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

Tom Achatz, PE
Global Technical Integration Engineer,
General Motors Company

John VanBaren, PE
President, Vibration Research Corporation

Biographies

- **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.

- **John Van Baren** is the president of Vibration Research Corporation, Jenison, MI, 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 15 years in the R&D department at a large environmental test equipment manufacturer. Van Baren has designed shaker systems, shaker amplifiers, shaker controllers, and thermal controllers. He was a pioneer in the application of time-history replication on electro-dynamic shakers, and continues to guide the company forward as a leader in the field of vibration testing.

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?

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.**

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

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

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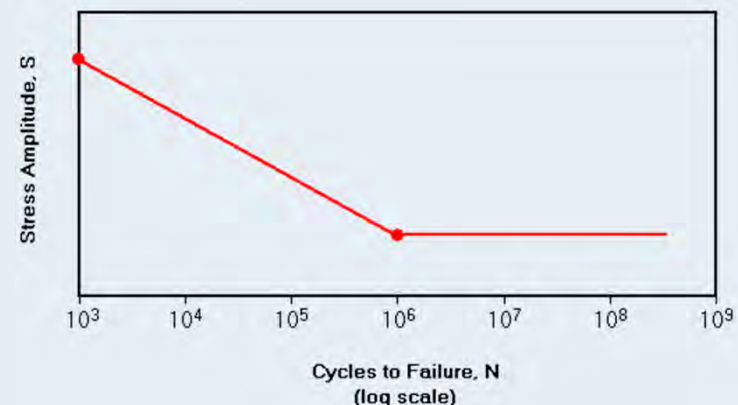
- ## Miner's Rule:
    - $N = c \times S^{-b}$
    - C is experimentally found to be between 0.7 and 2.2. Usually for design purposes, C is assumed to be 1.
    - $-b$ is related to the slope of the S-N curve

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

  - $D = \sum_i \frac{n_i}{N_i}$ $\qquad D \propto \sum_i n_i S_i^b$

  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

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
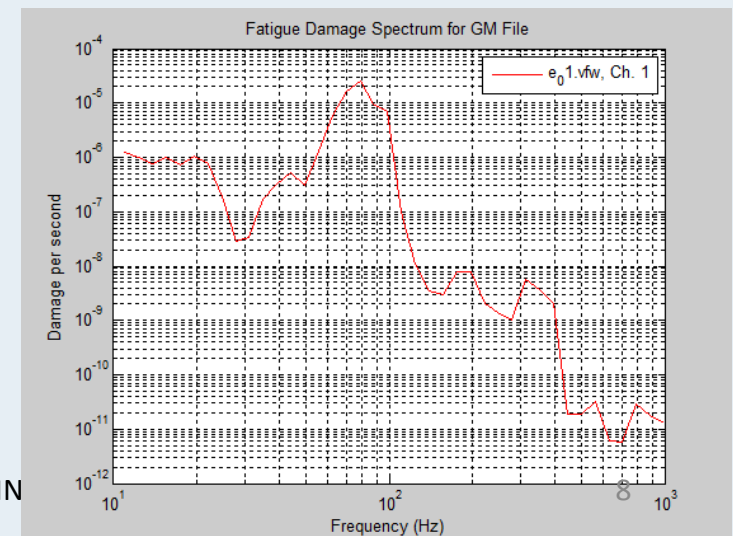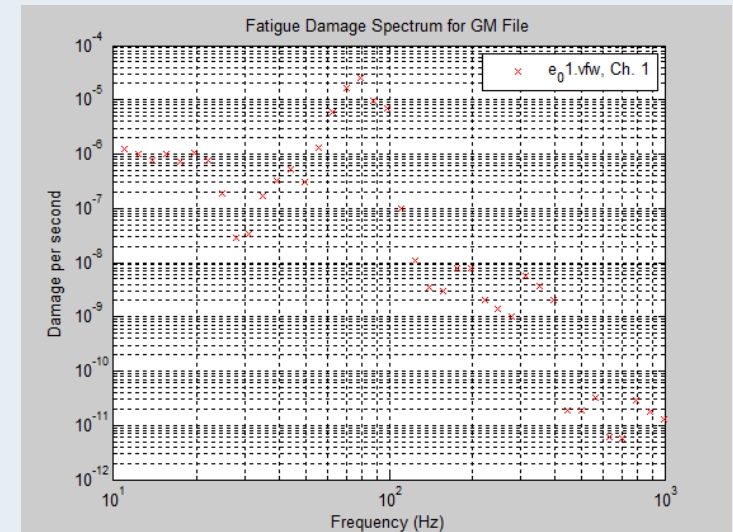
Fatigue Damage Spectrum
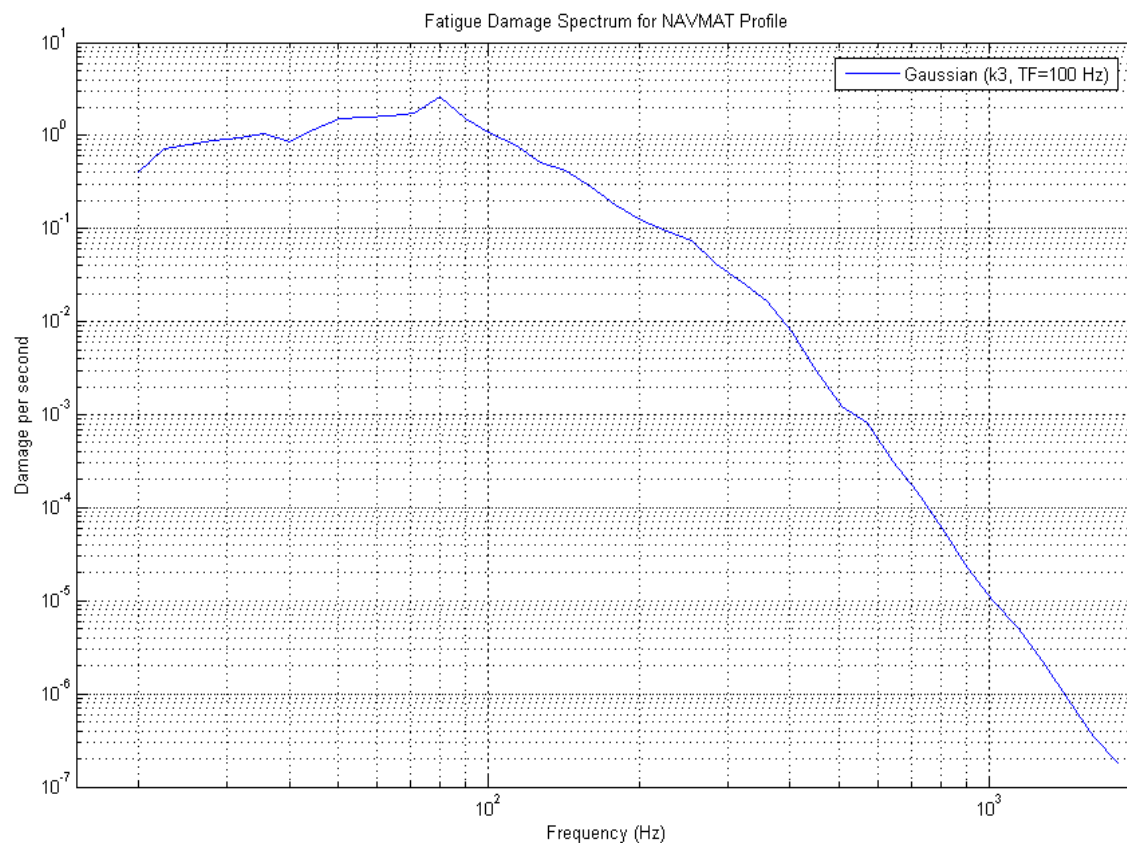
Generic FDS for NAVMAT Profile

