress-reversals. The rainflow method allows the application of Miner's rule in order to assess the fatigue life of a structure subject to complex loading.

The resulting tabular data is sometimes referred to as a spectra.

Algorithm

1. Reduce the time history to a sequence of (tensile) peaks and (compressive) troughs.
2. Imagine that the time history is a pagoda.
3. Turn the sheet clockwise 90°, so the starting time is at the top.
4. Each tensile peak is imagined as a source of water that "drips" down the pagoda.
5. Count the number of half-cycles by looking for terminations in the flow occurring when either:
    a. It reaches the end of the time history
    b. It merges with a flow that started at an earlier tensile peak; or
    c. It encounters a trough of greater magnitude.
6. Repeat step 5 for compressive troughs.
7. Assign a magnitude to each half-cycle equal to the stress difference between its start and termination.
8. Pair up half-cycles of identical magnitude (but opposite sense) to count the number of complete cycles. Typically, there are some residual half-cycles.

The ASTM standard in Reference 1 gives algebraic formulas using Boolean operators for carrying out this process.

An example is given in the next section using the ASTM implementation.

Rainflow Counting Example

Rainflow Counting Explained – Page 2

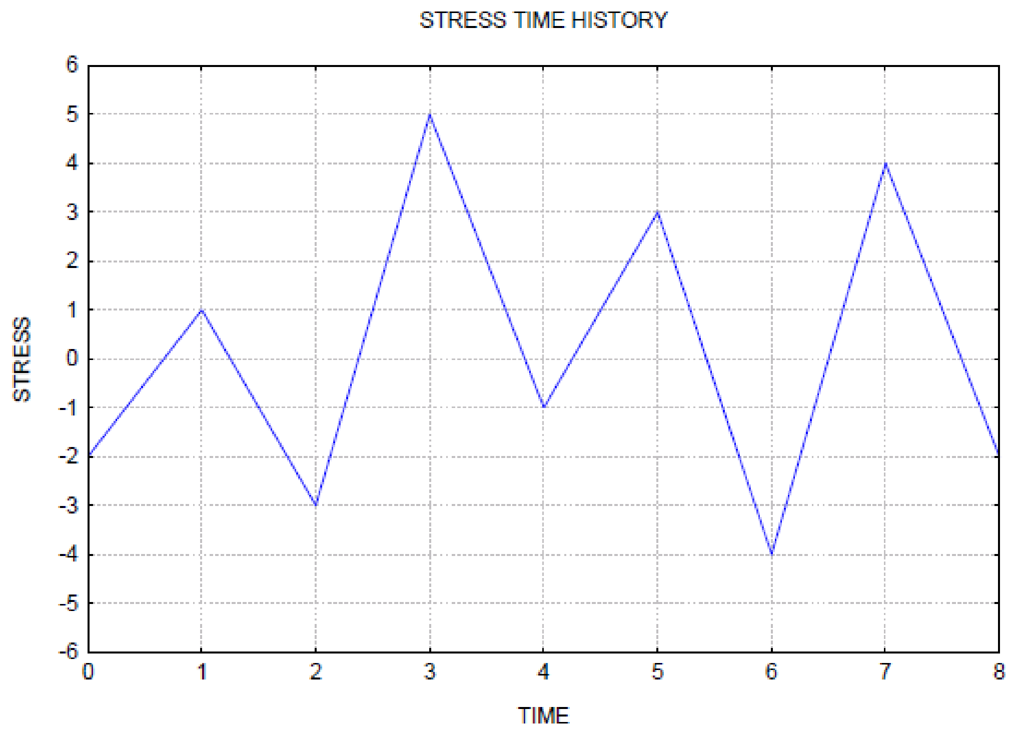


Figure 0.

A stress time history is given in Figure 0.

Rainflow Counting Explained – Page 3

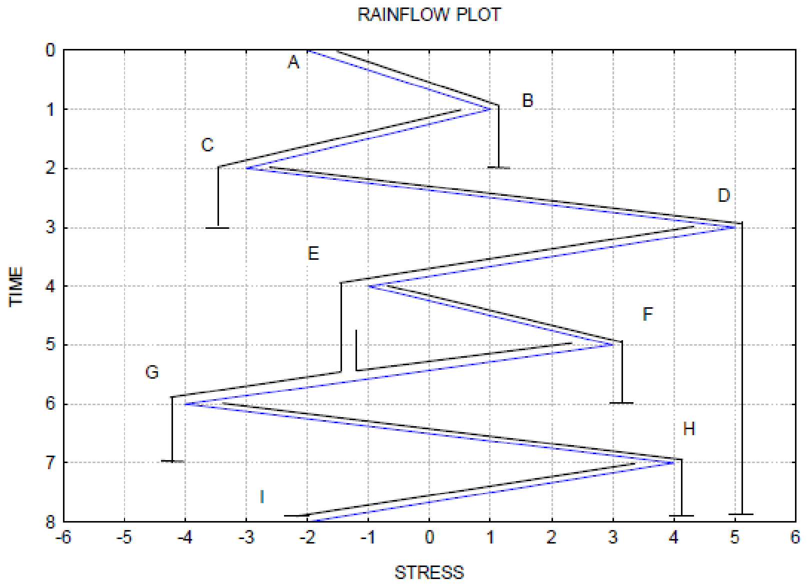


Figure 1.

Table 1. Rainflow Cycles by Path		
Path	Cycles	Stress Range
A-B	0.5	3
B-C	0.5	4
C-D	0.5	8
D-G	0.5	9
E-F	1.0	4
G-H	0.5	8
H-I	0.5	6

Note that E-F is counted as one cycle because is it considered to contain some of F-G.

Table 2. Rainflow, Total Cycles		
Stress Range	Total Cycles	Path
10	0	-
9	0.5	D-G
8	1.0	C-D, G-H
7	0	-
6	0.5	H-I
5	0	-
4	1.5	B-C, E-F
3	0.5	A-B
2	0	-
1	0	-

Another example is shown in Appendix A.

References

1. ASTM E 1049-85 (2005) Rainflow Counting Method, 1987.
2. P. Wirsching, T, Paez, K. Ortiz, Random Vibrations Theory and Practice, Dover, New York, 2006.

