Applications of the Damage Sum, Σ_{FDS}

This paper offers applications for what I've called the damage sum or Σ_{FDS}, the sum of all points on the FDS plot: a single number measure of cumulative damage of a fatigue damage spectrum. Allows a top-level, global comparison of the relative severity of excitations and end-use Environments (EUE). Applicable to FDS generated from one or more time histories.

Other **single value metrics are standardized for relating objective measurements and subjective evaluation of dynamic data.** Depending on application, p**ractitioners "think" in terms of gRMS, SEAT Number, Zwicker Loudness or Richter scale, for which complex or spectral information is summarized with a single number.**

If the question is "Can a single metric be of value characterizing the information contained in a spectrum?" One answer, as implemented by Henderson for the DP(f) introduced in 1995. 1995 Ref DP(f) was conceived for comparative analysis had two interpretations applied, micro and macro DP(f). The FDS and Σ_{FDS} have similar interpretations depending on objectives. Only the input parameters, the "m" and Q are different to accommodate the two objectives. Otherwise, they are calculated exactly the same. The first interpretation is the "micro" Σ_{FDS}, used to develop narrowband test profiles of estimated or field-equivalent damage when specific failure mode, material and self-resonant characteristics are known. JVB article-Ford Case study

The second interpretation calls for a "macro Σ_{FDS}, which is used to characterize the cumulative damage of a broadband FDS of one or more time histories. For this macro Σ_{FDS}, "m" and Q values should be kept conservative and constant for global comparison purposes. Henderson also began with a DP(f) RMS for the cumulative metric, but neither the DP(f) nor the FDS is a power spectrum because both include weighted vibration exposures and rainflow cycle-counted summations. Henderson changed to a $DP(f)_{AVG}$ because the RMS is defined as the root of the area under the spectrum. Further, the Henderson-Piersol DP(f) was PSD-based and the DP(AVG) ends up being an average of ensemble-averaged FFTs.

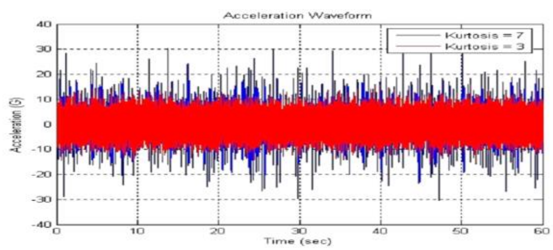
As reviewed below, there is no need to integrate the FDS to get the cumulative damage potential, Σ_{FDS} because it is not normalized per unit analysis bandwidth. This focuses on damage variances with frequency of the FDS as a spectrum when considering more predictive decisions.

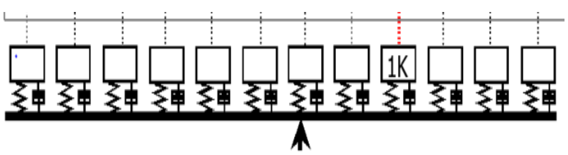
A significant driver of this Σ_{FDS} metric is the application to analyzing or characterizing damage exposure for other than generating a vibration test. As a comparative tool, FDS can be used to complement the test profile generation. Not addressing analysis applications abdicates both commercial opportunities and improving on current, less relevant techniques. A number were suggested in Ref S^2 S&V.

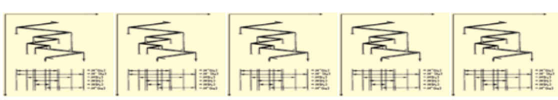
- **Summarizing an EUE at measurement locations,**

- **Comparing shakers (same manufacturer's models) and with shakers of different technologies),**
- **Fixture position-to-fixture position, product to product, and**
- **EUEs to Specs**

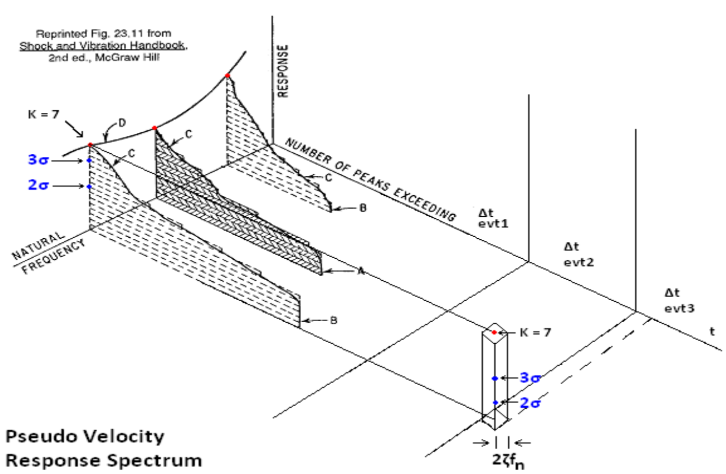
From the generation process of the FDS shown in Figure 1, the resulting plot of dimensionless damage vs. frequency IS a volume integral. The sum of points in any frequency bandwidth of the FDS represent the cumulative damage or severity of the excitation in that bandwidth. Σ_{FDS} is analogous to summing frequency bands of gRMS power contributions to a PSD, Zwicker Loudness (RMS Sound Pressure levels from the ear's cochlear membrane response) or an ISO 2631/10326 Seat Effective Amplitude Transmissibility (SEAT Number), Reference Appendix