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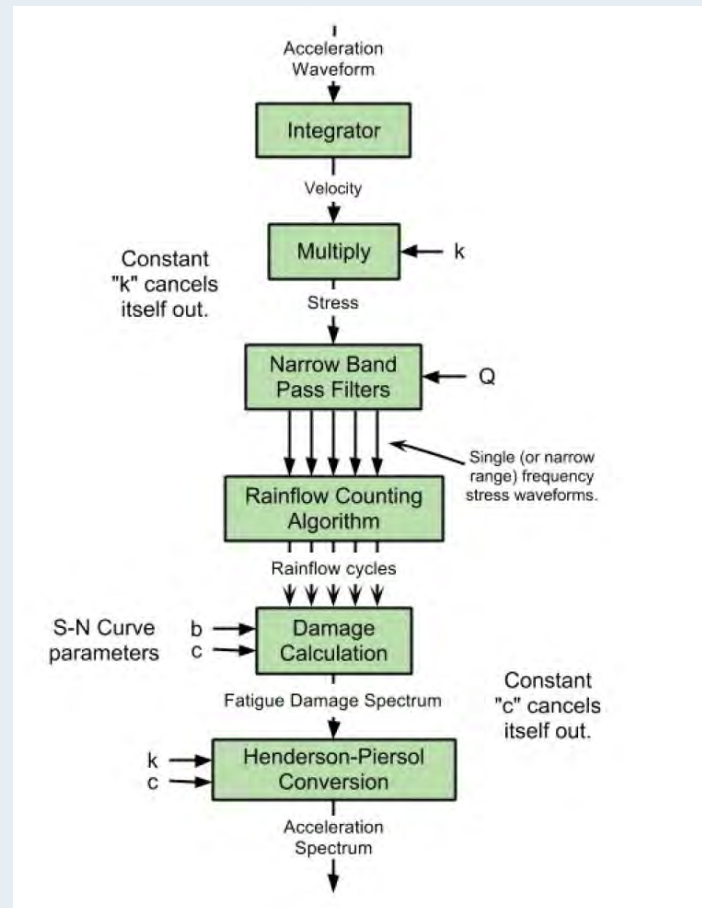
[1]Fatigue Damage Related Descriptor for Random Vibration Test Environments, Henderson/Piersol

How to Compute FDS

- Velocity is proportional to stress[1]

- NEW! It is demonstrated that you can use acceleration, velocity, or displacement, **all result in the same end PSD**

  - *FDS is different for acceleration, velocity, and displacement*

  - *But PSD is the same in each case* (because it is simply the equivalency of two waveforms)

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

FDS for A-V-D
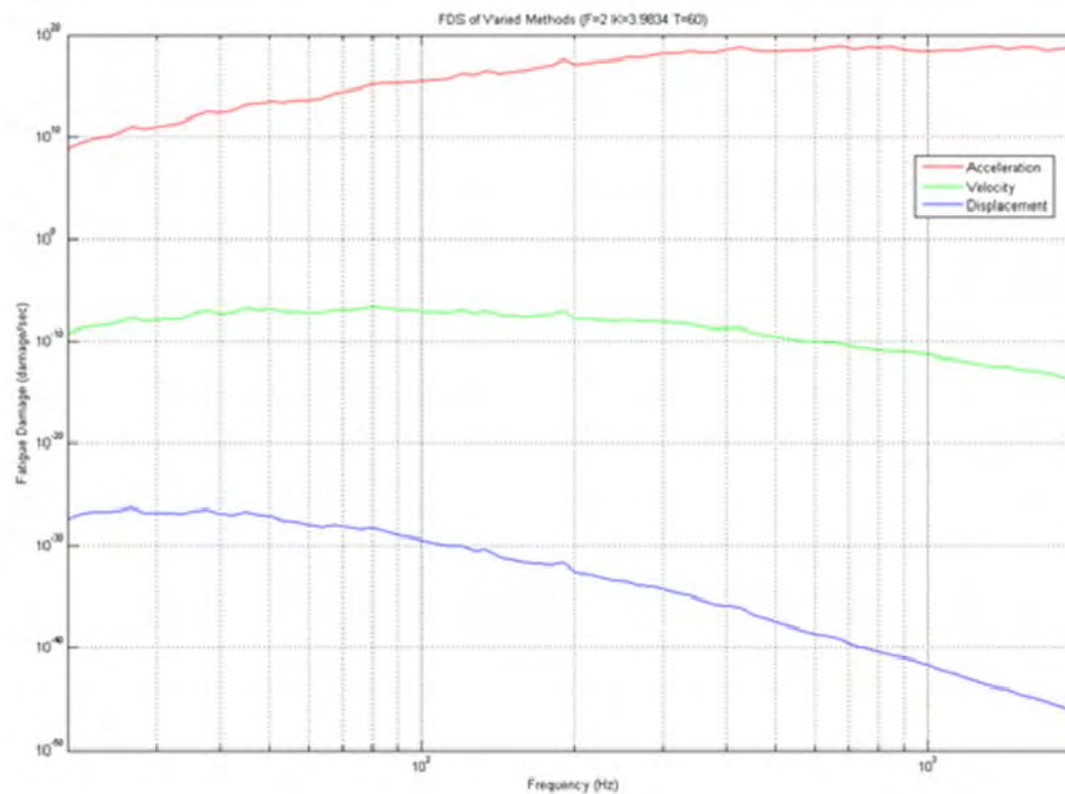
Different FDS for each methodology for a test of K=4