APPENDIX A

Single Wavelet Example

Rainflow Counting Explained – Page 5

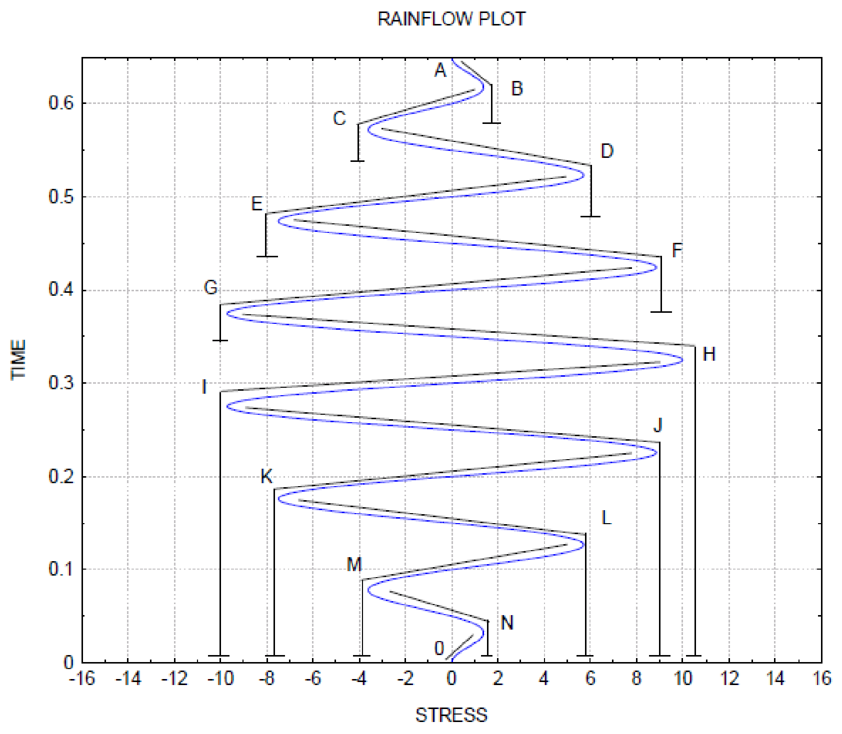


Figure A-1.

Each consecutive segment is a half-cycle in this case.

Creating the Fatigue Damage Spectrum

- ***Stress cycle amplitudes are weighted non-linearly** (because of power function) – see Henderson-Piersol assumptions[1]*
  - $N = c \times S^{-b}$
- ***Cycles are accumulated to get accumulated fatigue at that frequency; according to Miner's Rule***
  - $D = \sum_i \frac{n_i}{N_i}$
  - $D \propto \sum_i n_i S_i^b$

n_i = number of cycles applied with peak stress, S_i
Ni= number of cycles with peak stress, S_i, needed to cause failure
D = total damage

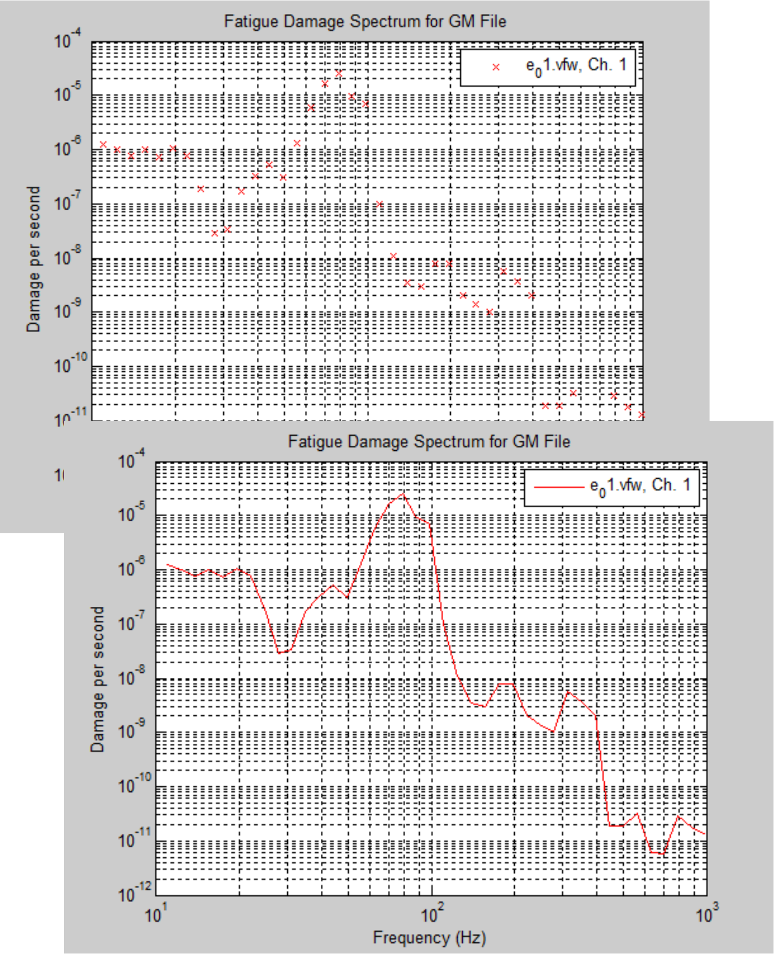
[1]Fatigue Damage Related Descriptor for Random Vibration Test Environments, Henderson/Piersol

VIBRATION RESEARCH

Creating the Fatigue Damage Spectrum

- ***Process is repeated at a spectrum of frequencies, with one fatigue number at each frequency***

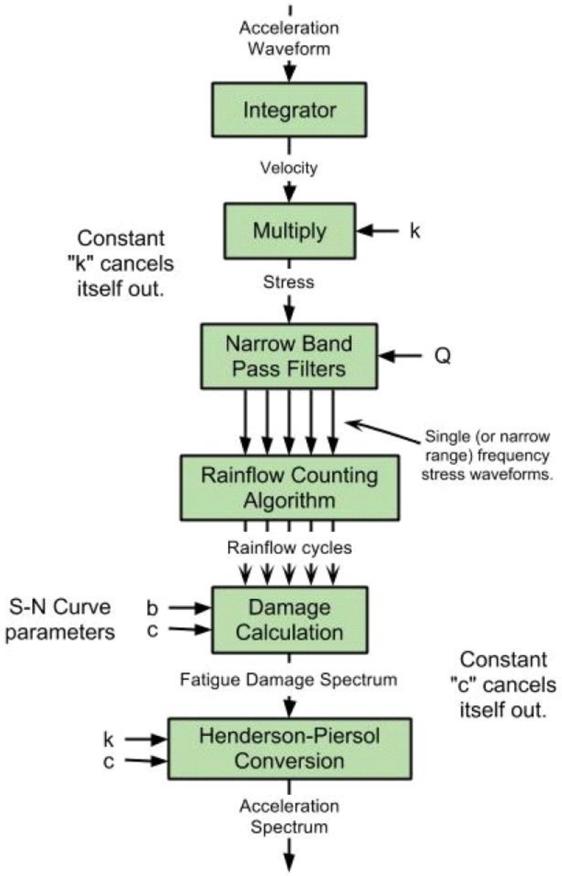
- ***Plot of Fatigue vs. Frequency is the fatigue damage spectrum[2]***