The rainflow cycle counted damage at each RIRDF (Smallwood) is represented below in the distributions at each SDoF.

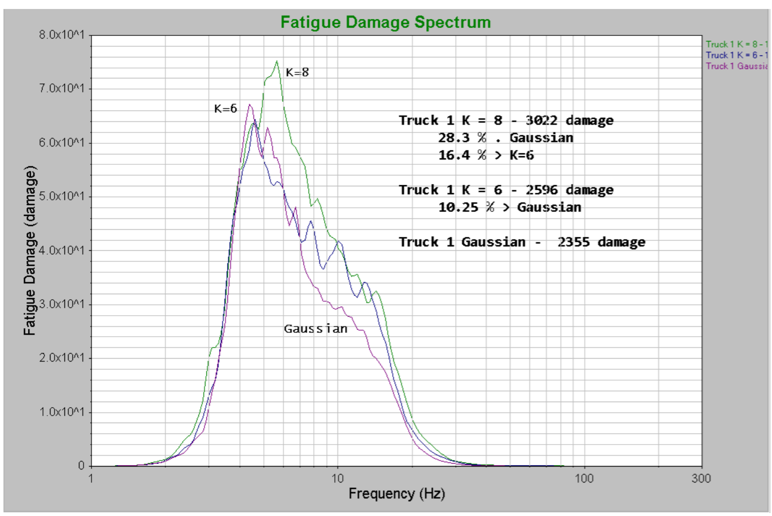


Without refining the m & Q inputs, the FDS points may represent a baseline perception similar to Henderson's macro DP(f) or Damage Potential as a function of frequency. a fitting term for the model. The VR FDS corrects the major DP(f) shortcomings, which were limitations and thus applicability only to Gaussian and stationary time waveforms. For estimating wider bandwidth damage, H-P started with—and then did… Henderson recommended an m=4 and a Q of 10. The Q of 10 represents a 5% critical damping, most common value for the SRS

When developing an equivalent damage test profile for a known failure, material, geometry and resonance characteristics, there is the need for specific m & Q values. For a summary of the effects of m & Q on the FDS, see VR App Note . However, an estimate of cumulative damage potential of a time history over a bandwidth greater than that of the SDoF, the FDS model and its Σ_{FDS} can be of value.

Fatigue Damage Spectrum and Σ_{FDS} for Transportation Tests

Applying the FDS to equal duration recordings of the ASTM Truck Assurance Level 1 PSDs and running with a Gaussian (K=3), K=6 and K=8 distributions allows severity comparison of the test protocols. Because a log vertical scale does not show distinguishable differences, the FDS were plotted on a linear vertical scale for damage. Ref ISTA China Presentation



velocity-based, proportional to stress, and Ref GRH notes (include in Appendix Because FDS is a velocity-driven spectrum, the FDS values decay rapidly after 20 HZ with little contribution to damage potential. For the 2 to 25 Hz bandwidth often associated with truck suspension fundamental frequencies, the Σ_{FDS} shows that Truck 1 K=6 excitation is 10.25 percent higher than the damage potential as a test run with a Gaussian (K=3) peak probability distribution. The Truck Level 1 test run with K=8 is 16.4 percent higher than as damaging as K=6 and 28.3 percent higher than that of the Gaussian (K=3) test. There is no difference in g_{RMS} for different kurtosis values. Fix Graph annotation

When a failure is known, material, Q, resonance characteristics one can deal with a narrower bandwidth to reproduce the failure with an equivalent damage PSD (Kurtosion or not), **MOVE**

Different Shaker Technologies

The Σ_{FDS} can represent an end-use environment (EUE) at any measurement point or, in the following example, a HALT (RS) machine. Below the crossover frequency of "equal damage", the ED shaker running the 6 gRMS NAVMAT profile has an Σ_{FDS} of XXX. Above the crossover frequency, the RS machine has an Σ_{FDS} of YYY or X% greater than the ED shaker. This emphasizes the need to consider the bandwidth of the cumulative damage, just as the PSD shape must be taken into account when using gRMS.

