2014 Workshop on Accelerated Stress Testing and Reliability

Fatigue Damage Spectrum for Repetitive Shock Machines & the HALT-HASS Process

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BIO

- **President-Smithson & Associates since 1983**
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- **Publications**
  - **Effectiveness & Economics-Yardsticks for ESS Decisions—IES Proceedings 1990**
  - **Shock Response Spectrum Analysis for ESS and Strife-HALT--IES Proceedings 1991**
  - **A Viewpoint on Fatigue Metrics-- Benefits for HALT, HASS and More 10th Annual Workshop on Accelerated Stress Testing & Reliability, Chicago, October 2004 & Test Engineering & Management, August-September 2004**

- **Representing**
  - **Vibration Research**
  - **ETS Solutions**
  - **Vibration & Shock Technologies**
  - **Instrumented Sensor Technologies**

Trip Down Memory Lane

IEEE Components, Packaging, and Manufacturing Technology Society

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ASTR 2004

A Viewpoint on Fatigue Metrics-- Benefits for HALT, HASS and More

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Author's name | ASTR 2004 October 2004, Chicago Illinois | Abbreviated Title Page 2
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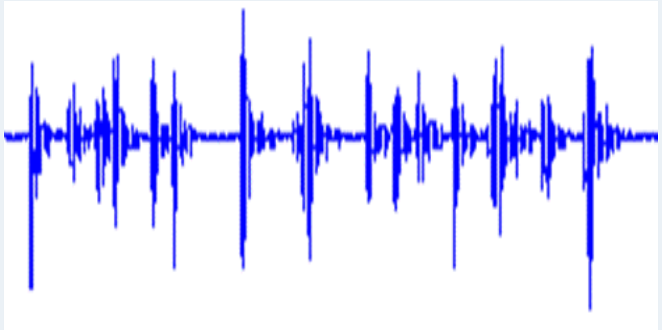
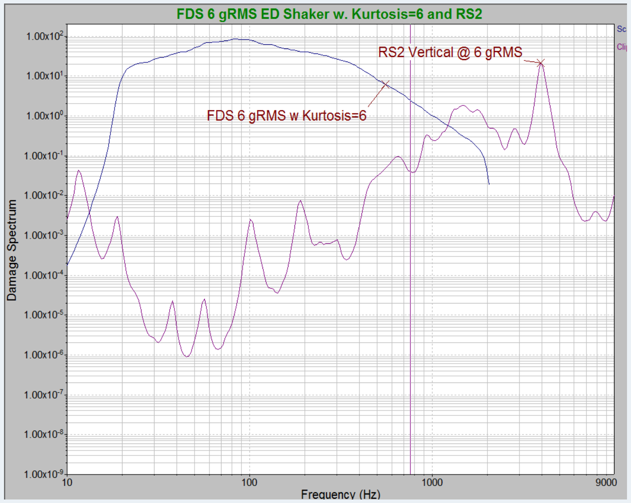
Abstract

- **Overcoming decades of shortcomings, applying a Fatigue Damage Spectrum (FDS) to Repetitive Shock (RS) machines used in HALT (Highly Accelerated Life Tests) and HASS (Highly Accelerated Stress Screening) provides an improved use and analysis. FDS can be used to benchmark RS excitations and product responses to correlate them with End-Use-Environments (EUE) and ED shakers, thus quantifying severities of different excitations for Analysis.**

Correlations Possible with FDS



$$FDS(f) = c\sum_{n=1}^{n_f} {\sigma_n}^b$$



Objective

To demonstrate Analysis applications of a relative cumulative fatigue damage metric for RS machines

That does not rely on the processing limitations inherent with traditional PSD and gRMS metrics:

- **Non-Gaussian**
- **Non-Stationary**
- **Overlap & Averaging of FFTs -- loss of peak data**
- **Strongly-mixed signals**

Benefits

FDS expands the benefits of RS machines and the HALT process by Quantifying:

- **EUEs and shaker excitations (RS and ED)**
- **Step stress levels, product strengths and margins, proof of screen, product responses and test compression**
- **Progress toward reliability and confidence goals.**
- **Analysis answers the questions–**
  - **“What are you doing to my product”**
  - **“When to “Stop HALTING”.**

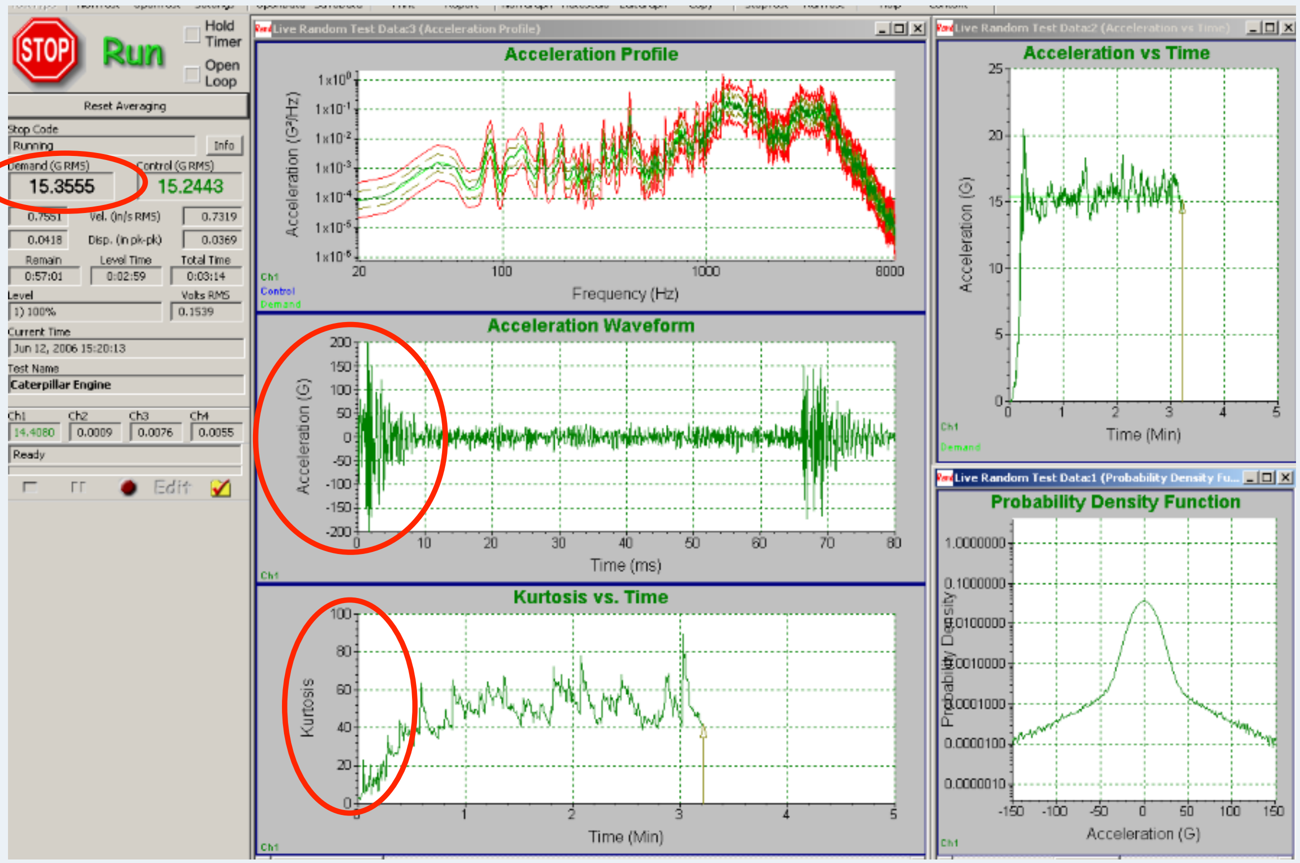
Must be a Spectrum

- **Be it for either control or Analysis, the FDS metric must be a spectrum with selectable frequency bandwidth and resolution**
- **Applies to all shaker types and EUE excitations and product responses—including acceleration and strain.**

$$FDS(f) = c\sum_{n=1}^{n_f} \sigma_n{}^b$$

Where *n* is the number of cycles counted by the rainflow algorithm at that frequency, and Total damage at every frequency is the sum of the individual damages due to the cycles at that frequency, where the individual damage due to every cycle is exponential based on typical S-N curves.