[2]The Fatigue Damage Spectrum and Kurtosis Control, John & Philip Van Baren

How to Compute FDS

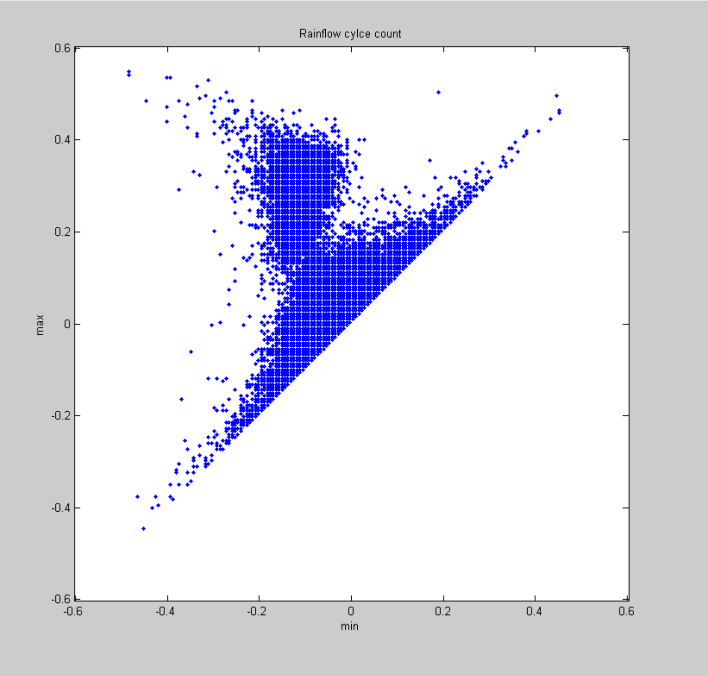
- *An acceleration waveform is converted to a velocity waveform*
  - *By integrating the acceleration waveform*
  - *Velocity is desired because Henderson-Piersol equations utilize velocity[1]*



[1]Fatigue Damage Related Descriptor for Random Vibration Test Environments, Henderson/Piersol

How to Compute FDS

- ***Stress waveform is narrow-band filtered***
  - ***Specific Q value is used***
- ***Filtered stress waveform has stress peak-valley cycles counted using a Rainflow counting algorithm***
  - ***Can be calculated with Matlab's Wafo Toolbox[3]***
  - ***VibrationView software internally calculates***

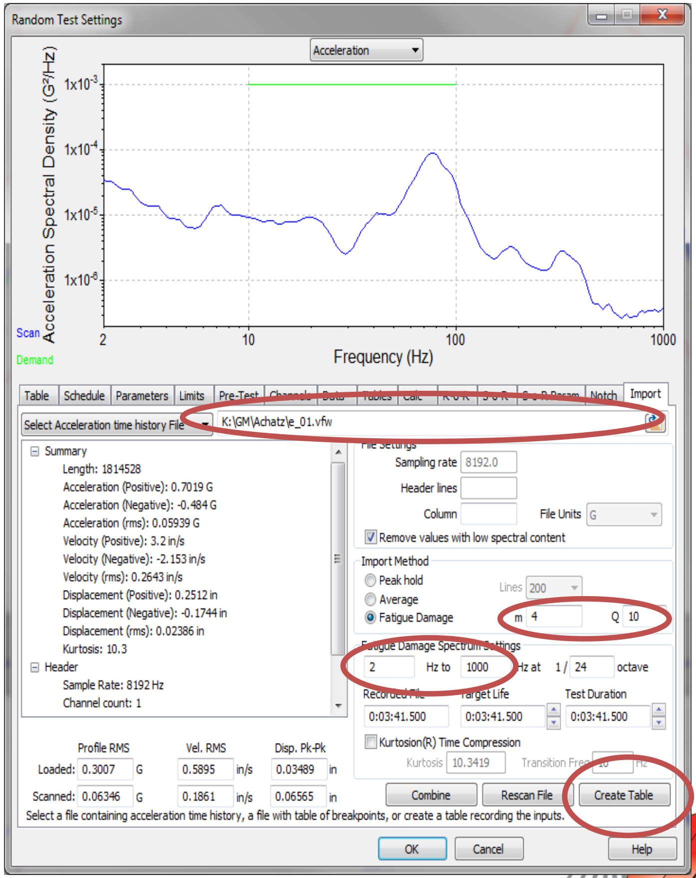


Rainflow Cycle Count for GM – E_01 File Using WAFO tools in Matlab

[3]Tutorial for WAFO version 2.5. Lund University, March 2011

Q1: How to Generate a Random Profile to Simulate End-Use Environment

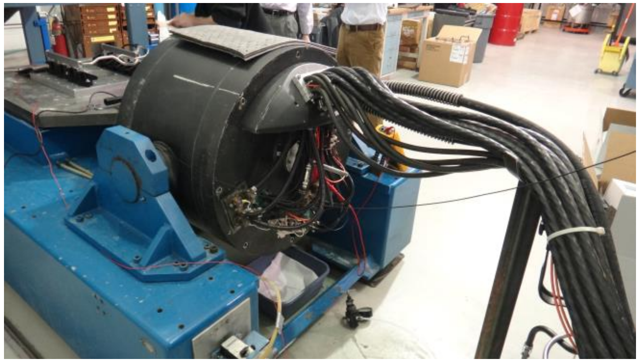
- *Import Recording*
- *Set m and Q values*
- *Set Frequency Range*
- *Create Table*



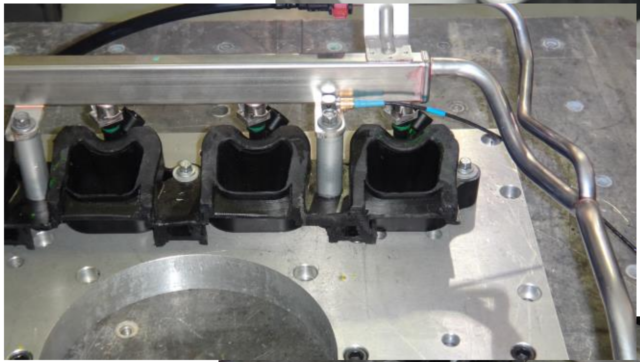
VIBRATION RESEARCH

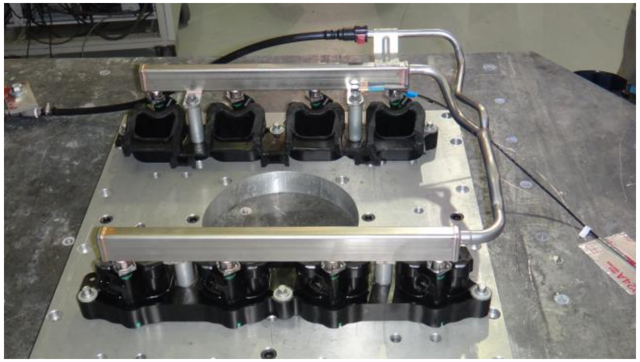
The Product, Unit Under Test, or "UUT"