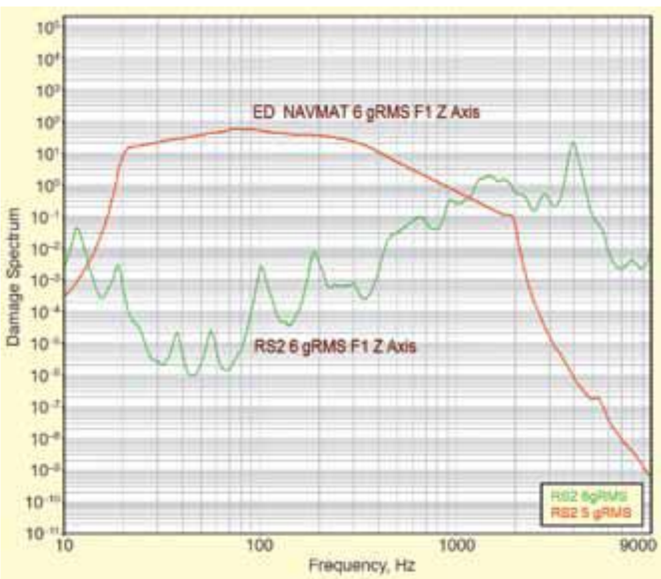


Figure xx shows two response FDS plots from different fixtures on an RS machine. Table shows different FDS transmissibilities at different gRMS setpoints. Shaker control time histories could also generate FDS plots and Σ_{FDS} characterizing the shaker excitation or an EUE. With a test profile generated from the EUE, refinements to m and Q produce FDS and Σ_{FDS}

Here are some observations and comparisons of other metrics supporting the FDS and Σ_{FDS} as providing better decision criteria than PSD and gRMS—S^2 article

- **SRS and FDS are time domain models----reflecting actual time history data including time and cycles, not FFT time to frequency domain transform averaged as in the PSD or peak only as in the case of SRS**

- **PSD/gRMS (statistical estimate of the average intensity per unit bandwidth) lacks the precision of +/- 3dB (+/-50%) magnitude variances even for Gaussian excitation.**
- **As a comparative measure here is little need for precision for the macro use of Σ_{FDS}. The FDS is dimensionless.**
- **SRS is also a model--a peak-hold algorithm regarded as a fragility metric and fingerprint, but not a measure of cumulative severity. Assumes a constant % critical damping which defines the half-power resonance response bandwidths.**
- **PSD, gRMS, SRS and the FDS <u>ALL</u> lose the ordering of stress cycles, only FDS incorporates cycle counting.**
- **FDS and SRS require input variables-m, Q, or damping respectively. PSD (all averages) and gRMS (non-unique) require and account for none**
- **Only FDS can re-introduce Kurtosion to account for actual imported time history peaks exceeding Gaussian 3-4σ.**
- **Test compression from FDS to equivalent damage PSD and re-introducing Kurtosion reduces shaker duty cycle**
- **In the frequency domain, RMS (power) is also additive for different time histories AND frequency bands.**
- **Combining and enveloping FDS to generate a test profile yield better decisions, not well-supported for PSDs-for which Combining and enveloping assumptions have gRMS based shortcomings**
- **From the FDS, an Σ_{FDS} transmissibility is currently in use**
- **FDS value at SDoF center frequency implies constant damage over ½ pbw- CHECK/re-do THIS**

At 4 Hz and critical damping of 5%, halfpower bandwidth is 3.6 to 4.4 Hz or 0.8 Hz
At 1000 Hz, it's 900 to 1100 Hz
From 10 Hz to 10kHz, there are ~240 values
?Conservatively high?
SCS and VR Q comments

Caveats

- **Ratio for damage comparison reflects the above and division implies multiple subtractions of non-SDoF center frequency points**
- **When m, Q and failure are not known-Henderson recommended 4 & 10**
- **Assumes there are resonances at all SDOF and ½ pbw as does SRS.**
- **A worst case model—keep m and Q consistent**