PSD resulting from A-V-D
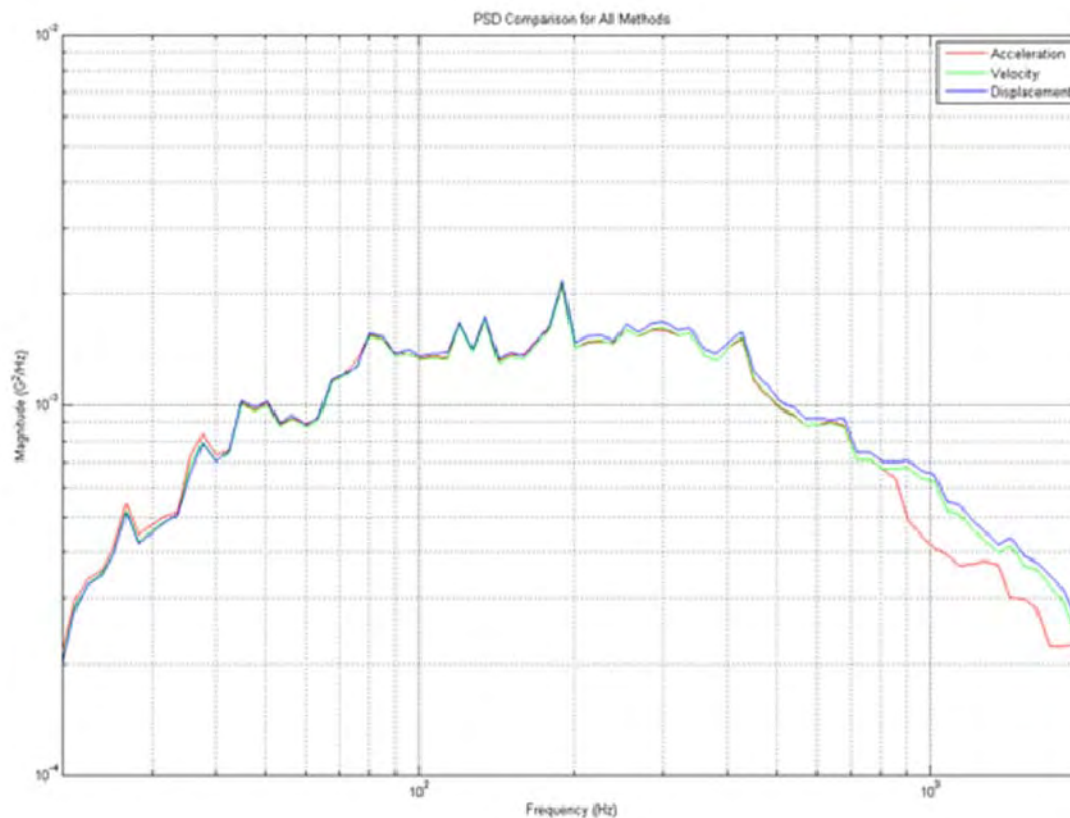
PSD for K=4 trial for all three methodologies

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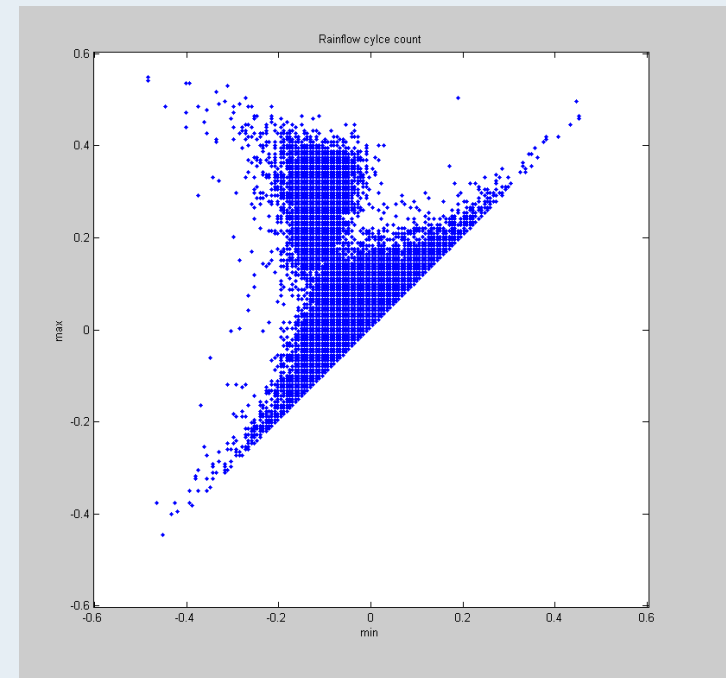
Rainflow Cycle Count for GM – E_01 File Using WAFO tools in Matlab

