Fatigue Damage Spectrum and Ford Motor Company

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Background

Laboratory test engineers vibrate products until some part of them fails. They do so in order to determine how long they can expect the product to survive while in-service or to investigate how to strengthen the product so that it can last longer.

For test engineers who want to break products quickly there are a number of random vibration test options available. As discussed in previous papers, there is Vibration Research Corporation's patented Kurtosion® method. With Kurtosion® test engineers can accelerate test times by putting the large and damaging resonant peaks that are found in the real-life data back into the random test. With traditional testing methods those large resonant peaks would be averaged out by the controller. But with Kurtosion®, the large resonant peaks are included in the random vibration test. In doing this, the test engineer does NOT add any new energy to the system – the PSD plot remains the same at all frequencies when the kurtosis level is increased. With this method, the total energy of the test remains the same. All that will change is the distribution of that energy so that there is a greater occurrence of the large resonant peaks that aid in destroying the product more quickly. With Kurtosion®, test engineers can bring products to failure more quickly ***without increasing the total energy of the test***.

Another test option available to test engineers is Vibration Research Corporation's newly developed Fatigue Damage Spectrum. With the Fatigue Damage Spectrum (FDS), test engineers accelerate the test time for the life of a product, ***by increasing the energy of the system***. Test engineers can crank up the RMS of a test to destroy a product more quickly if they like. But to what level should they crank up the RMS? The answer to that question depends (within reason) on how long of a test the engineer wants to run. With FDS, the test engineer uses the principle of Miner's Rule of Damage. Fatigue damage will accumulate for a product until the life-dose of fatigue for that product has been met. At that point, the product will experience some failure. Knowing this, test engineers can be confident that no matter what RMS level they choose, the total amount of fatigue for the product will not increase. From a recorded waveform, VibrationView software can compute the Fatigue Damage Spectrum for a particular product. Based on that FDS, test engineers can set the test duration for whatever value they desire and a corresponding RMS value will be computed. In this way the exact amount of RMS (energy for the test) can be computed to bring about the failure of the product in the desired length of test time. By working the other direction, FDS can help predict the life-expectancy of a product. If a test engineer knows a desired RMS for the test, the Target Life can be adjusted to obtain that desired RMS value. The Target Life that produces the desired RMS will be the predicted life-expectancy of the product.

Recently, FDS was used by Ford Motor Company (FORD) to help them assess a situation they were investigating with the fuel-rail systems on their 5.0 L and 6.2 L BOSS engines. FDS helped to show that the laboratory tests that FORD was performing were over-testing the fuel-rail systems and it helped FORD predict the life-expectancy of the fuel-rail systems and test them more realistically.

Fatigue Damage Spectrum Theory

The Fatigue Damage Spectrum is based on Miner's Rule of Damage, which teaches that fatigue damage will accumulate 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 (ie: quickly or slowly), the product will experience a failure mode when it reaches its life-dose of fatigue damage.

A Fatigue Damage Spectrum is produced in the following way (Figure 1).