Applications & Opportunities

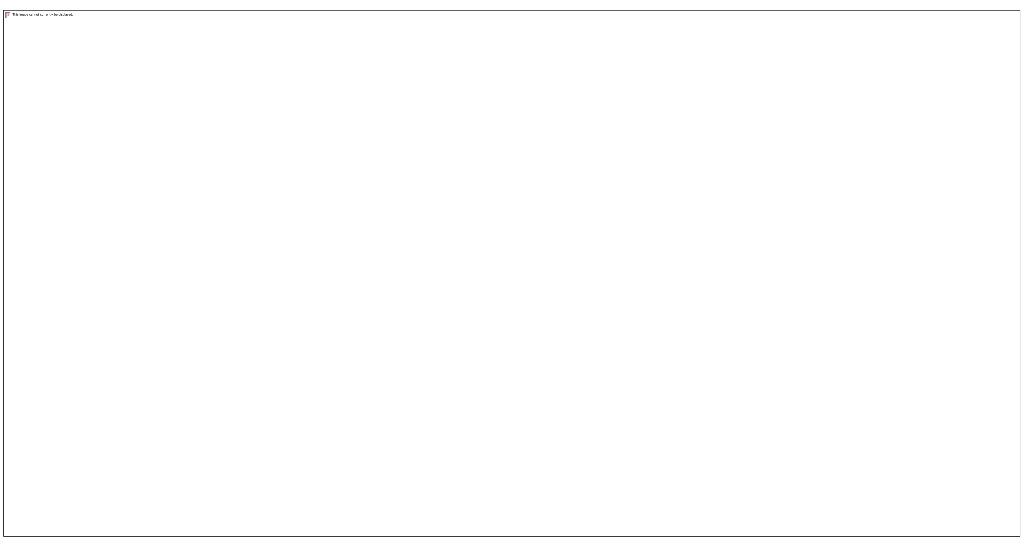
- **Transport time histories**
- **Compare specs and actual-combine, envelope and customize**
- **RS/HALT/HASS step stress and cumulative damage to failure—S^2 article**
- **Comparison of shakers-diff types, and even different sizes of same mfgr**
- **Seismic-IEEE344 reporting has cycle counting to ensure equivalent damage**

- **Coherence— for FDS transmissibility-assemblies, fixtures**
- **Improvement over gRMS for test acceleration ratios and reliability estimates**

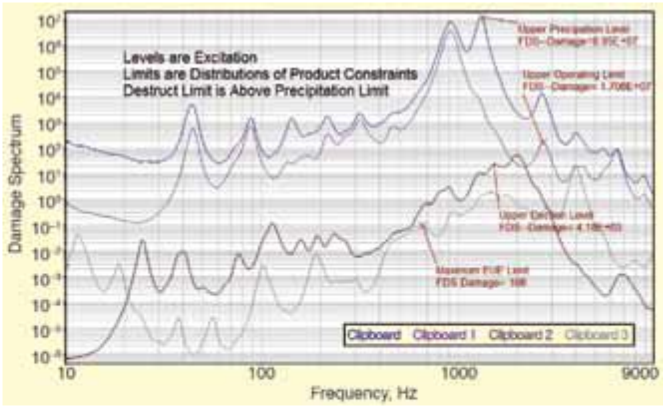
Opportunities:

- **Richter intensity is based on the highest peak amplitude and specific distance to peak location from epicenter, a single metric to characterize entire, broad area seismic event. One might use Σ_{FDS} for site time histories site time histories to document location variation instead**
- **Improved dosimetry for gRMS-b**ased **wholebody vibration and Hand-arm vibration**
- **With caveats as listed, there is no downside or risk that use of the macro Σ_{FDS} will be anything other than a big picture guidance to relative cumulative severity**
- **An opportunity lost is the analysis applications met by ObserVR 1 and 2 for RS/HALT/HASS and a better comparison of EUE, shakers, specs and product strengths.**

The idea of using the FDS and Σ_{FDS} as a measure of product strength and robustness should recognize strength as a distribution developed from multiple exposures to EUE, HALT step stress, qual tests and accelerated reliability demo and growth testing (RDGT). Σ_{FDS} can be used to quantify product margins, and reliability and confidence estimates because it is superior to gRMS by accommodating non-Gaussian and non-stationary excitations.



For vibration, Figure X might be truncated to the left of the lower spec requirement. However, when considering product strength and margins for combined stimuli like vibration under temperature or temperature cycling, the full scale might prove valuable. The Σ_{FDS} quantifies these margins for comparison of improvements.