Accommodate Excitations



- Greatly different peak probability distributions (PPDs)—above gRMS=15, Kurtosis = 55
- Produce identical PSDs and gRMS
- Do not represent the severity of the excitation in terms of damage.

VIBRATION RESEARCH

Background

- **Dedication to a limited definition and purpose of the HALT process, "stimulate it, break it, fix it"**
- **Acknowledging "stimulate-not simulate" and the value of feedback and corrective action**

BUT,

- **No Analysis to relate the process, the test levels and the results to any other environments the product might see.**

Insufficient Metrics- 1

- **FFT-generated PSD is neither mathematically nor practically valid for the non-Gaussian, non-stationary excitations of repetitive shock (RS) machines.**
- **A spectral shape and a gRMS level are not sufficient to describe an EUE, test spec, or product strength (operating and destruct limits) or service life.**

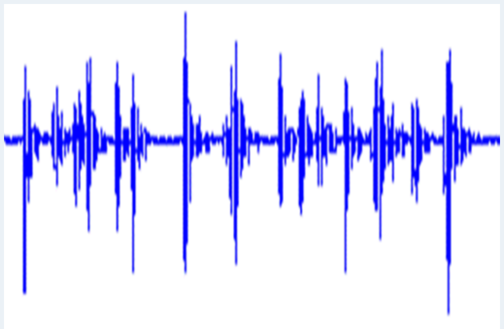
Insufficient Metrics- 2

- **PSD is a statistical snapshot of a random process, use of PSD (g^2/Hz) and gRMS lacks elements that correlate to failure mode, fatigue cycles, field exposure including amplitudes more severe than Gaussian.**
- **Does not lead to the reliability and confidence numbers (MTBF, MTBUR) or % of life used many seek from the HALT process.**

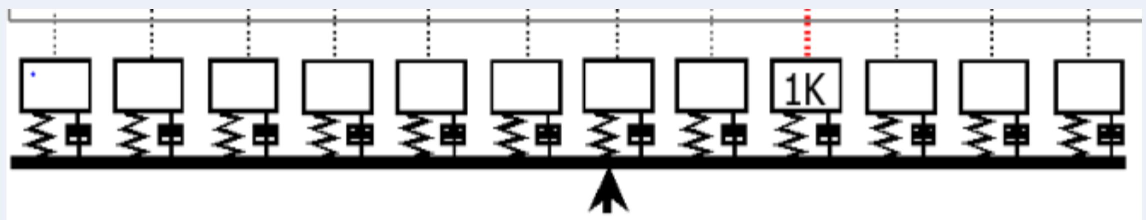
Caveats

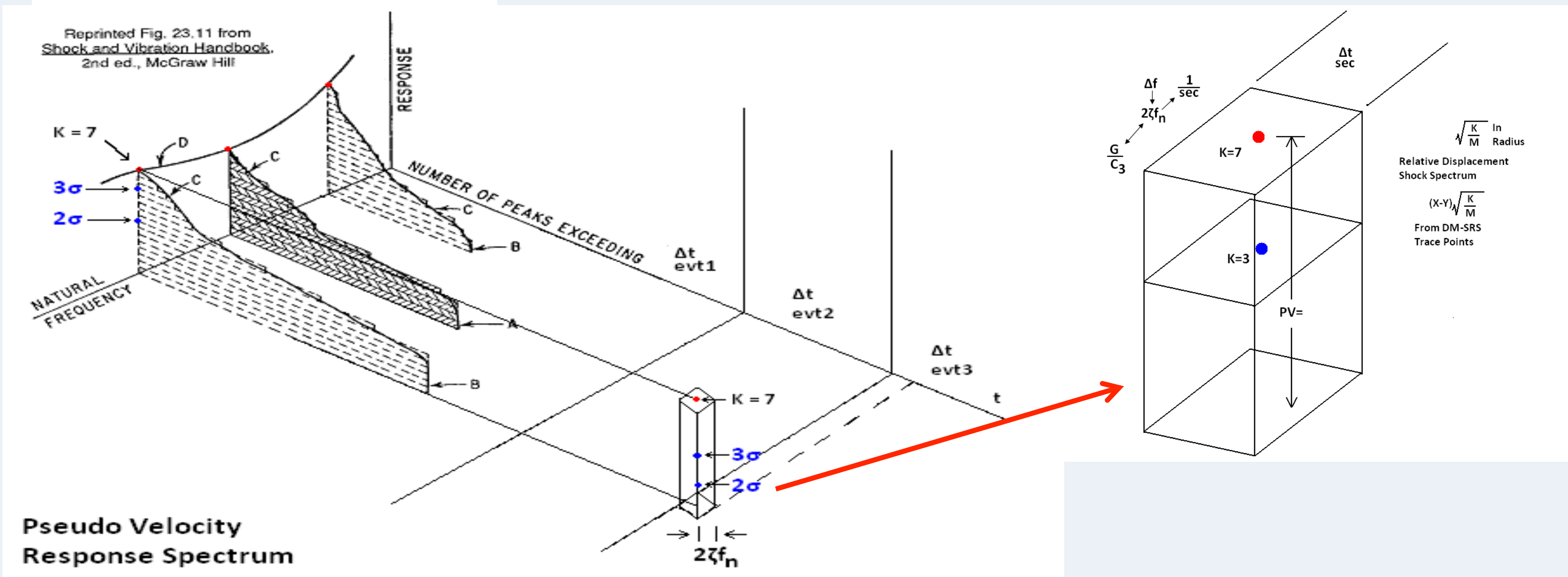
- RS machines RS1, RS2 & RS3 are of different manufactures, vintages and designs. Their common feature is a 48" x 48" table.
- RS "control" was on table bottom for RS1 & RS2 and near top table center for RS3.
- This exercise is NOT a Comparison of HALT system designs or manufacturers, but demonstrates a better method for doing so and quantifying relationships long ignored. FDS could be used for such.
- Unless expressly stated, reference to HALT denotes the HALT process and NOT just Repetitive Shock (RS) machines
- Both the PSD and the FDS lose relationships of phase and ordering of stress cycles so FDS is NOT a replication tho FDS yields an equivalent damage.
- FDS is a means of generating a statistically more accurate random test based on cumulative damage from multiple field exposures. Summing PSDs using enveloping or a Mil-Spec formula still rely on PSD and gRMS shortcomings.