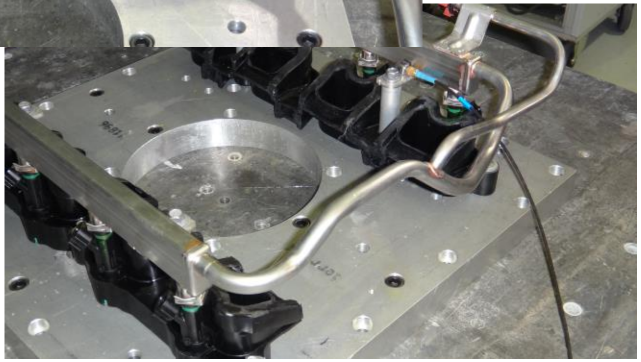
Shaker Setup

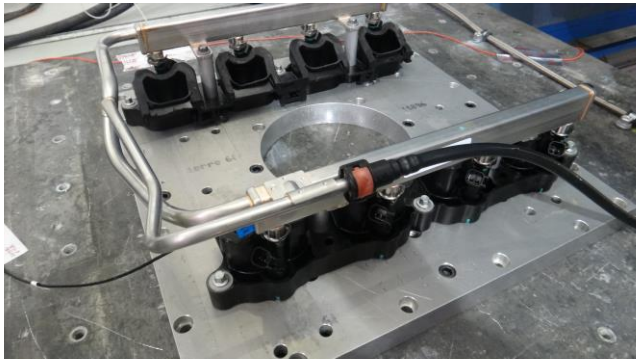


Fuel Rail Mounted to the Shaker, accelerometer with cylinder head input









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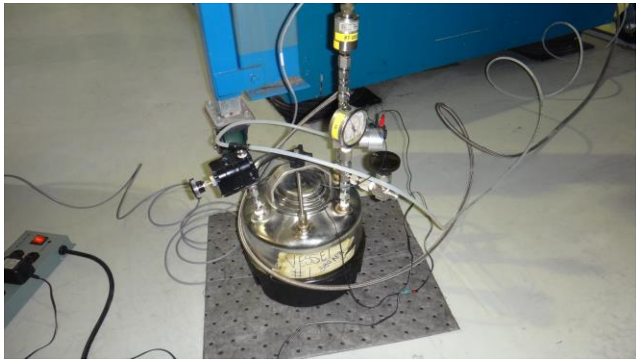
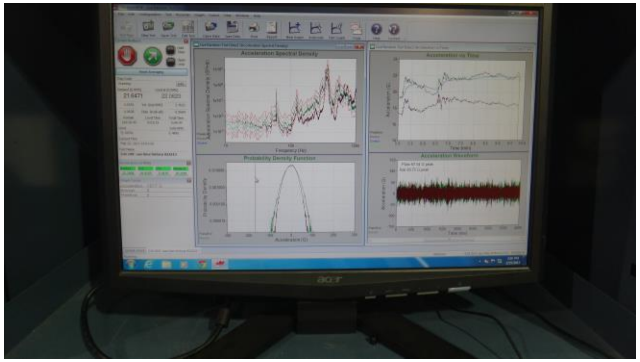
Fuel under Pressure simulator



Controlling the Test



Failure Noted

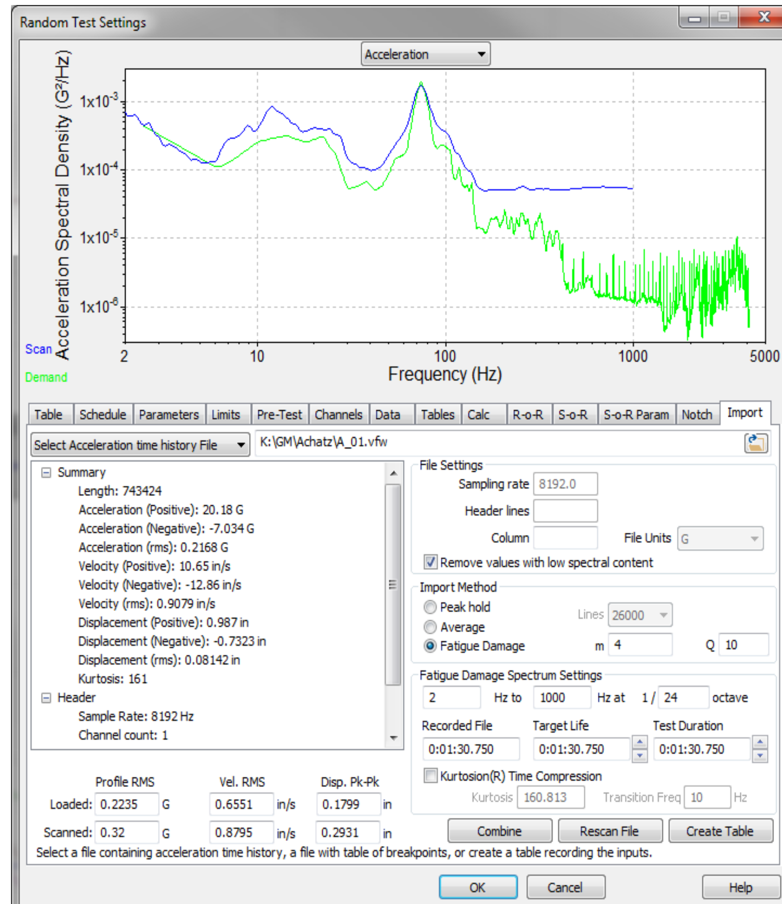
Illustration Videos

- Engine Run up data (2:21):
- http://www.screencast.com/t/lKG9CvumG
-
- FDS import and random profile generation process (4:46):
- http://www.screencast.com/t/IgRZX2YR
-
- These two files are also found on our web site, in slightly lower resolution:
- http://www.vibrationresearch.com/fds.html

Q2: How to Combine Many Different Environments into one Accelerated Test

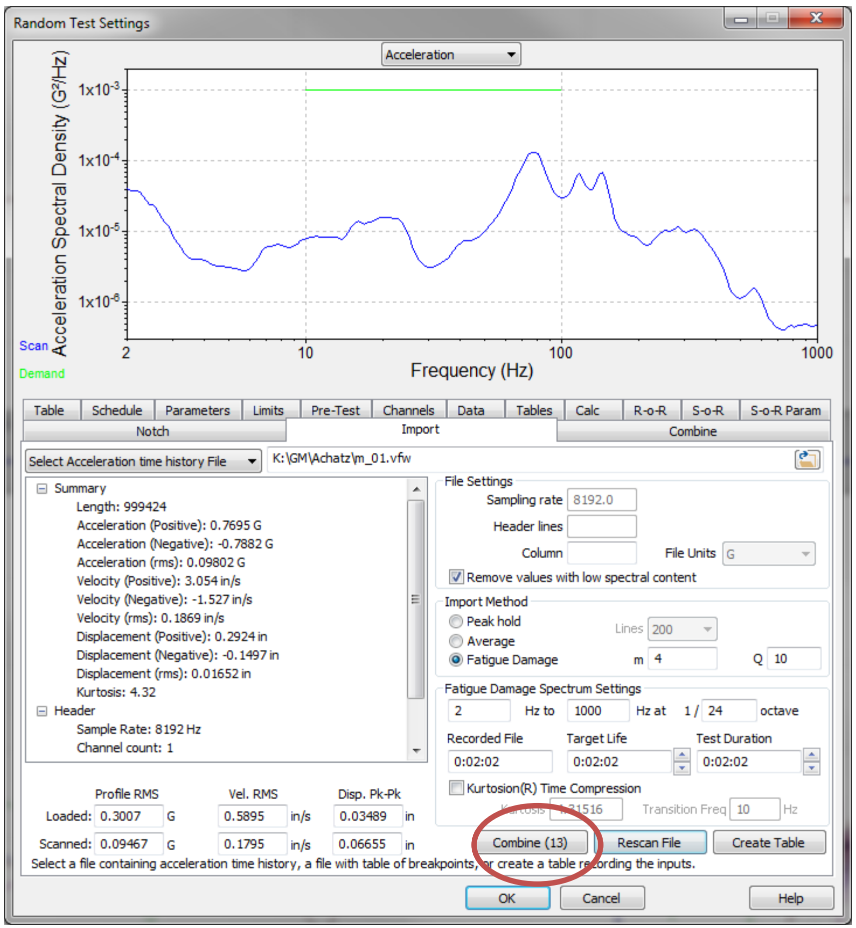
- *Import Recording*
- *Set m and Q values*
- *Set Frequency Range*
- *Create Table*
- *Repeat for as many environments as you have*