[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
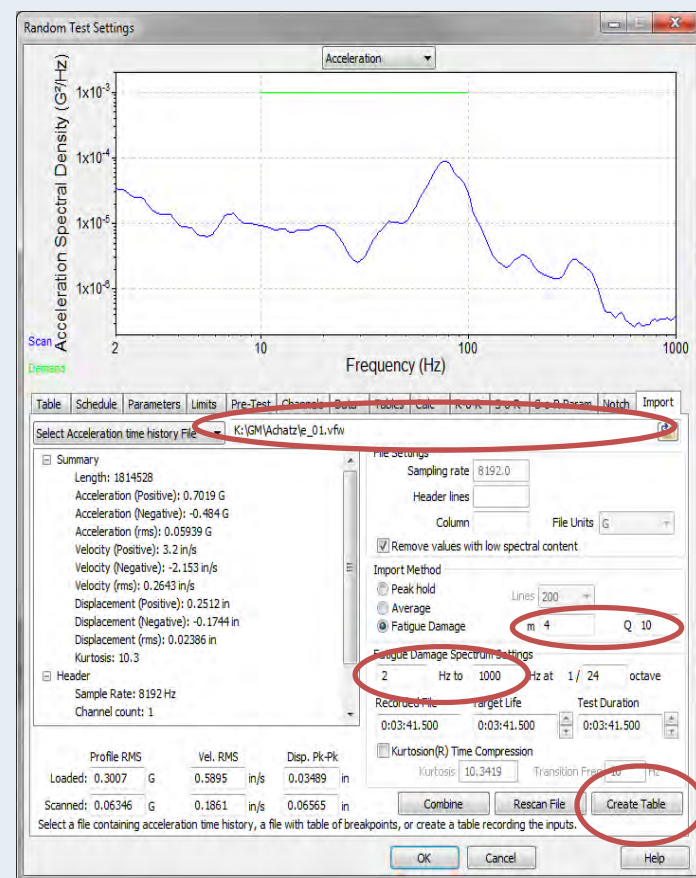
Illustrating Random Profile and End-Use Environment Recordings are Same
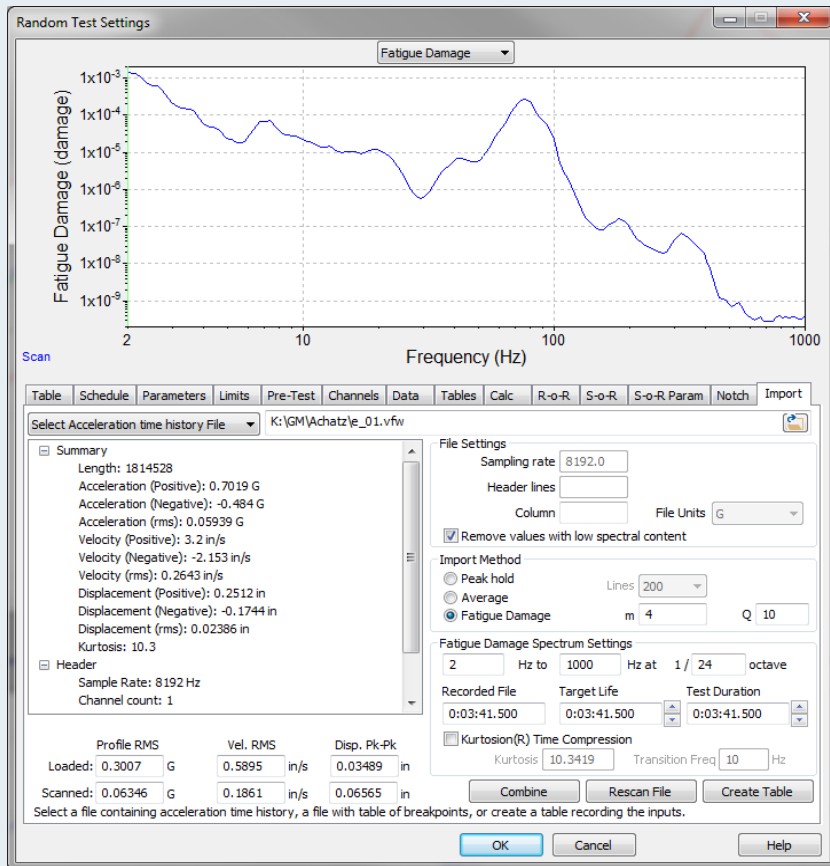
Original End-Use Environment
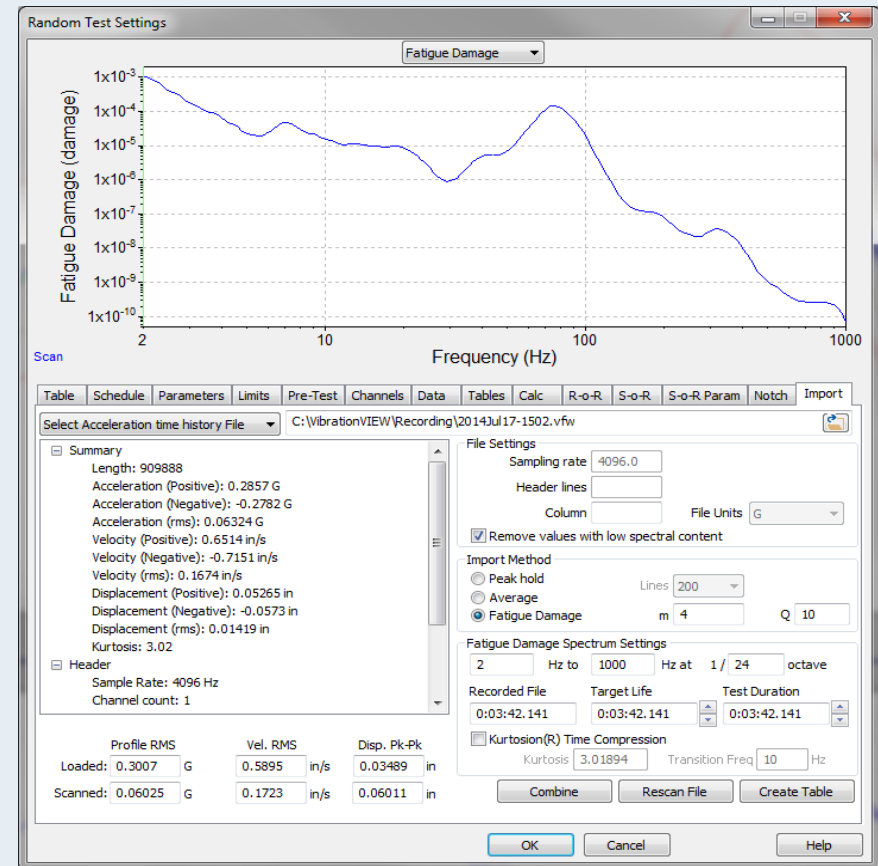
Recording of End-Use Environment

Equivalency Test Demonstration

- Used GM D01

- Equivalency test run – produced same FDS
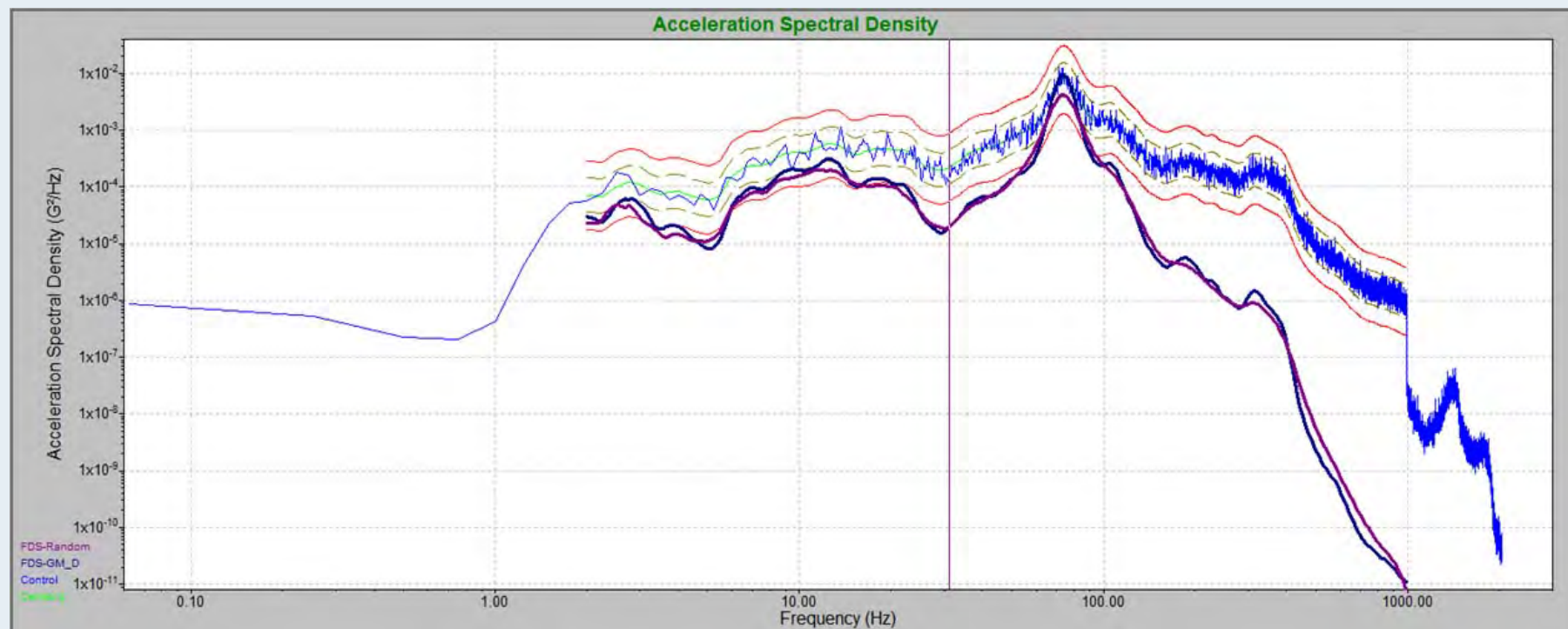
Q2: How to Combine Many Different Environments into one Accelerated Test