Graphical Description of the FDS



SDoF-RIRDF





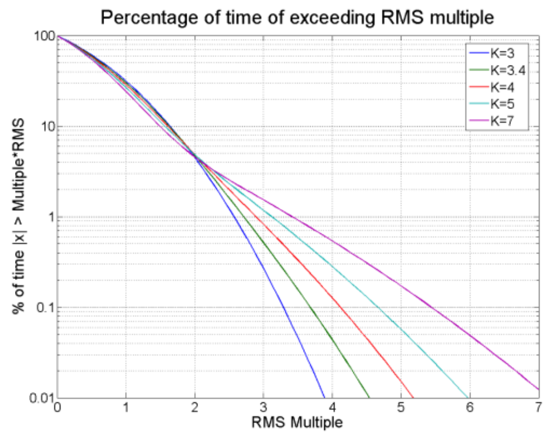
Crest Factor -- Kurtosis Relationship

Increased kurtosis = More time at peaks

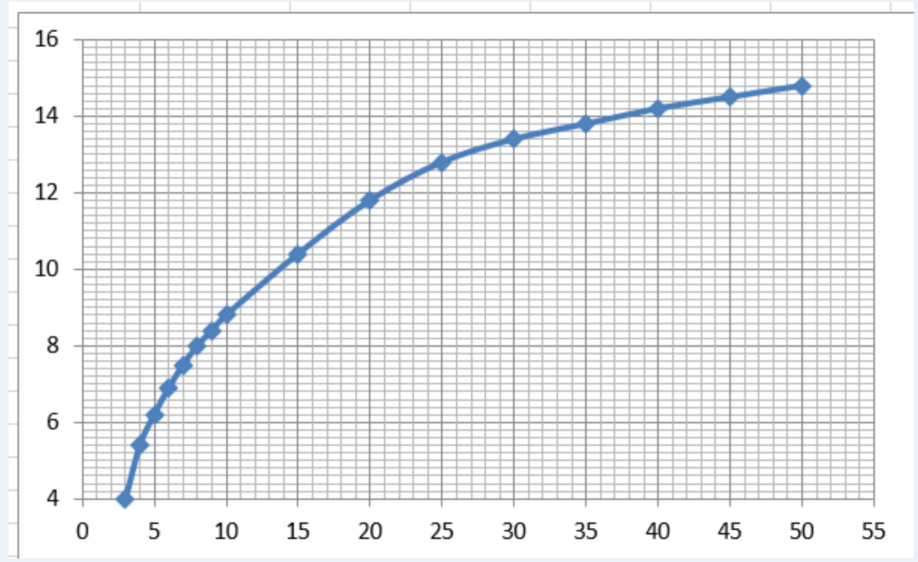
Kurtosis = 3 is > 3σ
0.27% of time

Kurtosis = 4 is > 3σ
0.83% of time

Kurtosis = 7 is > 3σ
1.5% of time



Note: 1.5% of a 1 hour test is nearly a full minute above 3σ



$$k = \frac{\frac{1}{N}\sum\left(x_i^4\right)}{\left(\frac{1}{N}\sum\left(x_i^2\right)\right)^2}$$

****Kurtosis is the 4th statistical moment about the mean of a data set. The Mean is the 1st, the standard deviation the 2nd and skewness the 3rd. Kurtosis describes the "peakiness" of the data and is described by the tails of the PPD and reflects a higher incidence of higher peak amplitudes.**

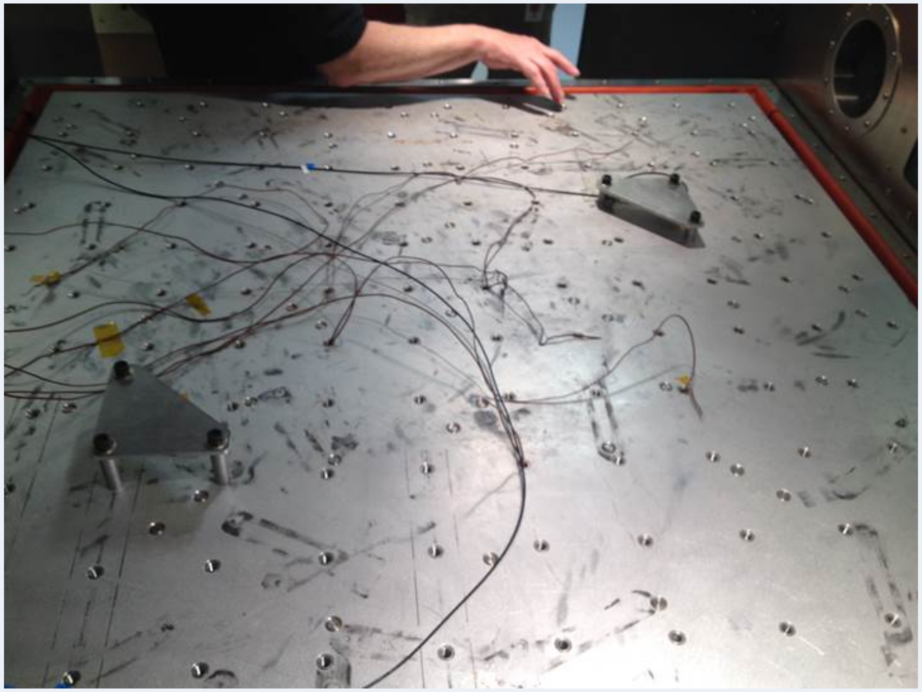
Test Set-up and Equipment

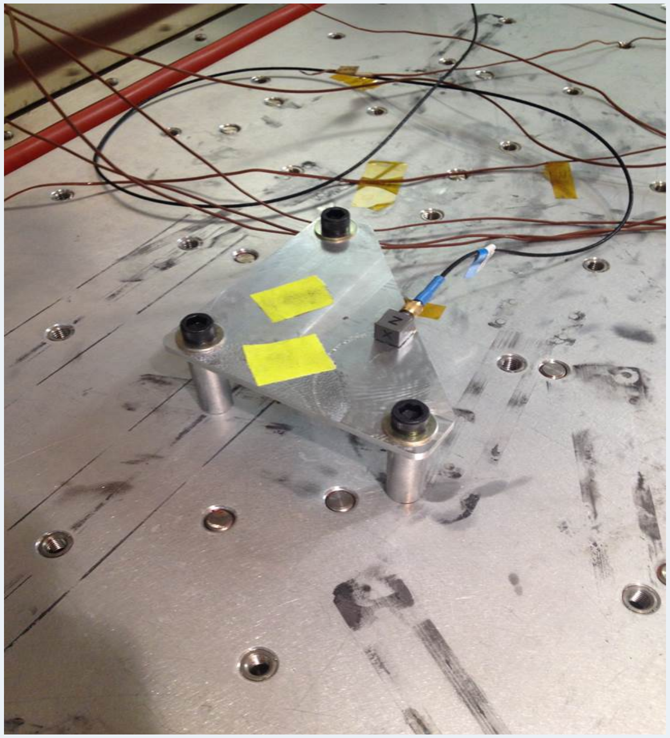
- The early characterization of RS table performance was conducted by the late George Henderson, President of GHI Systems. George incorporated a triangular fixture with stand-offs for the accelerometer mounting. George did a gRMS table spatial survey.—showing 35:1 variation in z-axis gRMS and 10:1 variations in x-y balance, again in gRMS

- To allow and accommodate the beneficial variations in RS machine excitation due to hammer configurations, rep rates and table dynamics, this exercise utilized thinner, resonant-rich plates on 1" and 2" stand-offs (picture 1), to emulate the "equally compliant" fixtures--long-recommended for pneumatic RS machines and to act as simulated product mounting points.

- Data Sampled at 100 kHz for 5 minutes for each Setpoint and Fixture

RS Table & Fixtures





VR9500 Revolution – 8 Channel

Triangle fixtures F1 and F2 recorded 5 minute histories from 2 Dytran triaxes and the "control" accel from each RS machine used for closing gRMS setpoint with air pressure.

Time histories were streamed to the pc hard drive via VR9500s RecorderView.