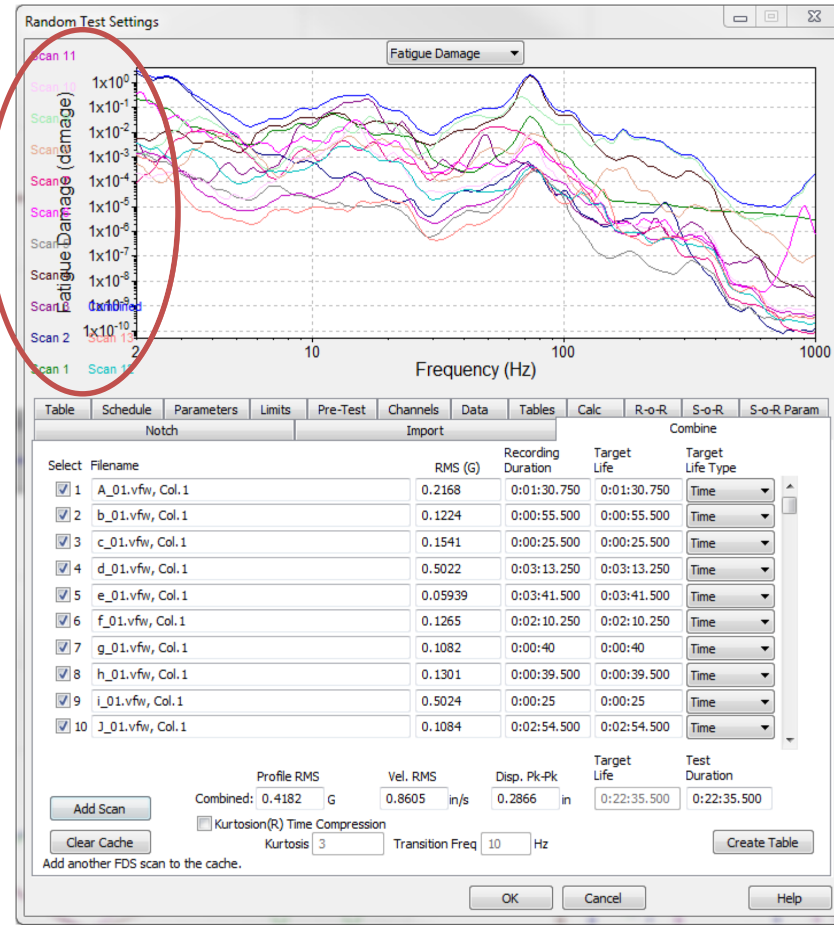
INPUTS		
FILENAME	REPETITIONS	Dyanmic amplification, Q = 10
A	400	Spring stiffness, K = 1
B	90	SN coefficient, A = 1
C	100	SN coefficient, C = 1
D	2000	SN exponent, b = 4
E	4000	
F	16	
G	200	
H	200	
I	8	
J	1800	
K	1200	
L	1800	
M	1600	



Spreadsheet of GM Files and Recommended Number of Repetitions

Combining Recordings

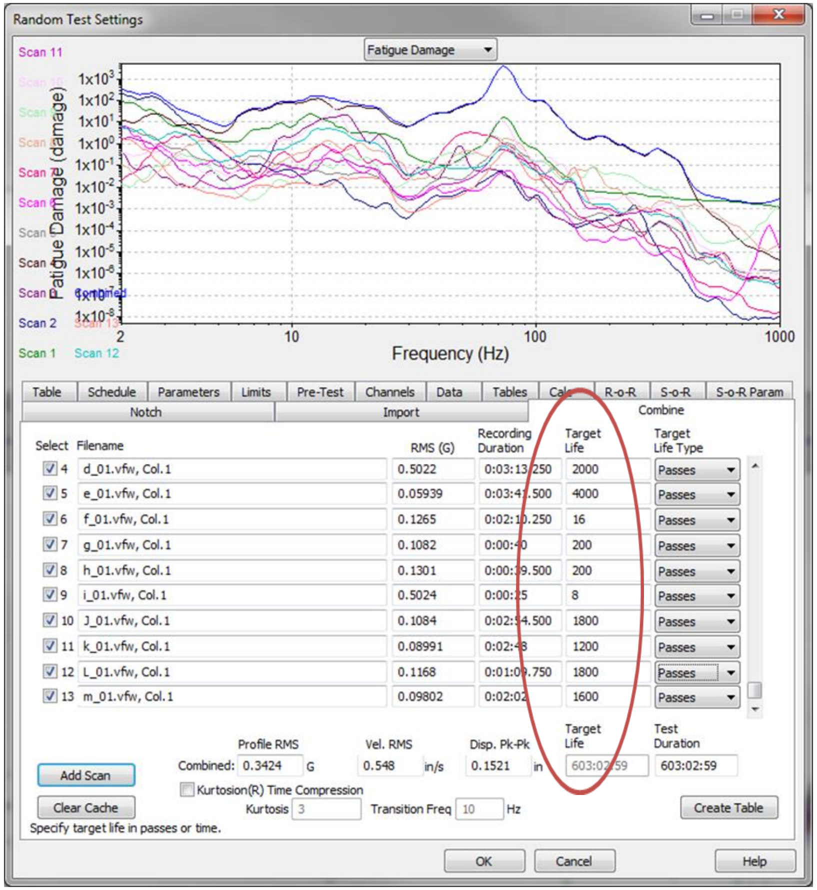




As many files as are imported, show up in the “Combine” button. Click “Combine” and the FDS for each file is shown; including the FDS of the Combined plot.