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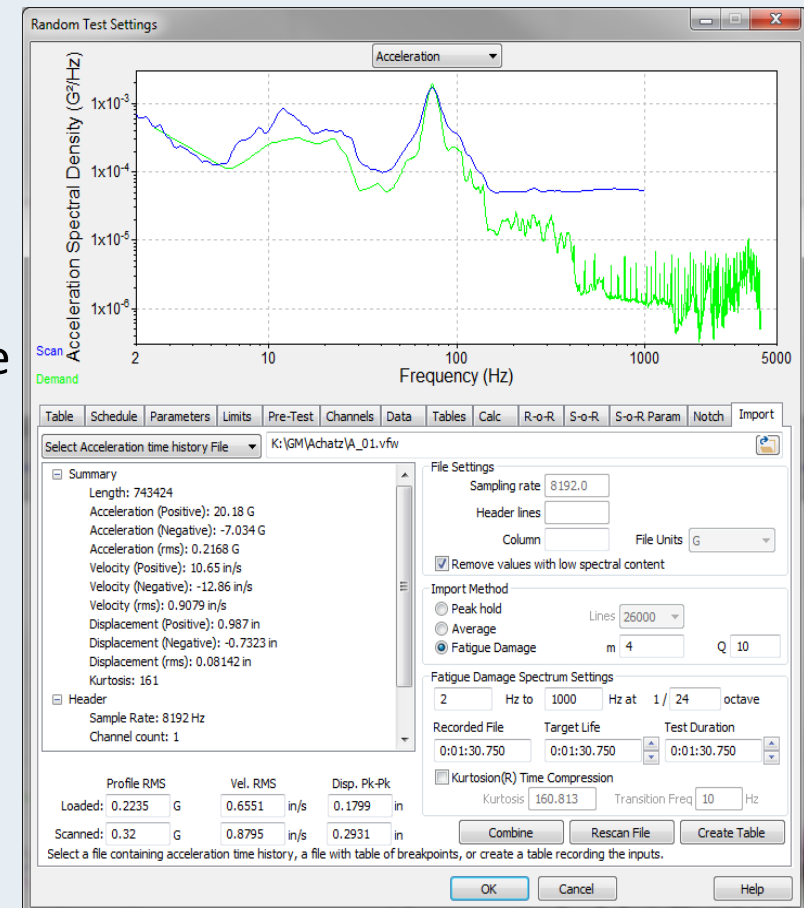
Combining Recordings
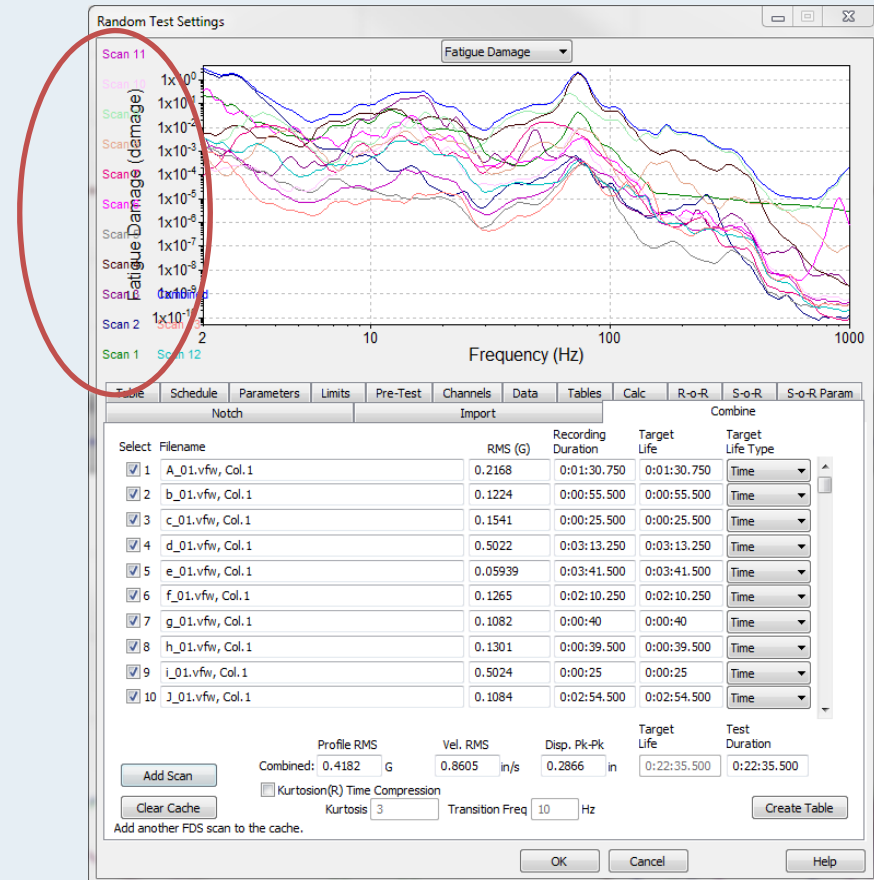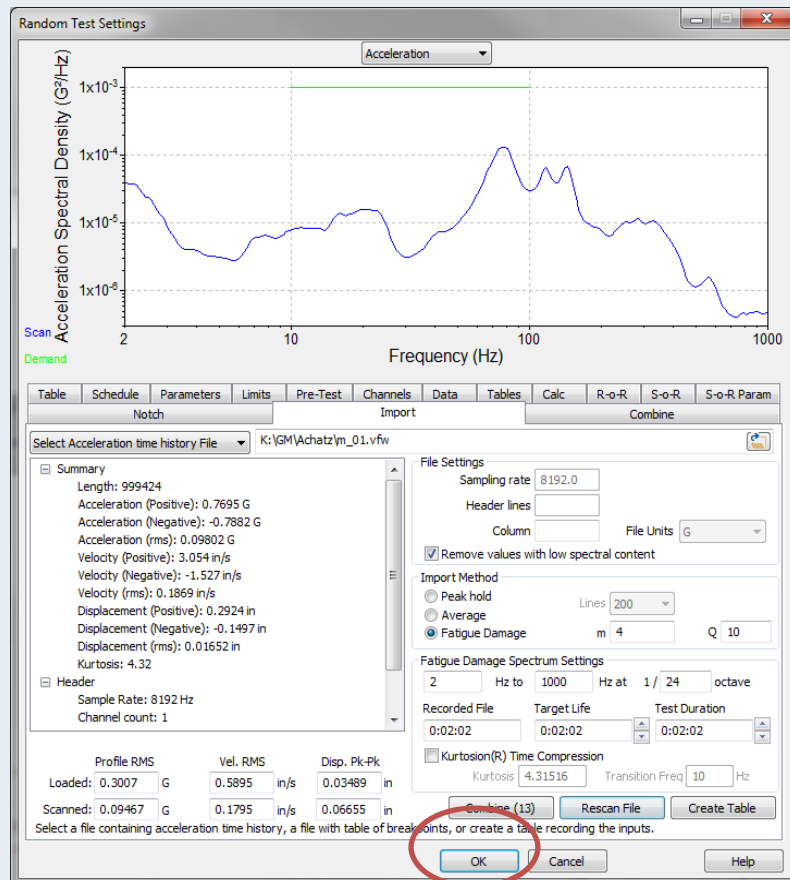
As many files as are imported, show up in the "Combine" button. Click "Combine" and the FDS for each file is shown; including the FDS of the Combined plot.

