

Fatigue Damage Spectrum – A New Tool to Accelerate Vibration Testing

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The Fatigue Damage Spectrum (FDS) function has been added to a vibration test controller in order to regulate the rate at which fatigue is induced into a unit under test without distorting the real-world Power Spectral Density (PSD) profile.

The old adage “time is money” is a foundational concept in the vibration testing industry. Engineers want to test products to failure so they can determine how long they are likely to survive in service and find ways to improve them. However, they do not want to spend any more time than is absolutely necessary to reach these goals.

In response, the industry has developed technologies to help engineers break their products faster using increasingly sophisticated random vibration testing methods. A key requirement for these techniques is to increase the rate at which fatigue is induced into the unit under test (UUT) without distorting the power spectral density (PSD) profile to which it will be exposed in real-world operation.

Kurtosis control, as applied in Vibration Research Corporation’s Kurtosion® method, lets engineers shorten test times by reintroducing large and damaging peaks found in real-world data into the random test. As described in the October 2012 issue of *Sound & Vibration*, Kurtosion does this without increasing the total energy of the test.

Vibration Research Corporation’s recently introduced Fatigue Damage Spectrum (FDS) uses a different approach, giving engineers a reliable way to accomplish this goal by *increasing* system energy. FDS is based on the principle of Miner’s Rule of Damage; that is, fatigue damage will accumulate for a product until the life dose of fatigue for that product has been met, at which point it will experience some failure.

All structures experience fatigue as they are repeatedly exposed to adequate levels of stress. This fatigue accumulates over time as the product continues to experience these stress levels – Miner’s rule. The total damage a product experiences in a particular time can be calculated from field data and plotted for a specific range of frequencies. The resulting plot of fatigue damage versus frequency is the fatigue damage spectrum – a means by which to quantify the stress-strain loads placed on a product.

Fatigue Damage Spectrum Theory

Miner’s Rule of Damage says that fatigue damage accumulates over time until it reaches a level that causes a crack or other deformation of a product. So, regardless of how a product arrives at its life dose of fatigue damage (quickly or slowly), the product will experience a failure mode when it reaches its life dose of fatigue damage. Figure 1 illustrates how a fatigue damage spectrum is produced.

First, a data file (acceleration waveform) is converted to a velocity waveform by an integration process. Integrating the field acceleration waveform to a velocity waveform is supported by the Henderson-Piersol method. They did so because it had been argued that stress (causing fatigue) is proportional to velocity.¹

As true as that may be, Vibration Research Corporation has recently demonstrated that the PSD produced for test purposes from the fatigue damage spectrum calculation will be the same whether the fatigue calculation is made based on acceleration, velocity, or displacement (see Figures 2 and 3). The reason this is true is because the final PSD is ultimately an equivalency of two waveforms. So whether the two waveforms during the process of calculating the PSD are acceleration waveforms or not, the plot showing the equivalency of the two acceleration units would be the same as if the plot was showing the equivalency of two displacements or two

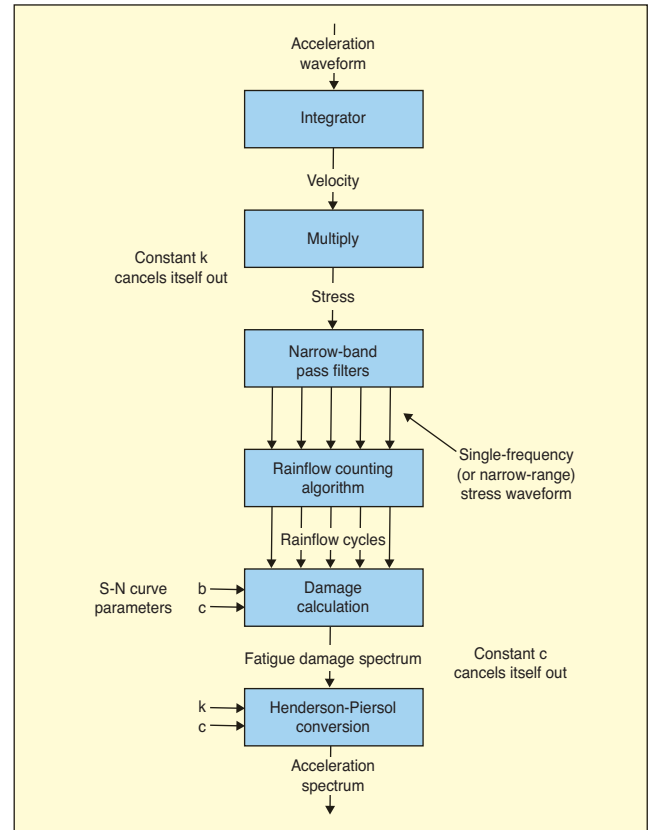


Figure 1. Fatigue damage spectrum calculation flowchart.