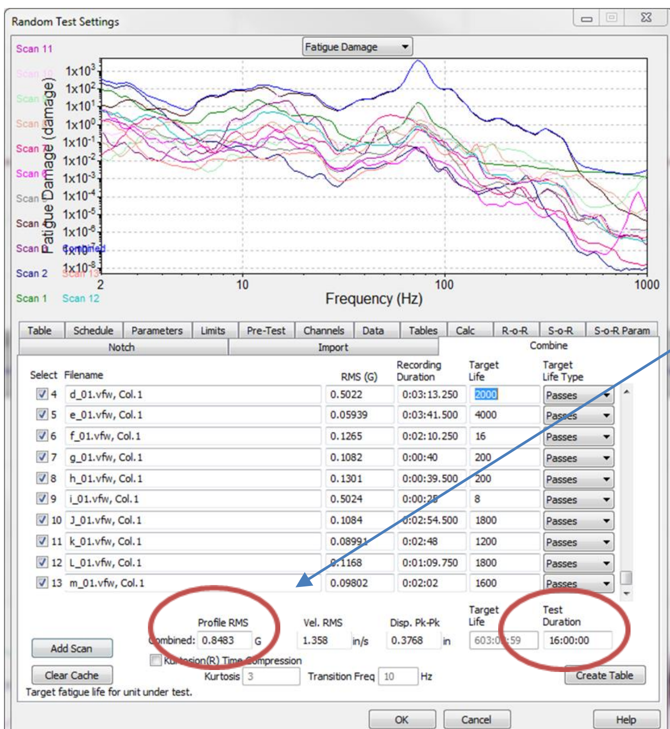
Setting Target Life

- GM's durability tests for a variety of environments are loaded
- Each file had a specified number of repetitions to simulate end-use environment
- The number of repetitions were entered as "passes" under Target Life



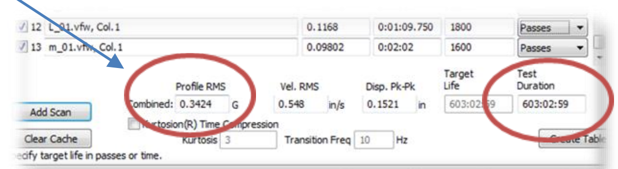
Setting Test Duration

- *Total Target Life for combined test was 603 hr.*
- *GM desired a shorter test (16 hr test)*



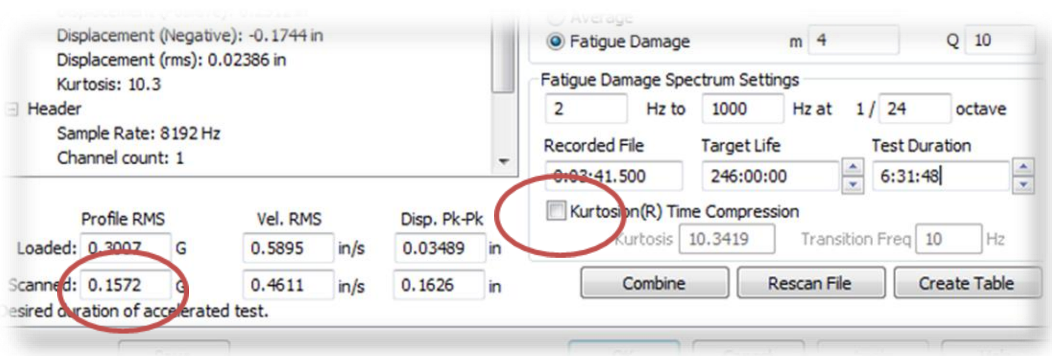
Note the increase in GRMS:

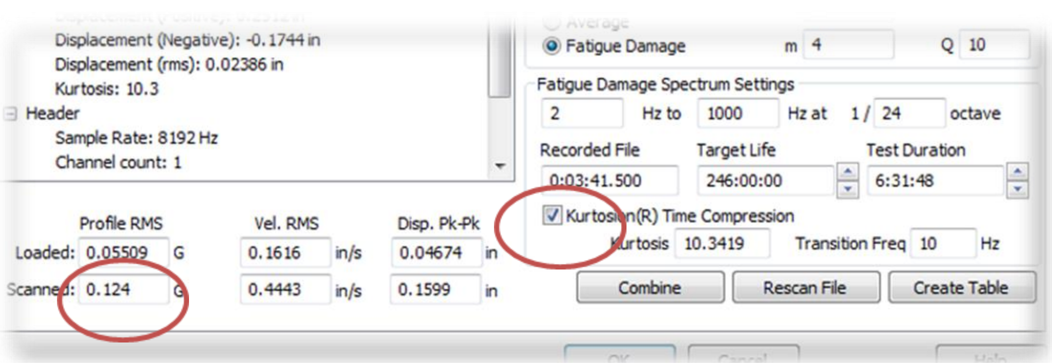
- From 0.3424 G to 0.8483 G



Q3: How to Use FDS to Accelerate a Test

- *Accelerate a test:*
  - *Use FDS*

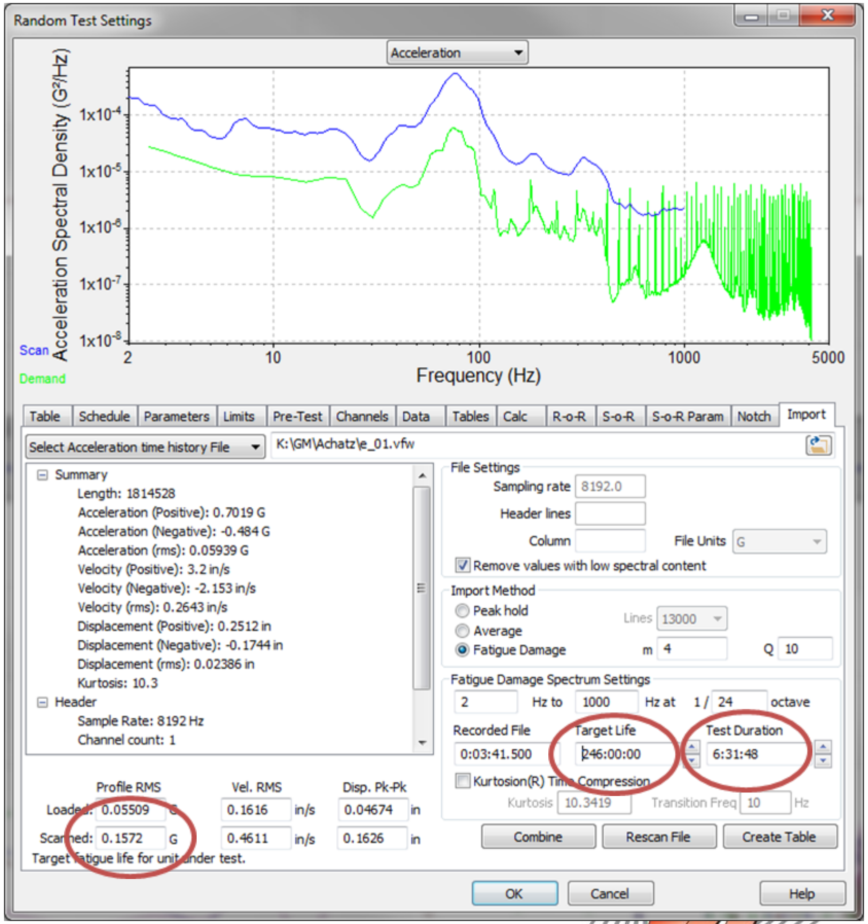




VIBRATION RESEARCH

Using FDS to Accelerate Tests

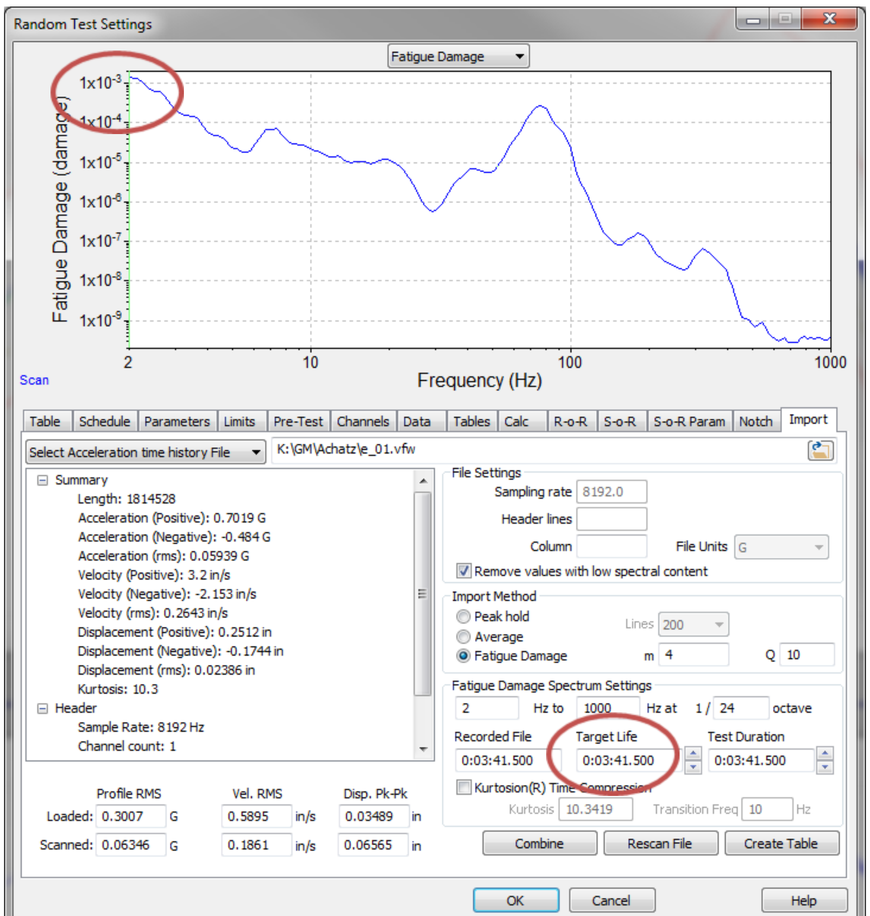
- GM file E01 was imported with Fatigue Damage Import
- M and Q defined
- Target Life and Test Duration set for desired levels
- Note the increase in GRMS and PSD (compared to Average Import)

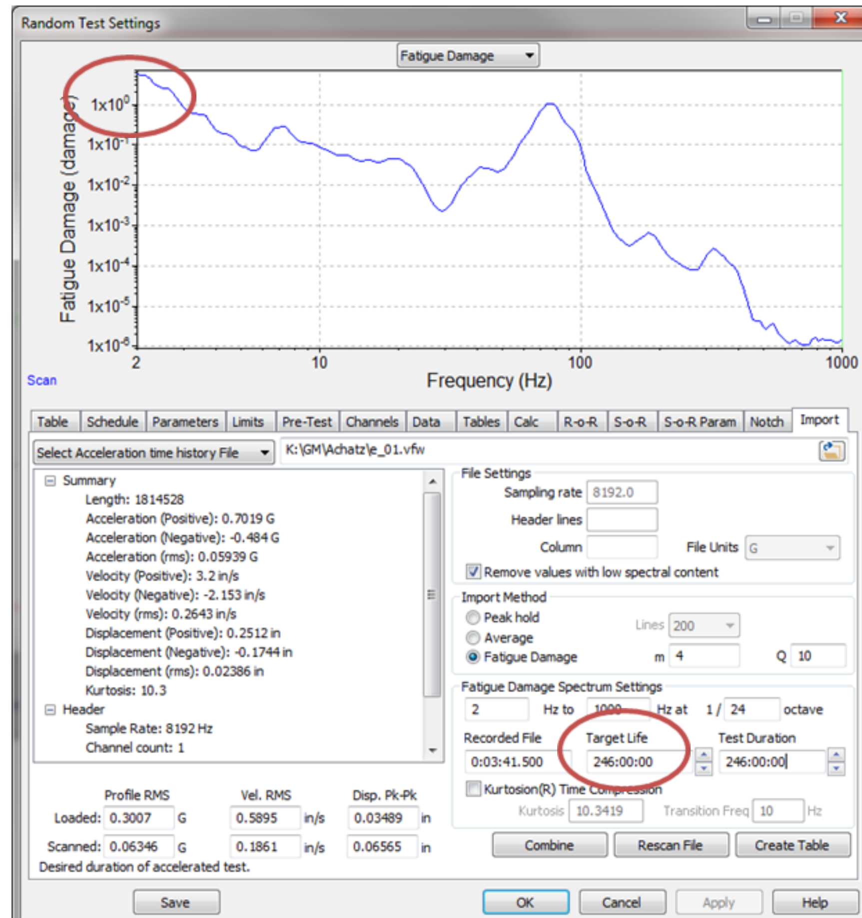


VIBRATION RESEARCH

Accelerating Test with FDS

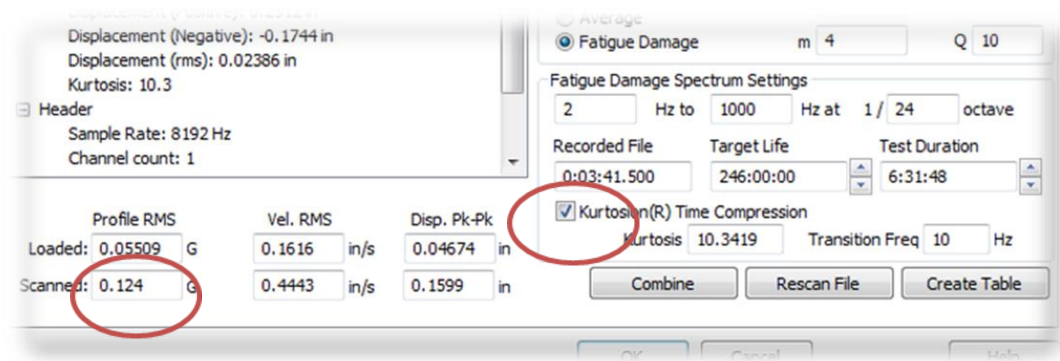
- *FDS plots of original imported file with adjusted Target Life and Test Duration Compare*