- **It is a model like SRS, major goal is to quantify fragility, margins and differences**
- **Σ_{FDS} Includes better info than RMS-an indicator of environment, strength and survivability**
- **"Limits" are not discrete, they are distributions with statistical mean**
- **Check Ford Case study for bandwidth of resonances and applied random rather than SRTD**
- **Well-accepted in acoustics and dosimetry—a single number summation from a spectrum is Zwicker Loudness-an objective metric characterizing subjective irritation of the cochlear membrane used for automotive and other wind noise.**

References

1. **JVB S&V article on the "intended" use of the VR FDS**
2. **S^2 S&V article introducing numerous FDS applications demonstrated with RS machine (non-Gaussian, non-stationary) data**
3. **Henderson 1995**
4. **Latest VR app note #0016 offering discussion of the m and Q inputs to the FDS**
5. **VR spreadsheet for calculation of "m" from multiple test runs to failure**
6. **Draft of Applications of the FDS to differentiate between "intended" profile generation and analysis tools**
7. **Zwicker Loudness link http://medi.uni-oldenburg.de/download/docs/diss/Launer_1995_LoudnessPerception/appendix.pdf**
8. **Effective Seat Amplitude Transmissibility (SEAT number) for ride comfort and seat comparison ISO 10326-1:1992, 9.1.**

Appendix

Henderson-Piersol DP(f) Intended Purpose

From GRH Correspondence

a. Direct spectral frequency comparisons of fatigue magnitude. This is the DP(f) value, similar in use to the g^2/Hz value of the PSD. Example: the before and after effect on fatigue caused by a change in design, component or fixture which effects certain vibration frequencies. The value is expressed as fatigue magnitude versus frequency and is most accurate at frequency peaks.

b. Indirect DP(Avg) comparisons of the area under the DP(f) spectrum. Exactly as gRMS is used to compare the relative intensity of an excitation, the DP(Avg) is used to compare the relative fatigue accumulation potential of an excitation over a bandwidth which is wider than the frequency peaks of (a.) above. This is very useful in determining the overall average fatiguing ability at different table/fixture locations, or the fatigue difference between two machines when running at the "same gRMS". The ProCAT provided this tool and when coupled with the spectral zoom function, can determine the relative fatiguing ability across specific product bandwidths, thus matching the overall bandwidth of all the components of an assembly, or one machine to another.

Zwicker Loudness

A relative measure of sound quality and irritation. The following diagram represents the input info and calculations to the industry-accepted Zwicker Loudness. A single value representing the 3rd octave response of the human cochlear membrane. The exponent is known and constant (0.23), but the value remains a cumulative, dimensionless metric (Sones) parallel to the proposed Σ_{FDS}.

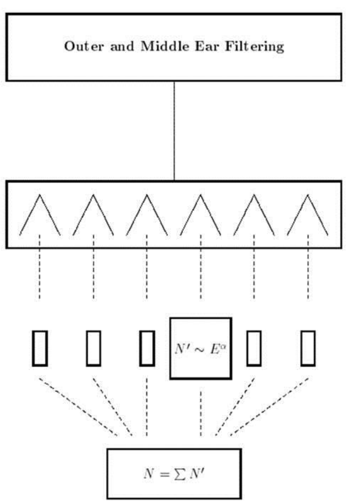


Fig. A.1: *Schematic representation of the different stages of Zwicker's model. A fixed filter representing transfer through outer and middle ear is followed by an auditory filter bank from which excitation patterns E are calculated. In the third step these excitation patterns are transformed into specific loudness N' by a power law relationship. Summing the specific loudness across bands yields the overall loudness N.*

ISO 2631/ISO 1-326 Wholebody Vibration & SEAT Number

Non-dimensional transmissibility--Seat Effective Amplitude Transmissibility (SEAT) value is a standardized metric for relating **objective measurements** and **subjective evaluation of dynamic seat performance.**

SEAT values are computed by:

$$\text{SEAT \%} = \frac{\text{RMS Vibration on Seat}}{\text{RMS Vibration on Floor}} \times 100$$

Substituting Σ_{FDS} for gRMS would accommodate time and cycles of a time history and be verifiable against dosage and exposure standards.

Recommendations for VR

- **FDS Graph- Default split cursors with annotated Σ_{FDS} indicating bandwidth damage**
- **Kurtosis calculation resulting in actual field time histories being re-introduced to the equivalent damage Gaussian PSD of multiple imported field time histories—Jerk?**
- **Add compare (ratio or % difference) and Envelope to FDS plot traces**
- **Market plan for FDS Analyzer Package-Hardware, keyed, pricing, promo**
- **Promote ESS/HALT/HASS potential**
- **Alternate linear FDS scale for narrowband duplication of known failures and JVB Magic Fingers**
- **These are market opportunities for VR**