Recorded Raw Data

			Z Axis Acceleration Readings on RS1, RS2 & RS3								
	Setpoint	6 gRMS		10 gRMS		20 gRMS		30 gRMS		50 gRMS	
Machine	Location	g RMS	g pk +/-	g RMS	g pk +/-	g RMS	g pk +/-	g RMS	g pk +/-	g RMS	g pk +/-
RS 1 Z Axis /	Fixture 1	14.26	443/442	32.41	262/279	37.82	422/434	103	981/727	N/A	N/A
	Fixture 2	19.38	399/350	40.05	241/230	75.2	447/452	105	784/822	N/A	N/A
	Kurtosis	K1=	8.36	K1=	4.32	K1=	6.73	K1=	3.96	K1=	N/A
		K2=	6.53	K2=	3.66	K2=	3.3	K2=	4.16	K2=	N/A
RS 2 Z Axis	Fixture 1	10.35	117/118	19.9	217/213	39.7	467/402	64.22	602/636	113	1000/923
	Fixture 2	6.35	88/86	12.48	147/145	31.7	387/321	51.56	624/521	103	1115/902
	Kurtosis	K1=	14.5	K1=	8.24	K1=	6.17	K1=	5.28	K1=	5.01
		K2=	14.2	K2=	9.19	K2=	6.02	K2=	5.91	K2=	5.63
RS 3 Z Axis	Fixture 1	15.4	89/82	24.05	137/119	41.6	418/402	55.5	410/443	52.4	1073/854
	Fixture 2	25.1	140/140	41.7	206/210	73.7	406/399	102	637/560	156	830/776
	Kurtosis	K1=	3.11	K1=	3.09	K1=	3.39	K1=	3.17	K1=	3.8
		K2=	3.29	K2=	3.03	K2=	3.03	K2=	3.04	K2=	3.06
Machine	Location	g RMS	g pk +/-	g RMS	g pk +/-	g RMS	g pk +/-	g RMS	g pk +/-	g RMS	g pk +/-
ED Shaker	Fixture 1	6.1	27/29	10	52/52	20	98/93	31	157/159	50.04	249/246
	Kurtosis*	K1	3		3		3		3		3

Table summarizes Z (vertical) axis acceleration data as excitation and responses coincident with the RS machine "control" accelerometer.

RS2 and RS3 50 gRMS setpoints over-ranged the triax accels

Observations—Raw Data

- The RMS levels of the RS machine excitations varied significantly from the desired “control” or setpoint
- The positive to negative g peaks far exceeded the Gaussian range expected from a random excitation. Hence the RS or Repetitive Shock designation for the machines producing a series of damped transients.
- For RS1 and RS2, kurtosis values exceeded the K=3 of a Gaussian peak probability distribution (PPD).
- For RS3, the kurtosis values indicate a more Gaussian PPD and compare with the ED shaker at the same gRMS setpoints.
- The variations in responses of Fixtures 1 & 2 emphasize the critical dependency on the geometry, stiffness and resonances of the unit under test (UUT) AND location on the RS table.
- Kurtosis values are reasonably consistent between Fixtures 1 and 2 at each gRMS setpoint level for all 3 machines.

FDS Values

		RS2--- Input "Control" & Responses				
		Fixture 1 with 1" Stand-offs				
Setpoint						Combined
		CONTROL	X1-Ch2	Y1 Ch3	Z1 Ch 4	X1+Y1+Z1
6 gRMS		110	125	64	74	263
10 gRMS		570	433	414	1175	2019
20 gRMS		6596	11321	8829	30559	50709
30 gRMS		36938	102661	62059	225923	390643
50 gRMS		116808	236245	236245	1700371	2172861
		Fixture 2 with 2" Stand-offs				
		CONTROL	X2 Ch 5	Y2 Ch 6	Z2 Ch 7	X2+Y2+Z2
6 gRMS		110	124	516	601	1242
10 gRMS		570	841	516	601	1959
20 gRMS		6596	30559	18180	10386	59126
30 gRMS		36938	147632	89835	252272	489740
50 gRMS		116808	587214	337916	2380313	3305443

Cells represent the FDS sums for 2 fixtures:

- 5 minutes @ each Setpoint
- X, Y & Z + Combined
- Non-linear w. set-points due to hammer rep rates, table and fixture geometry & structure and # cycles of rep rate harmonics

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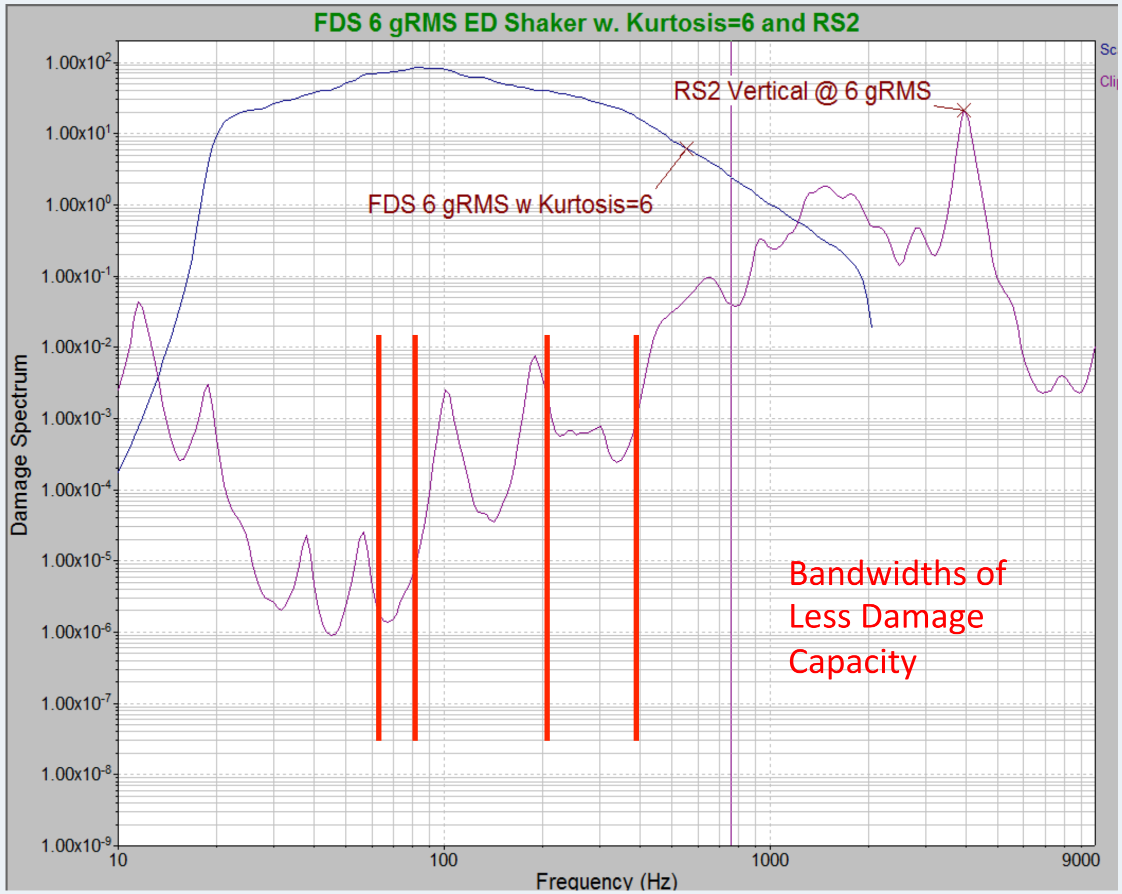
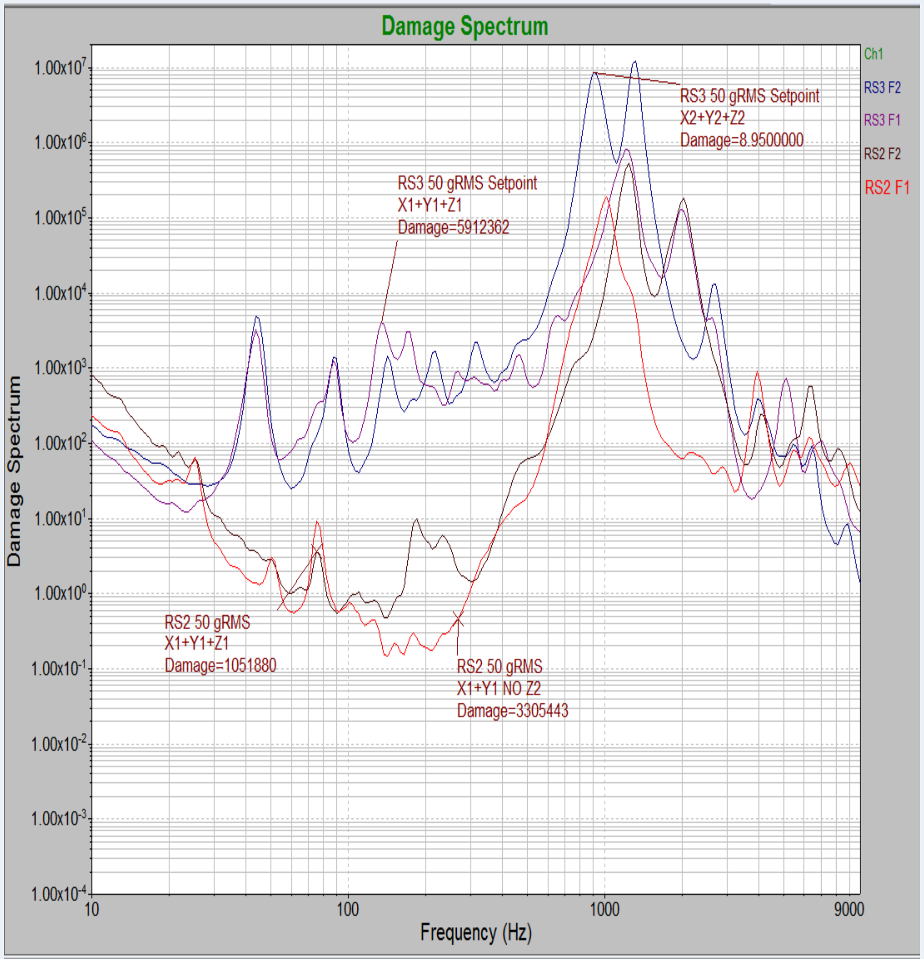
ED Shaker and RS Machine-Basic Comparison