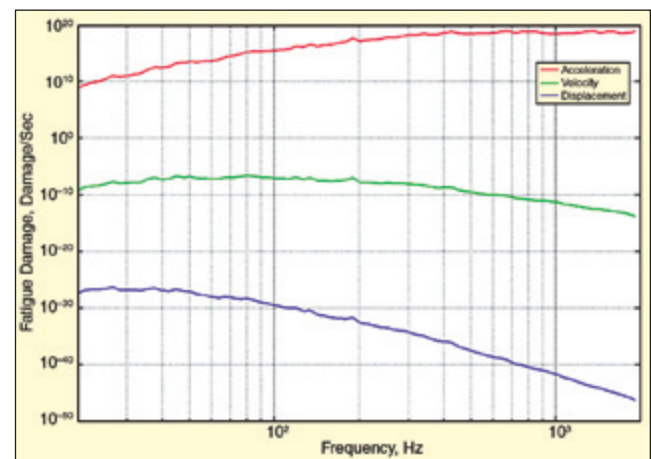


Figure 2. Fatigue damage spectrum calculated based on acceleration, velocity, and displacement waveforms.

velocity waveforms. Figures 2 and 3 demonstrate this.

The converted velocity waveform is run through a narrow-band filter using a specific Q value. Then a specialized calculation tool is used to determine the fatigue damage for the data filtered for each frequency band. This is accomplished by using a rainflow counting algorithm to count the stress peak-valley cycles.²

The stress cycle amplitudes are weighted non-linearly, because of the power law function found in Miner’s rule ($N = cS^{-b}$). These cycles are accumulated to get the accumulated fatigue at that

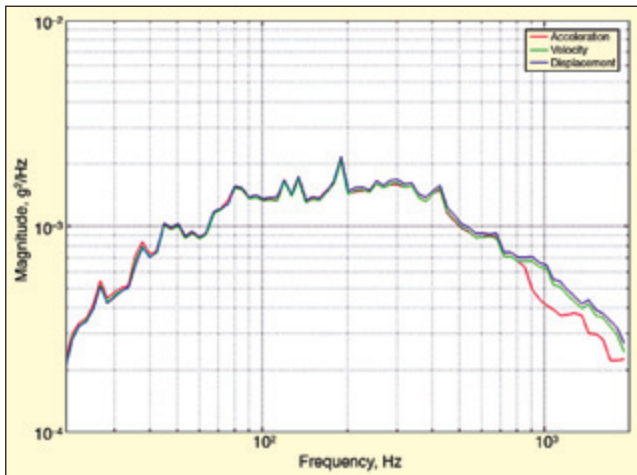


Figure 3. PSD calculated based on acceleration, velocity, and displacement FDS calculations; no matter what FDS method was used, the final PSD was the same.

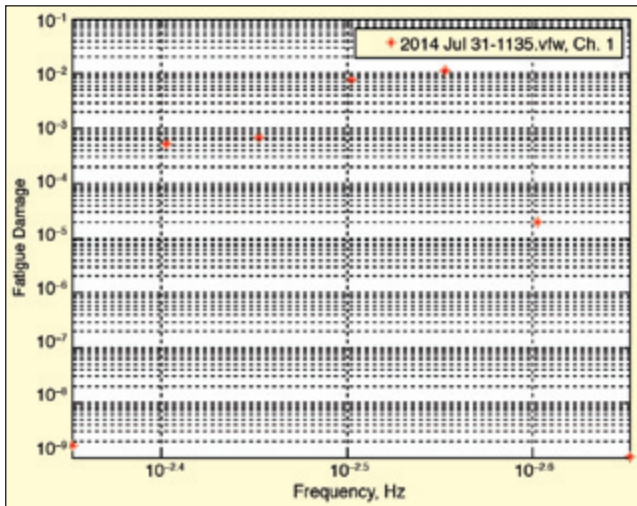


Figure 4. FDS plotted (one fatigue value per frequency bin).

specific frequency according to Henderson-Piersol's fatigue calculation method.