Q3: How to Use FDS & Kurtosion® to Accelerate a Test

- ***Accelerate a test:***
  - ***Use FDS***
  - ***Use FDS and Kurtosion®***

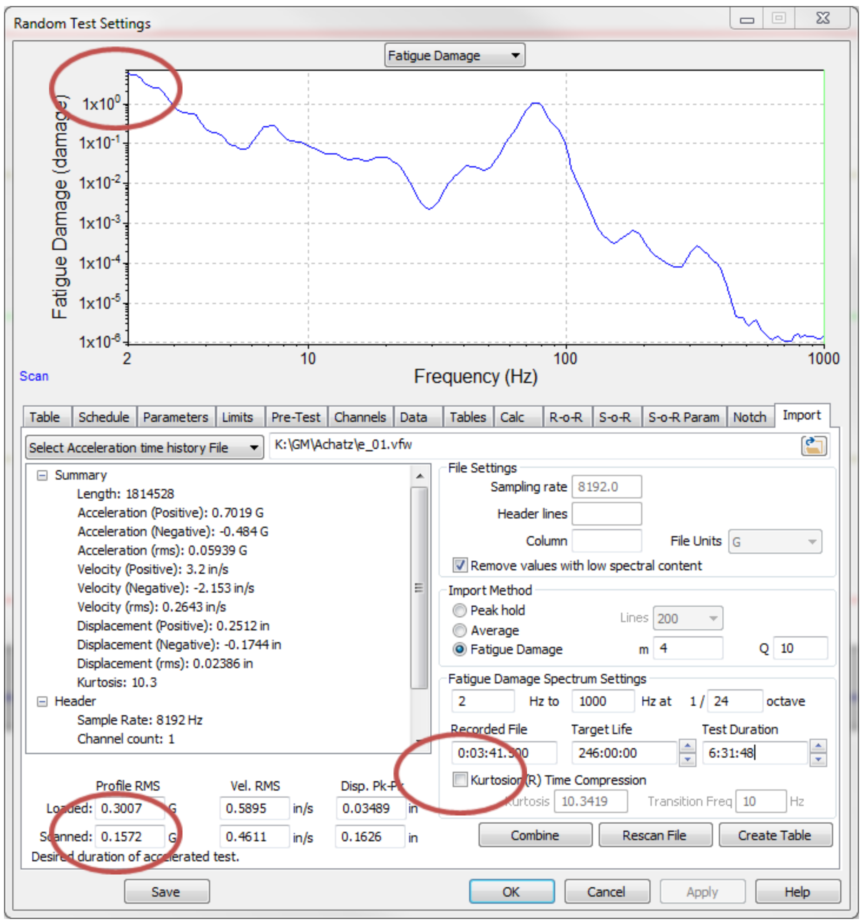


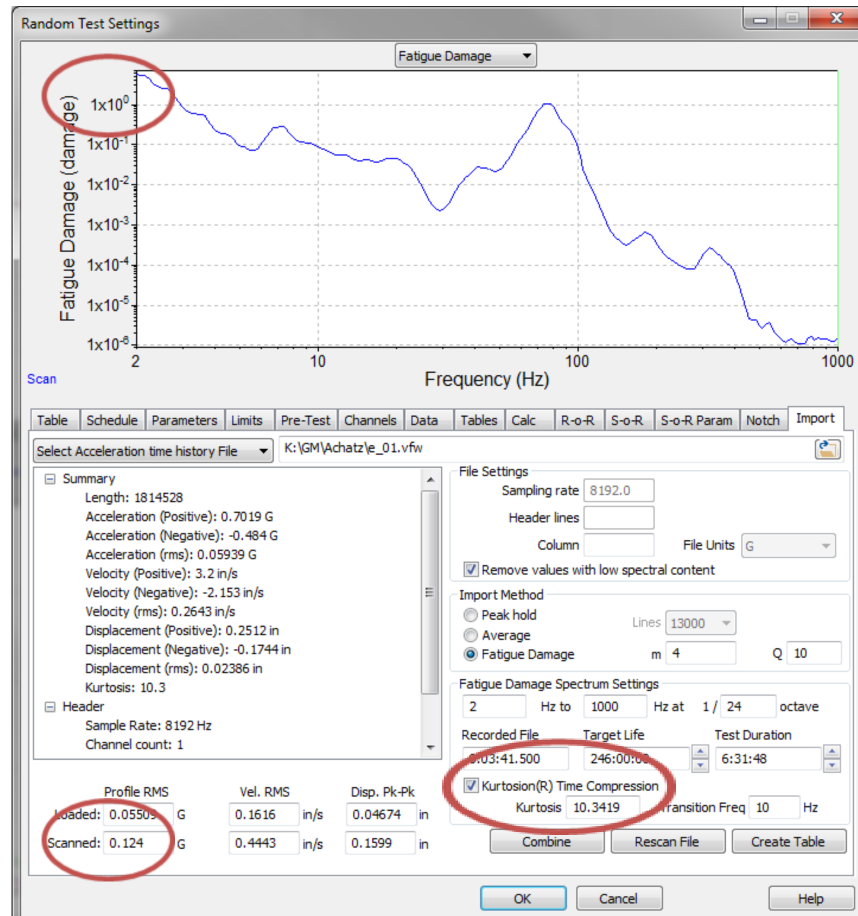
VIBRATION RESEARCH

Using Kurtosion® with FDS to Accelerate a Test

- *Original Fatigue Damage Import assumes Gaussian distribution. Converting the FDS back to a PSD (through Henderson-Piersol equations) assumes Gaussian*
- *Kurtosion® can be added to Fatigue Damage Import to further accelerate test*
- *Kurtosion® will provide the same amount of total fatigue damage, but do so in a faster time (because large peaks are restored to the test)*

Using Kurtosion® with FDS to Accelerate a Test





VIBRATION RESEARCH

CONCLUSIONS

- *End-Use Environment can be simulated with Random Profile using Fatigue Damage Import*
- *Multiple End-Use Environments can be easily combined with Fatigue Damage Import*
- *Random Vibration Tests can be Accelerated using FDS and Kurtosion®*

VIBRATION RESEARCH

QUESTIONS???

How to simulate vibration condition on internal combustion engine mounting condition using FDS, keeping the RPM distribution in mind?

How do you insure that you are not over accelerating your test?

Can signals not acquired with the vibration view software be read?

Can you use FDS to simulate Sine Vibration environments?

What are the limits to the method? e.g. how much acceleration scaling is valid?

What if I don’t know my m or Q? What should I use?

QUESTIONS???

Is it expected that the higher value of Kurtosis, say 6-9 is attenuated back to 3 during testing?

Can the software tell you if your shaker won't be able to handle the kurtosis?

What is the default transition frequency resolution?

QUESTIONS???

If you would like answers to any of these questions feel free to email us or give us a call and we would be more than willing to help out.

Website Registration

- Go to http://www.vibrationresearch.com/forums/register.php?do=signup
- In the sign up form, please do not include “HTTPS” in your company’s website

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