- ED NAVMAT 6 gRMS
- Damage Cross-over is approx 1300 Hz.
- Different bandwidths excited by ED & RS machines.
- Compare With UUT frequency response plots.

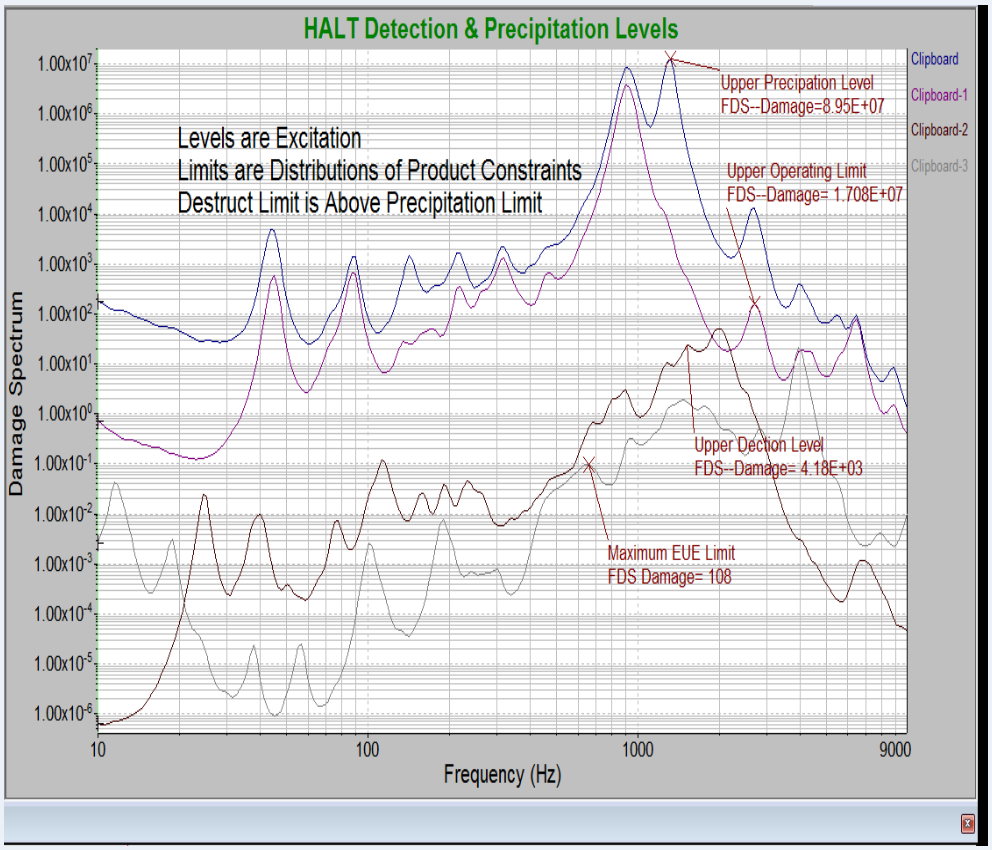


Combined X, Y & Z FDS w. Damage Sums

- FDS for RS2 & RS3 @ 50 gRMS setpoint with Damage Sum.
- Damage Sum the sum of all points on the FDS -- broadband or selected bandwidths.
- The “volume integral” described above and is a global indicator of the total damage
- Tool for comparison with other RS machines, ED shakers, EUEs and test specifications.

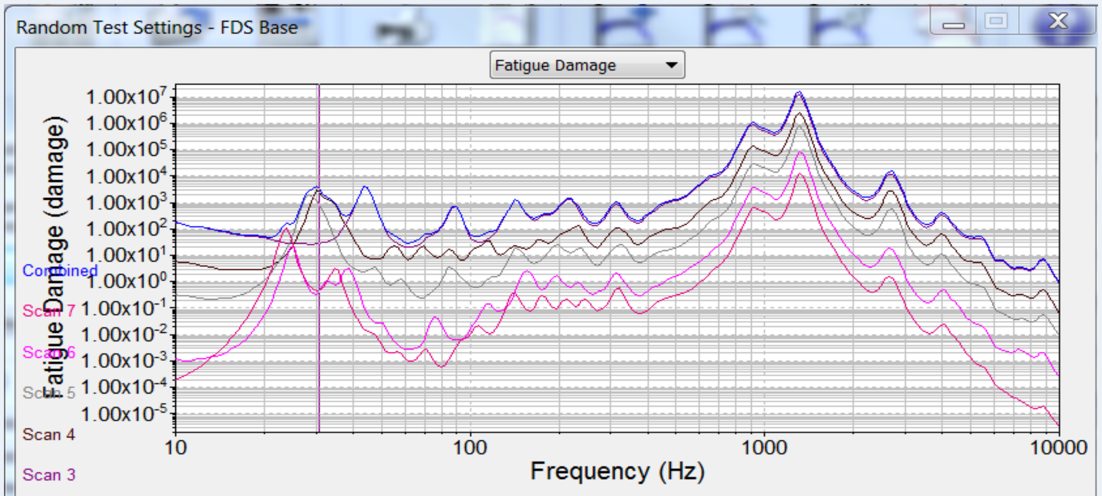


Detection Levels & Precipitation Limits



- **Step Stress Levels can be related to the Detection and Precipitation screen in terms of damage via the FDS.**
- **Proof of screen and UUT exposure to HASS levels can be generated as a % of the cumulative HALT damage achieved.**
- **Or, as a % of cumulative life model derived from multiple time histories and weighted proportions.**