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
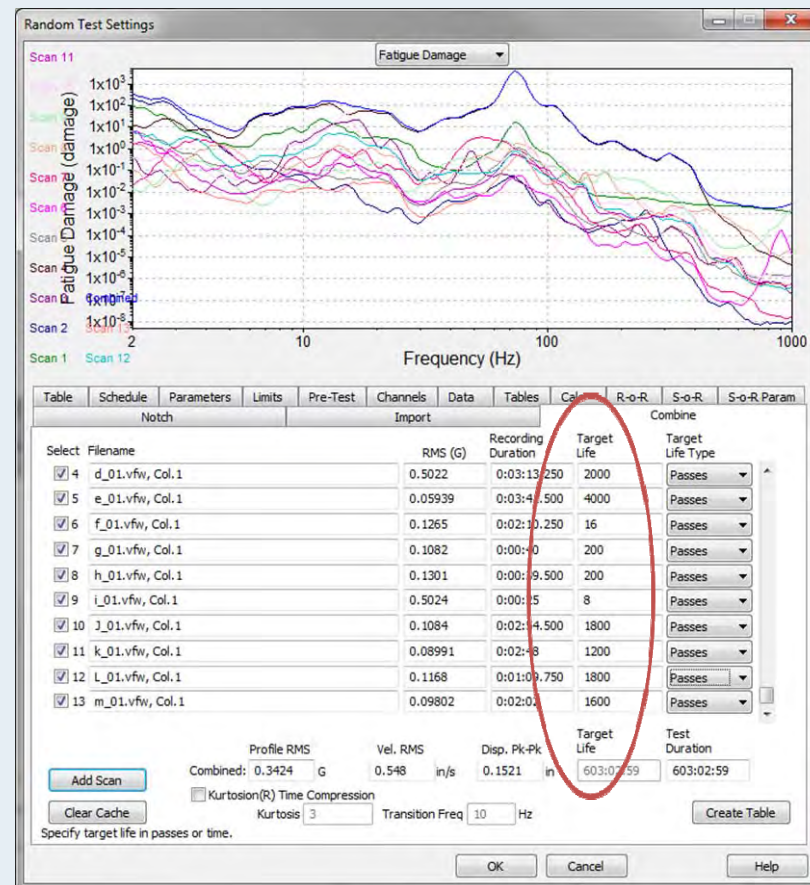
Setting Test Duration

- Total Target Life for combined test was 603 hr.

- GM desired a shorter test (16 hr test)
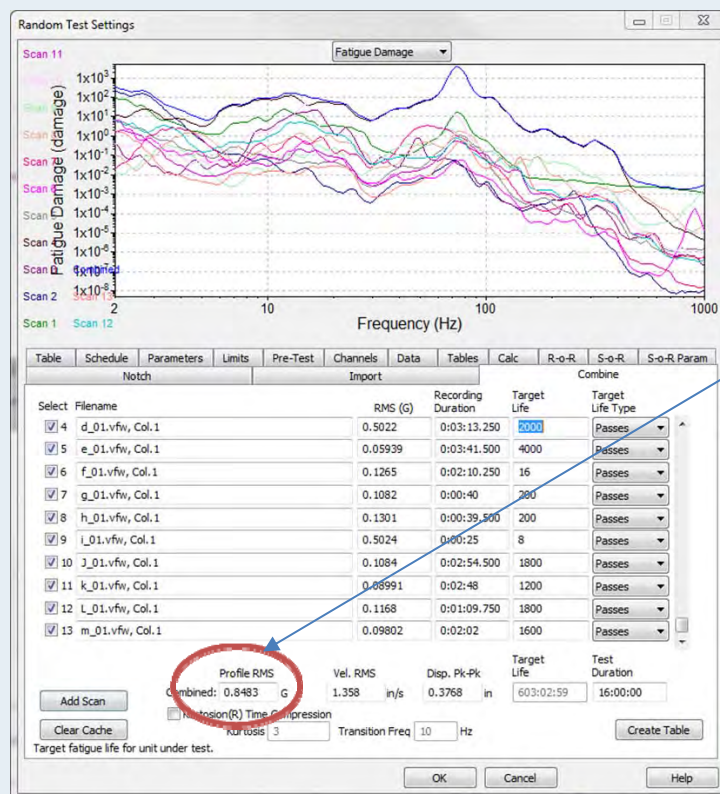
Note the increase in GRMS:
- From 0.3424 G to 0.8483 G
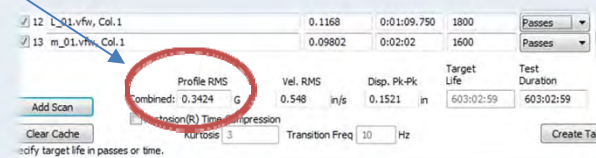
Q3: How to Use FDS & Kurtosion® to Accelerate a Test