At this point, since the Q of the resonance has been specified, as well as the b value (assumed to be the slope of the S-N curve for the material composing the UUT), the fatigue damage value for each frequency can be calculated. These fatigue damage values are plotted in Figure 4, and the collective plot of all of these fatigue damage values is the fatigue damage spectrum, shown in Figure 5.

Useful Analogy

The Fatigue Damage Spectrum is essentially a plot of the amount of fatigue at every frequency in the spectrum that the product will experience in its lifetime (Figure 5). The amplitude at each frequency represents the total life-dose of fatigue for the UUT at that frequency.

If one were to invert the plot and envision the curve as the bottom of a series of buckets, the amount of water required to fill a frequency "bucket" is the analogue of the life-dose of fatigue for the UUT (Figure 7) at that frequency.

The amount of water needed is constant, but the rate at which the water is added is not. By controlling the rate at which the water (fatigue) is added one can fill the "buckets" (reach the life-dose of fatigue) in any amount of time that might be desired. The amount of water (fatigue) added to the "buckets" (UUT) is constant, only the time required to add it changes.

Putting Theory to Work

Test engineers have always been able to crank up the RMS excitation level of a test to destroy a product more quickly but have not had a tool to reliably determine just how much to crank it up

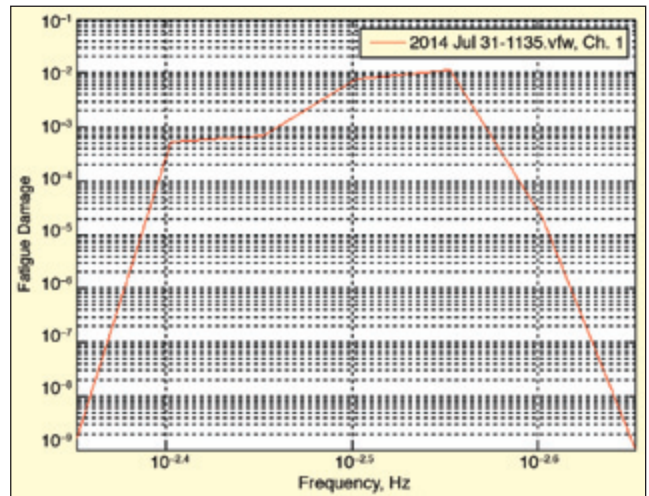


Figure 5. Collective FDS plot.

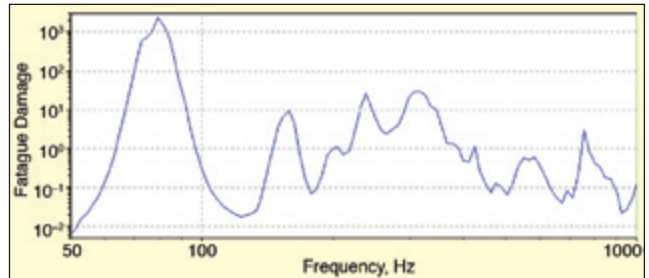


Figure 6. Typical FDS plot.

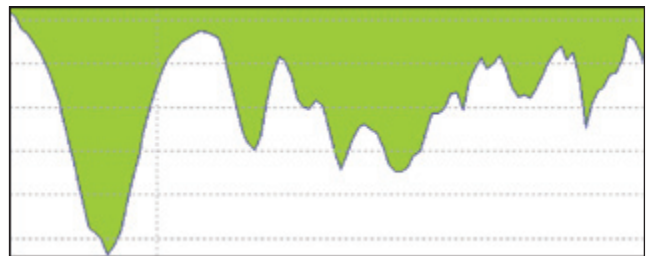


Figure 7. Inverted FDS plot (bucket) filled with life-does of fatigue at every frequency (water).

or to achieve a *relevant* test duration. Vibration Research Corporation's FDS provides that tool, allowing an engineer to increase RMS excitation level with the assurance that the total amount of fatigue induced into the product will not increase.

From a recorded waveform, VibrationVIEW software can compute the FDS for a particular product. Based on that FDS, test engineers can set a desired test duration, and a corresponding PSD will be computed. The combination of severity (PSD shape and RMS power) and duration will reflect a compressed test time of the same cumulative fatigue.

Note that the FDS does *not* change as the test duration setting is changed. Regardless of where the FDS test duration is set, the total fatigue damage remains the same. This makes sense, since a change in test duration merely increases the *rate* at which the fatigue damage accumulates – without increasing the total amount of fatigue that the UUT experiences. This is illustrated in a comparison of FDS for a simulated data file with test duration set at 120 hours versus 16 hours (Figures 9 and 10).