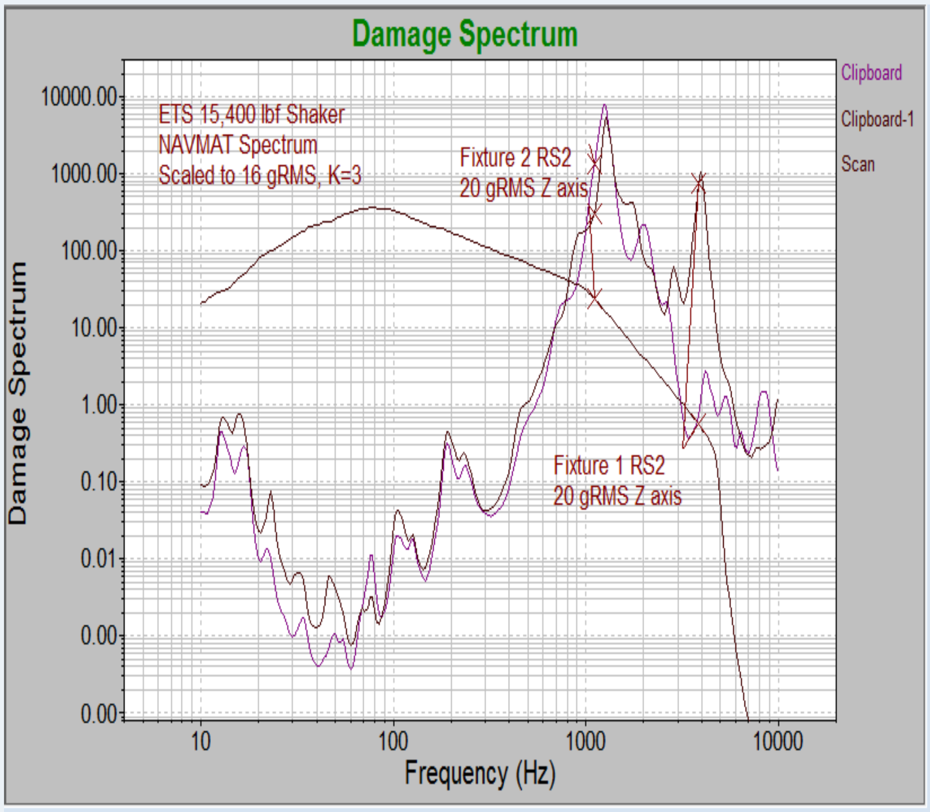
Step Stress 6, 10, 20, 30 & 50 gRMS + Combined



Select	Filename	RMS (G)	Recording Duration	Target Life	Target Life Type
☐ 1	NAVMAT 6gRMS.vfw, Col.1 Ch1X1	7.477	0:05:29.799	0:05:29.799	Time
☐ 2	NAVMAT 6gRMS.vfw, Col.4 Control Z	6.074	0:05:29.799	0:05:29.799	Time
☑ 3	Element 50gRMS.vfw, Col.4 Ch4 Z2	156.1	0:05:00.115	0:05:00.115	Time
☑ 4	Element 30gRMS.vfw, Col.4 Ch4 Z2	102.2	0:05:00.366	0:05:00.366	Time
☑ 5	Element 20gRMS.vfw, Col.4 Ch4 Z2	73.73	0:05:00.222	0:05:00.222	Time
☑ 6	Element 10gRMS.vfw, Col.4 Ch4 Z2	41.17	0:05:00.076	0:05:00.076	Time
☑ 7	Element 6gRMS.vfw, Col.4 Ch4 Z2	25.11	0:05:00.084	0:05:00.084	Time

- **Combined trace is the “global” sum of the damage from 6, 10, 20, 30 and 50 gRMS setpoints for RS machine 2, analogous to the gRMS power of a random test.**
- **Documents a HALT step stress progression in terms of damage. Also product responses.**
- **With powered and monitored product and outputs, product failure or parameters exceeding acceptance limits can send an alert of “Limits Exceeded” or abort the test**
- **Cumulative damage to time of failure or limit exceedance..**

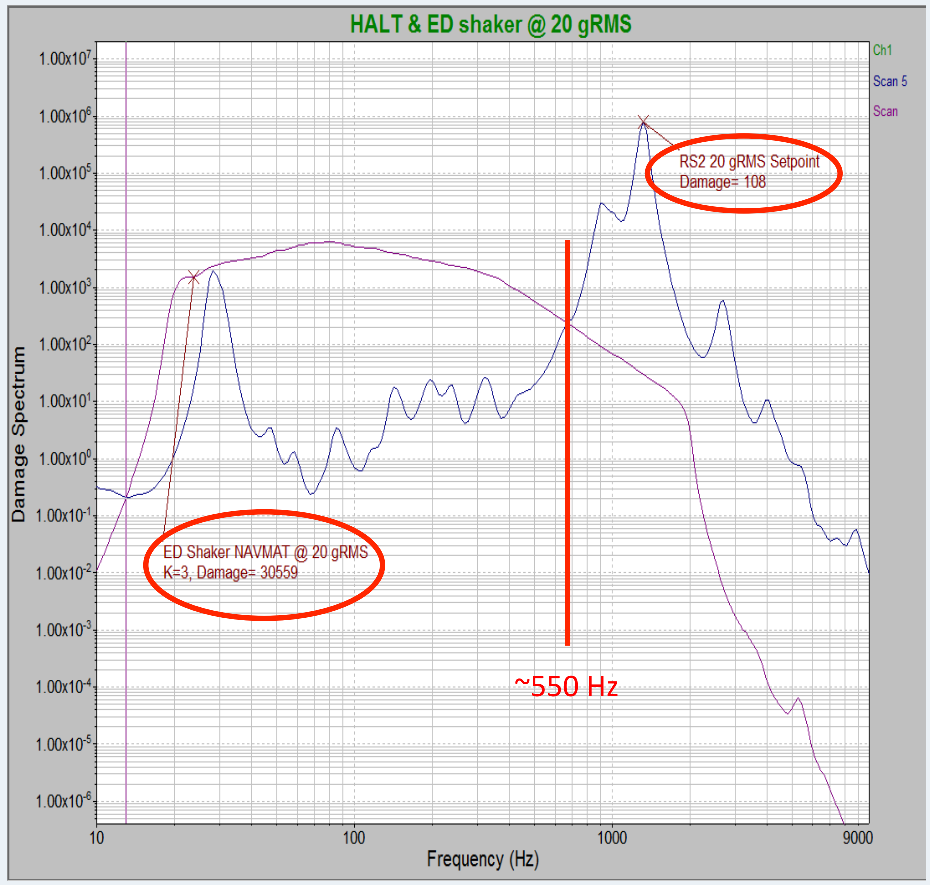
RS2 at 20 gRMS vs. NAVMAT to 4000 Hz at 16 gRMS