- ## Accelerate a test:
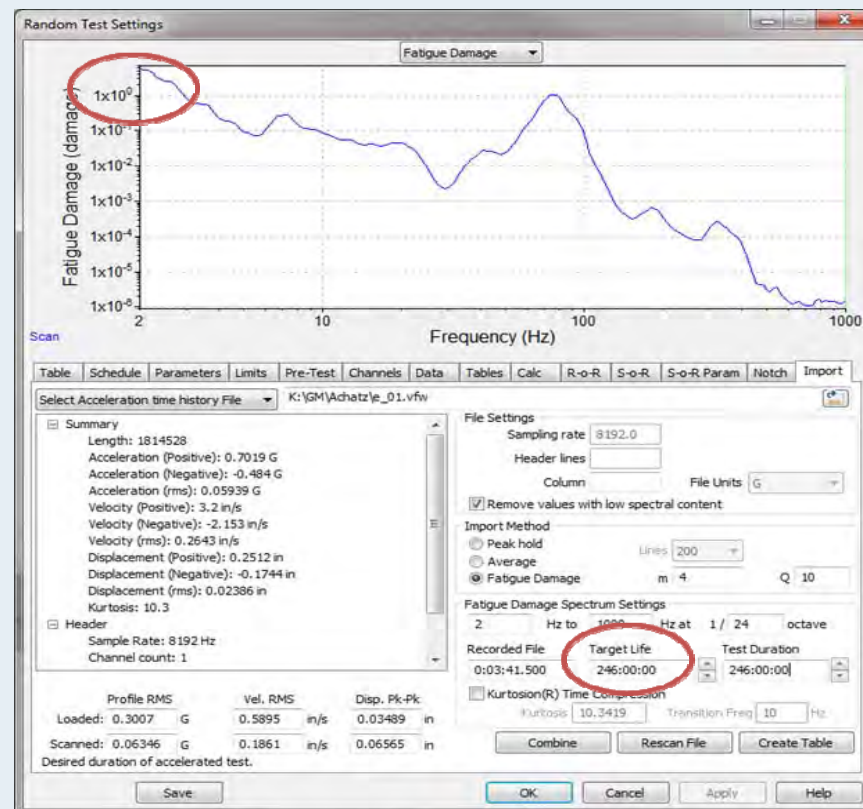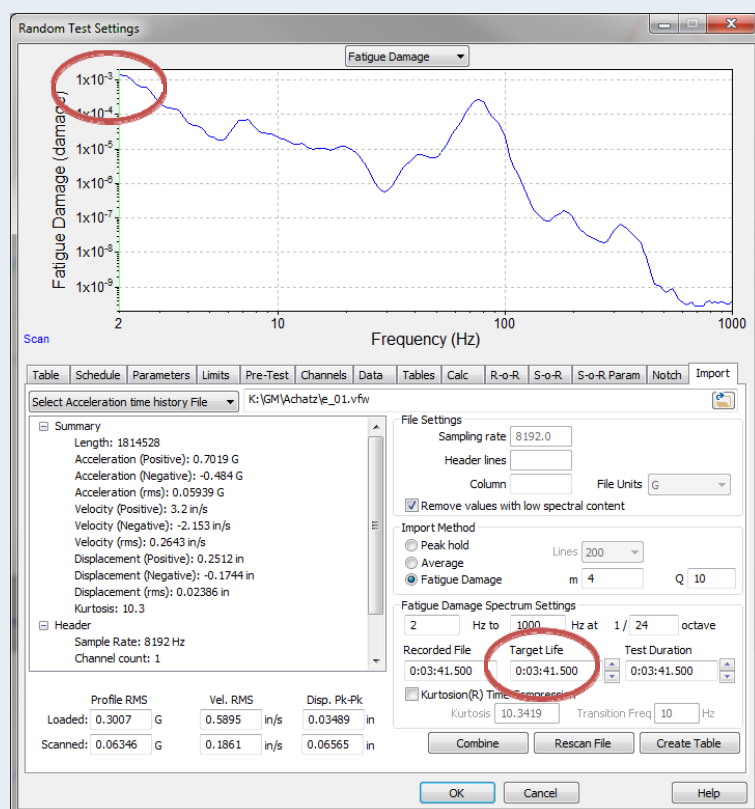 - ### – Use FDS

  - ### – Use FDS and Kurtosion®

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)**
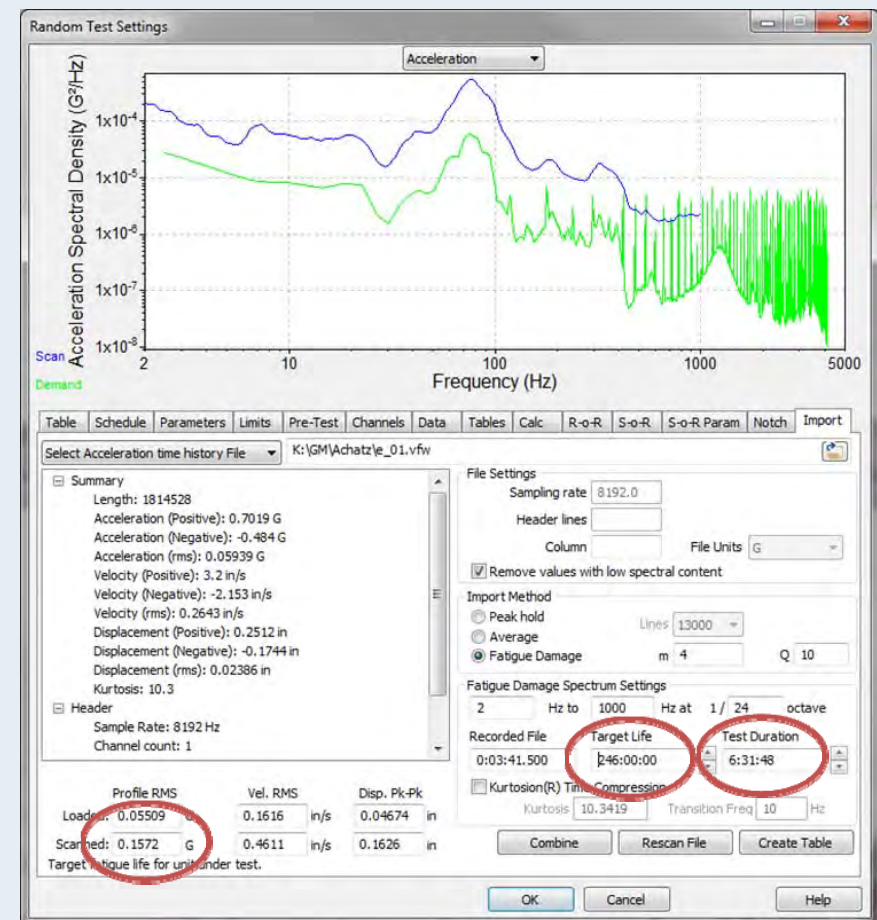
Accelerating Test with FDS

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

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)