By working the other direction, FDS can help predict the life expectancy of a product. If a test engineer knows a desired PSD and RMS level for the test, the target life can be adjusted to obtain that desired FDS. The target life that produces the desired FDS will be the predicted life expectancy of the product.

Summary

The fatigue damage spectrum is based on Miner's Rule of Damage that indicates fatigue damage accumulates for a product until a life

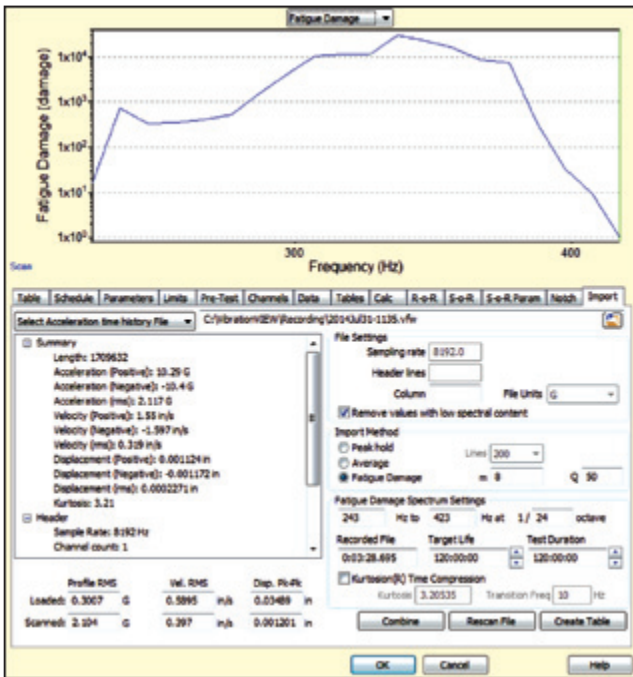


Figure 8. FDS of recording of test using the FDS import, with test duration set for 120 hr.

dose of fatigue for that product has been achieved. With FDS, a test engineer can statistically simulate the end-use environment for a UUT. Once the end-use environment is simulated, the test engineer can accelerate a test to a desired test duration value (Figure 8).

In addition, a test engineer can predict the life-expectancy (target life) of a product by adjusting the target life to produce a desired PSD and RMS excitation for a test (Figure 9). FDS is an innovative tool to simulate end-use environments and to accelerate the test

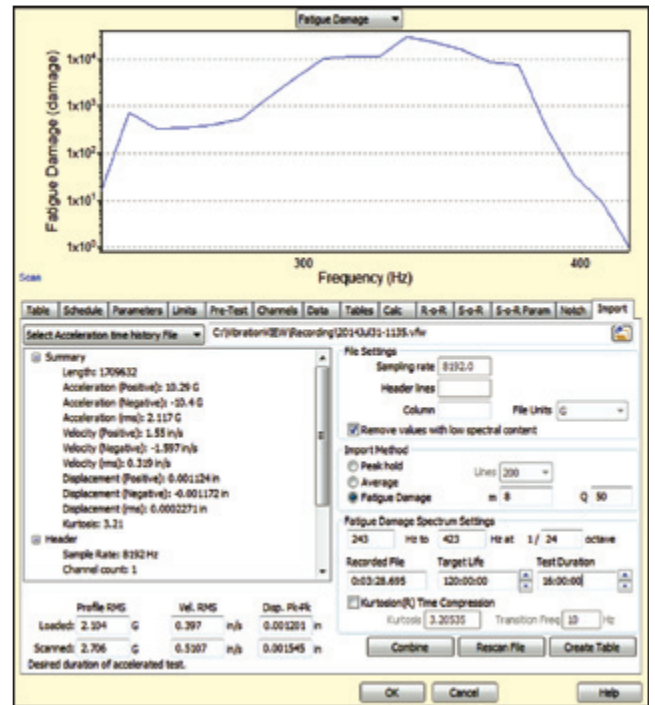


Figure 9. FDS of recording of test using the FDS import, with test duration set for 16 hr; notice that FDS is identical to 120-hour case (compare to Figure 8).

of life-expectancy of a UUT.

Finally, it should be noted that FDS and Kurtosion can be combined synergistically to make random vibration testing more effective and realistic than previously possible. They can accomplish this in less time, which ultimately means for less money. **SIX**

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