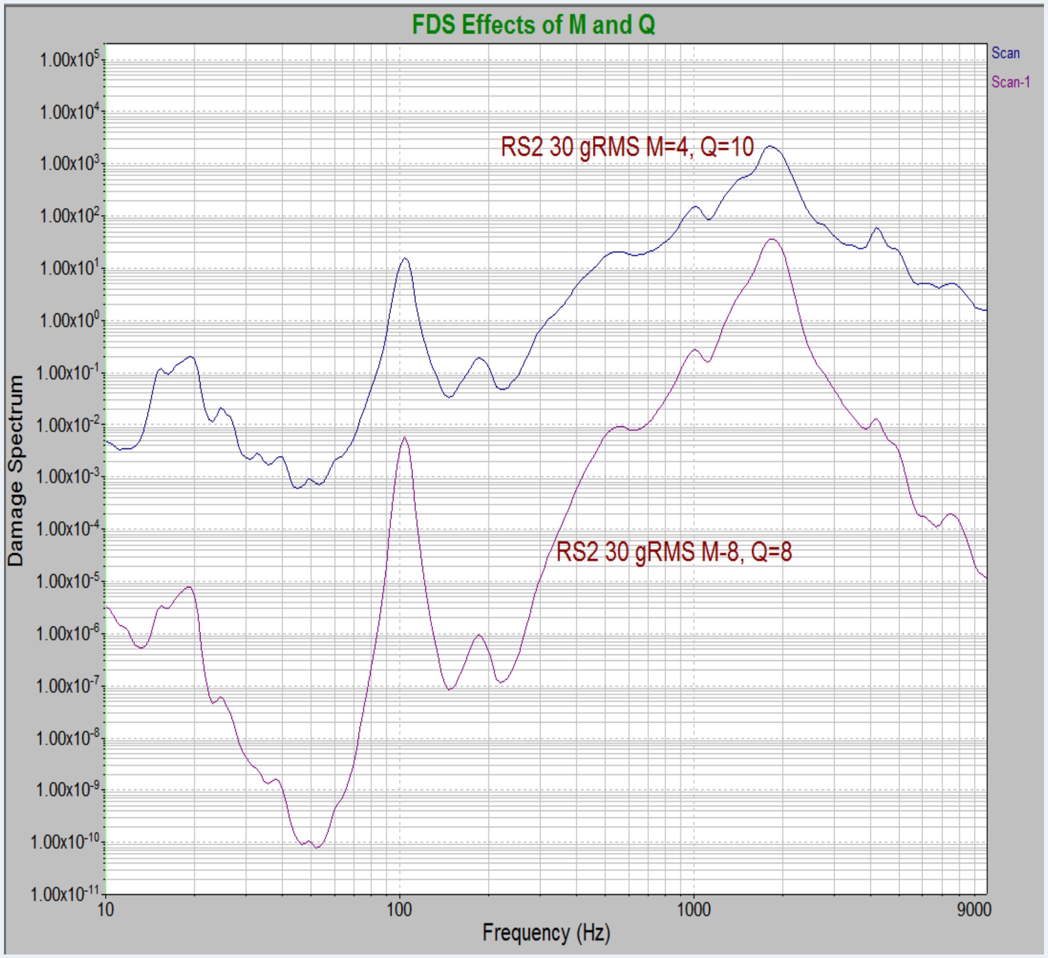
- FDS of NAVMAT “haystack” spectrum on an ED Shaker @ 6 gRMS K=6 to 4 kHz compared with RS2 @ 6 gRMS.
- The frequency bandwidths to excite UUT Resonances differ significantly. Damage cross-over is approximately 1300 Hz

RS2 at 20 gRMS vs. NAVMAT ED at 20 gRMS,with K=3 and Damage Summed

- HALT & ED Shaker @ 20 gRMS and with Kurtosion=3. Damage Summed.
- Damage cross-over at approximately 550 Hz.
- ED shaker RMS power, extending to 2500 Hz
- Kurtosis and gRMS can be adjusted to achieve maximize or equivalent damage.

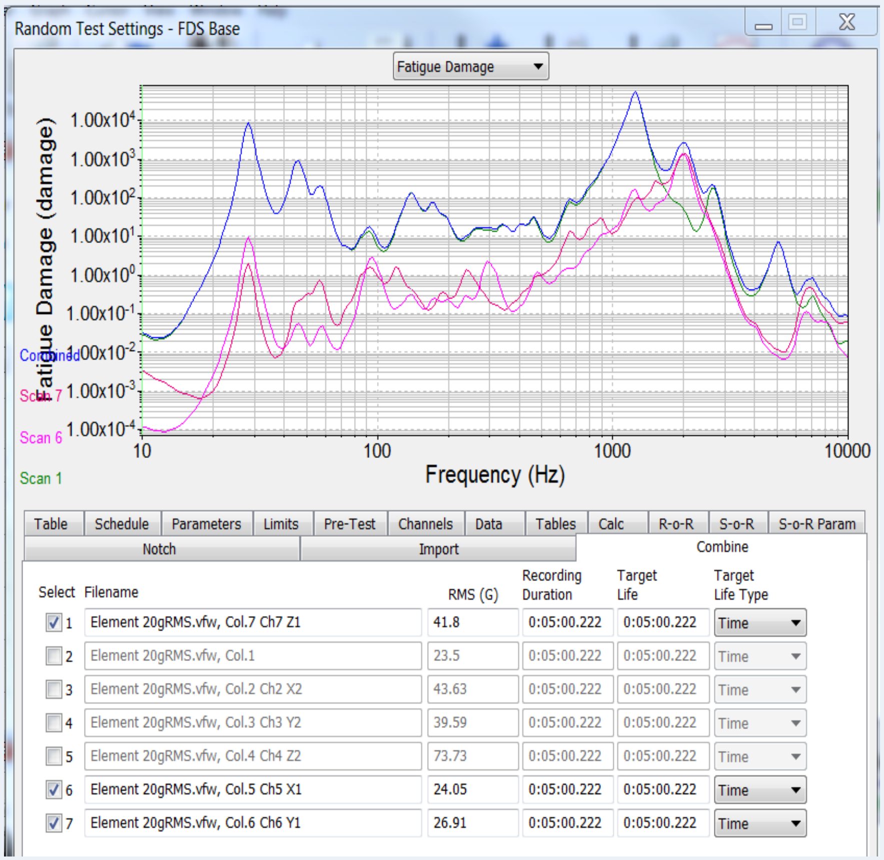


FDS for Assembly Input & Response



- Select “m” & “Q” specific to assembly material & resonances @ UUT Location
- Compare response w. input across Mounting Brackets
- Shown: same time history, vary “m” and Q”
- An FDS Transmissibility—use bandwidth cursors

Global 3 Axis Damage



- Combining the FDS damage traces from orthogonal axes (X1+Y1+Z1) provide a global indication of the 3 DoF severity of RS machines.
- The summation includes cross-coupling between axes, but still presents a spectrum.
- The UUT structural stiffness, resonant responses and damping remain variables in the path to a more precise solution.
- The UUT response functions can be compared with the excitations to identify resonant response bandwidths of potential damage.

Recommendations

- For data acquisition and analysis, a Vibration Research VR9500 and 4 channel ObserVR operate on the same software modules.
- RS machine control can be accomplished using VR9500 with output modified for interface for i/p valve. Use channel averaging or extreemal tho UUT exposure due to table variances should be managed using FDS updates.
- Higher channel counts for comprehensive table mapping, fixture analysis and UUT response.
- The FDS tool can be of value quantifying simultaneous 3 axis ED shaker proposed for HALT processes on product not sufficiently stimulated by RS machines.
- FDS can be used to evaluate cross-axis inputs from ED shaker with different suspensions.
- Should designer engineers and Physics of Failure (PoF) investigators pursue relative contributions of RS machine cross-axis and rotational inputs, product and component assembly responses can be evaluated.