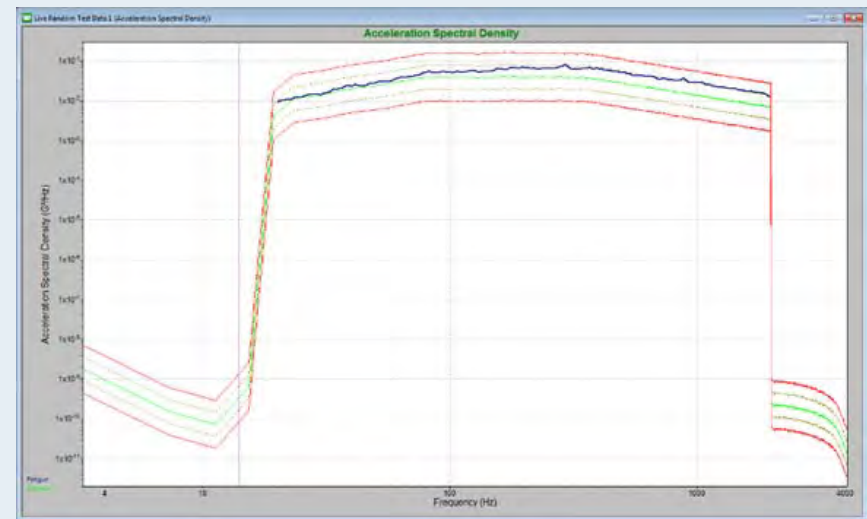# Using Kurtosion® with FDS to Accelerate a Test
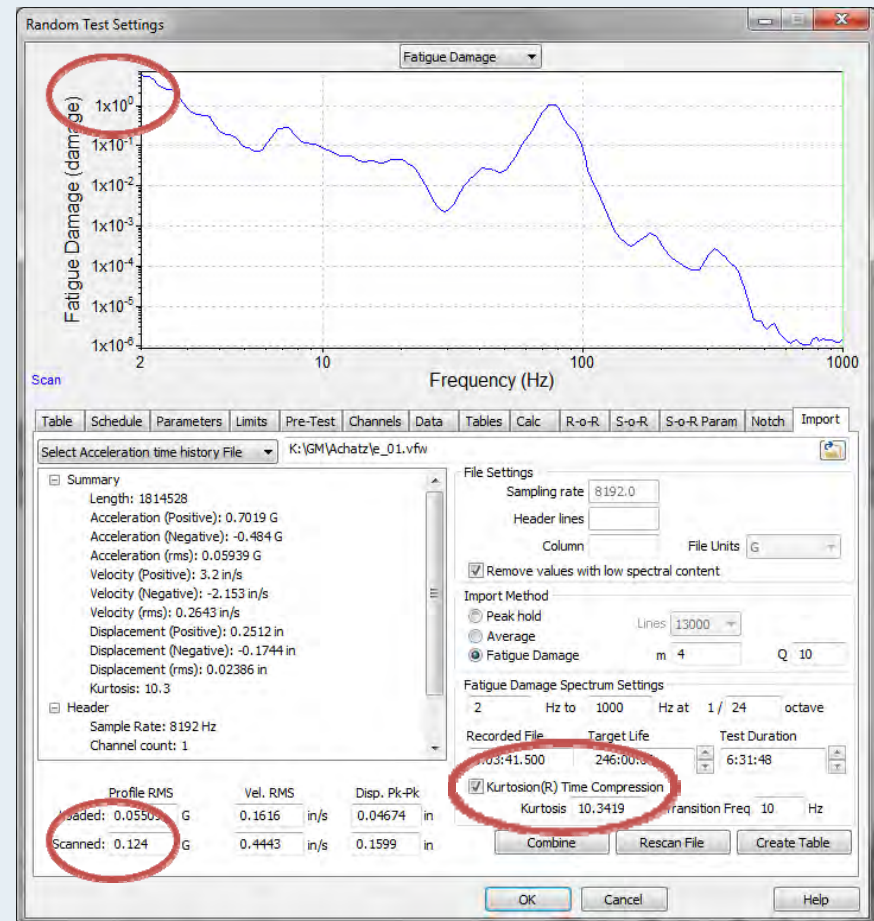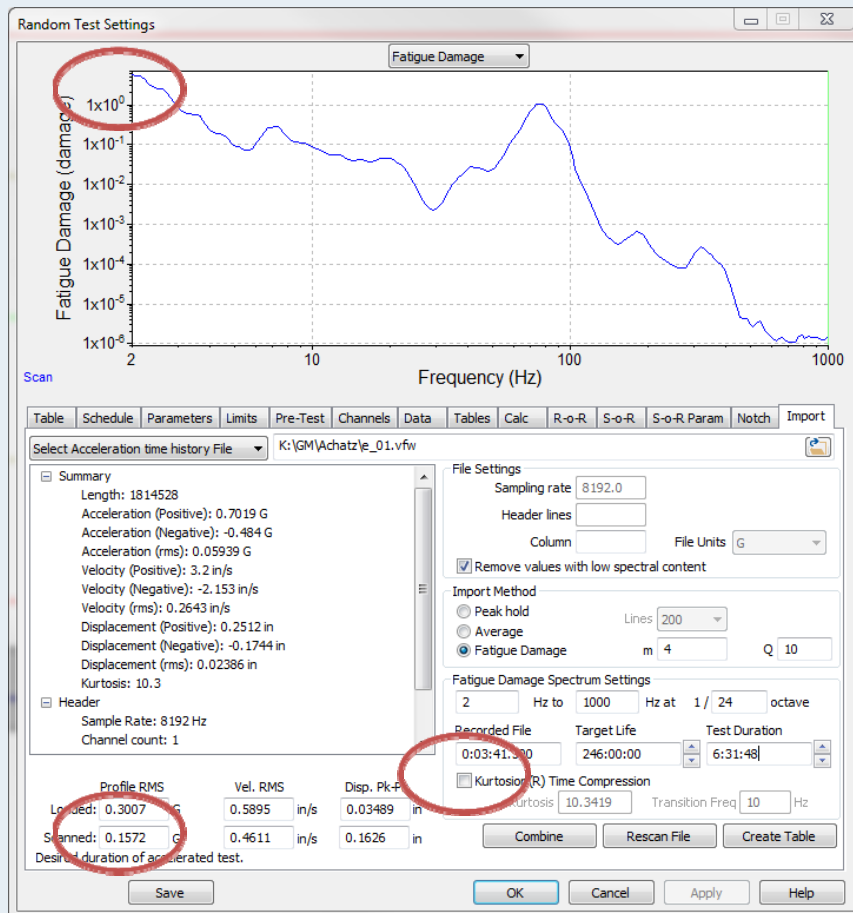
Kurtosion® Accelerates Test

- ## Kurtosion will NOT add to the fatigue
  - Fatigue bucket fills faster
  - Fatigue bucket fills with a lower GRMS level
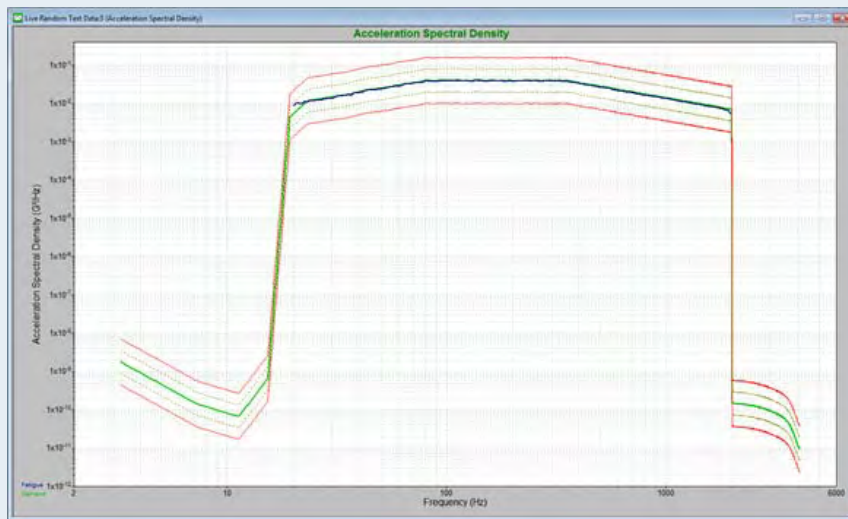
Navmat K=3

Navmat K=7

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®

QUESTIONS???