The Big Recommendation

Ford Mustang Fuel Rail EUE

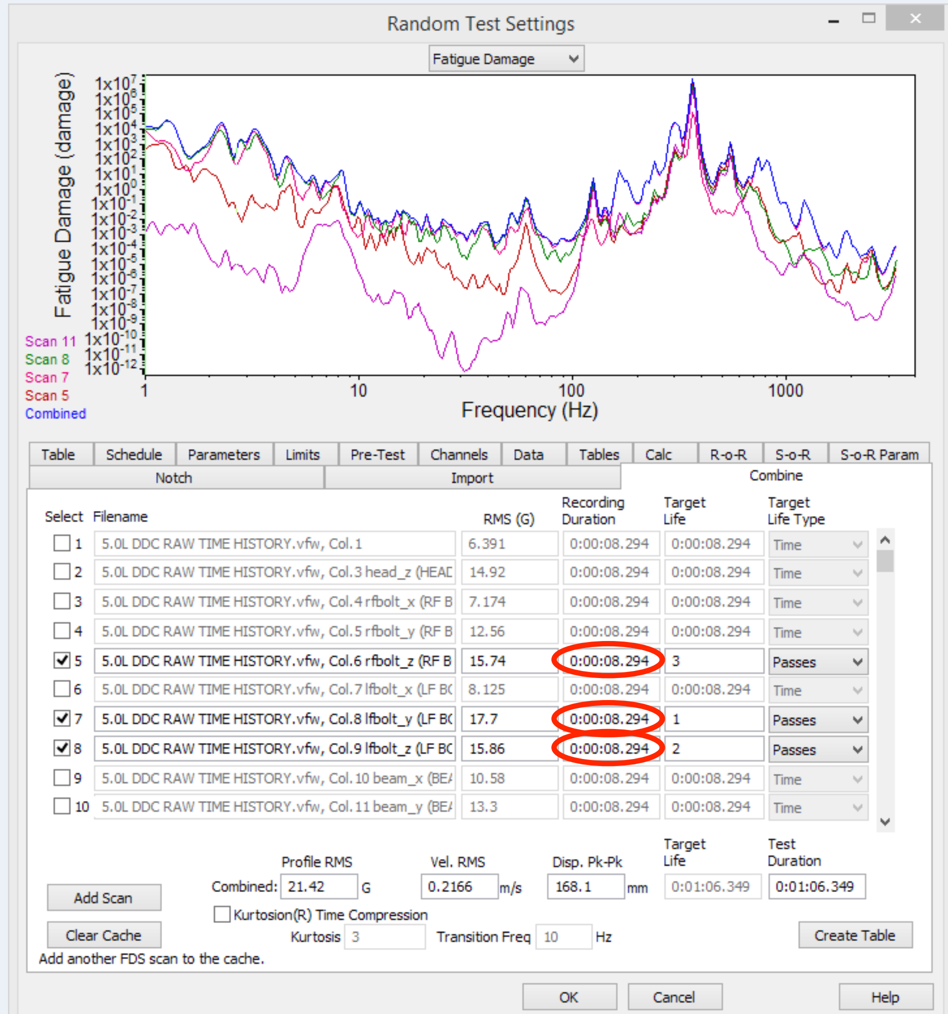
Product vibration specs be augmented in terms of FDS– cumulative damage incorporating EUE kurtosis and cycle- counting.

A Gaussian spectrum can be generated from FDS and Kurtosion© re-introduced.

The approach improves test tailoring, eliminates the shortcomings of PSD and attendant gRMS metrics and is applicable to EUE and shaker excitations.

Based on velocity, FDS is proportional to stress and accommodates multiple EUEs and weighting for duty cycle. It applies to strain as well.

Suggested Field Exposure for Customer Profile



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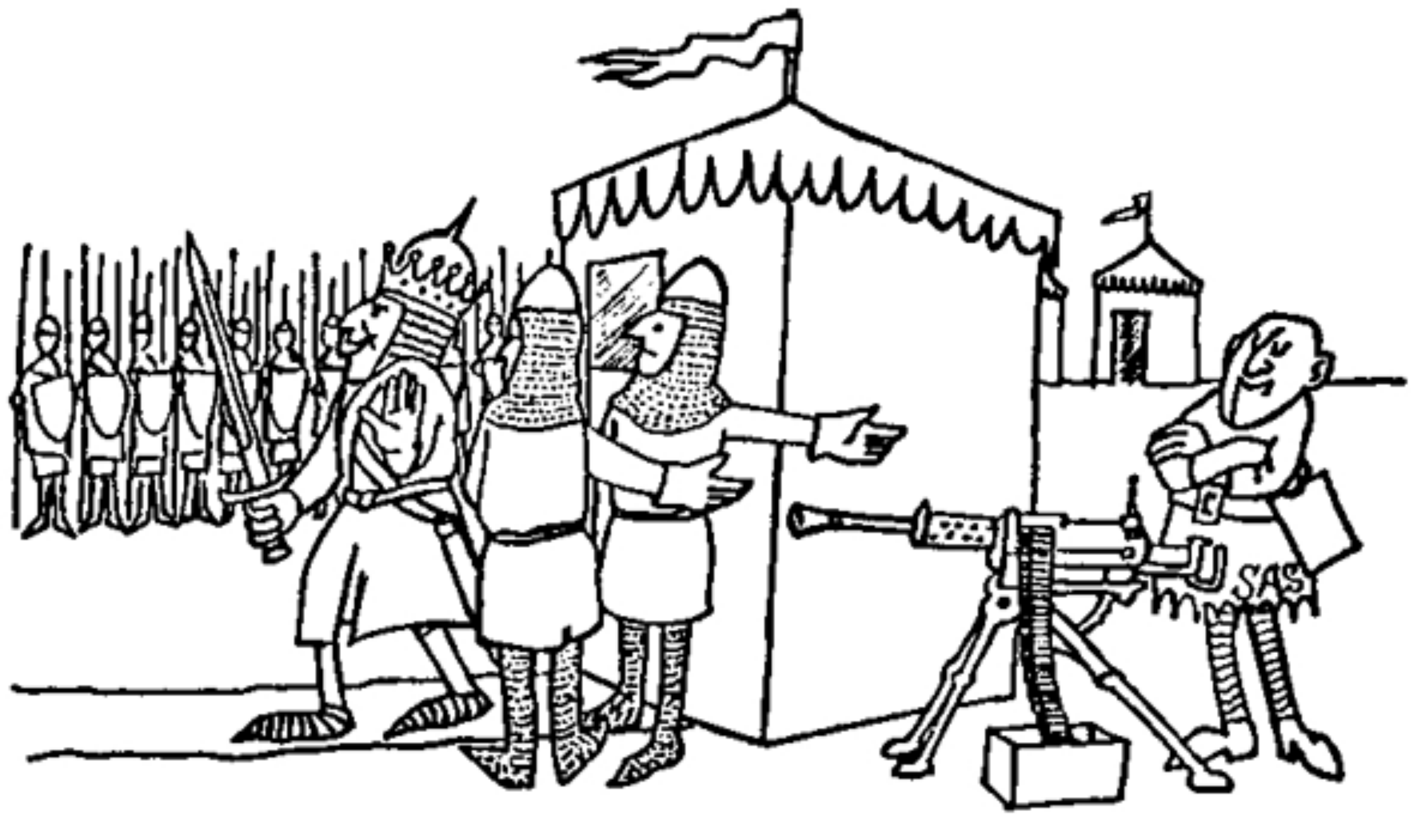
Thank You



"No! - I can't be bothered to see any crazy salesman - we've got a battle to fight!"