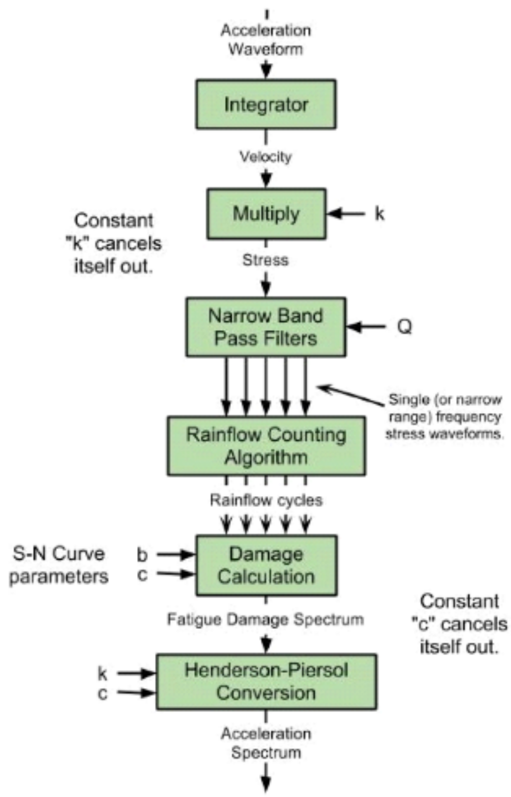


Figure 1: Fatigue Damage Spectrum Calculation Flowchart

First, a PSD data file (acceleration waveform) is converted to a velocity waveform by an integration process. The original acceleration waveform is converted to a velocity waveform because the Henderson-Piersol method of calculating fatigue originally based their calculations on using a velocity waveform. 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 from the Fatigue Damage Spectrum calculation will be the same whether the Fatigue calculation is made based on acceleration, velocity, or displacement (See Figure 2, 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 displacement or two velocity waveforms. This is demonstrated in Figures 2 and 3.

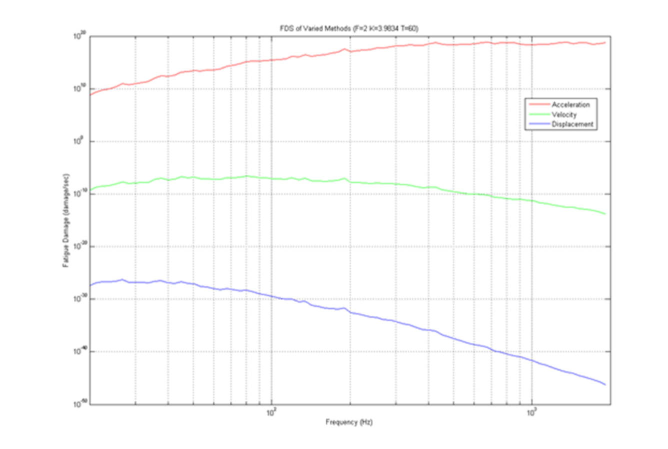


Figure 2: Fatigue Damage Spectrum calculated based on Acceleration, Velocity, and Displacement waveforms

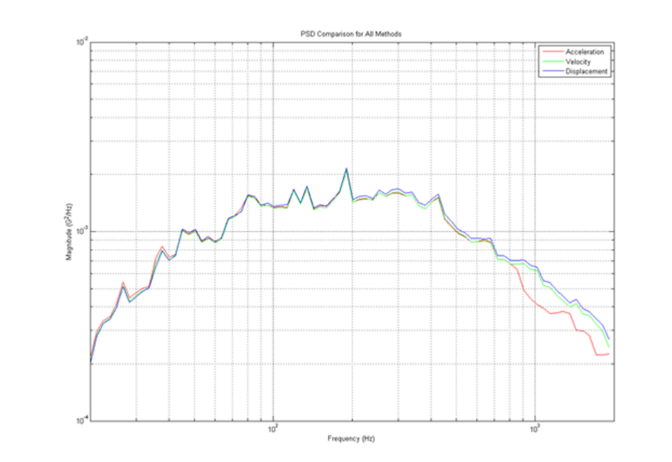
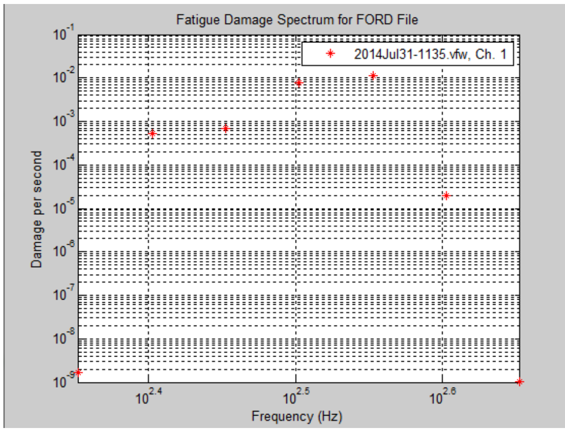


Figure 3: PSD calculated based on Acceleration, Velocity, and Displacement FDS calculations. No matter what FDS method was used the final PSD was the same.

Secondly, the converted PSD data is run through a narrowband filter, utilizing 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 ($N = cS^{-b}$). "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" (MIL-STD-810 G; Method 514.6, Annex A). These cycles are accumulated to get the accumulated fatigue at that 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 (Figure 4). The collective plot of all of these fatigue damage values is the Fatigue Damage Spectrum (Figure 5).



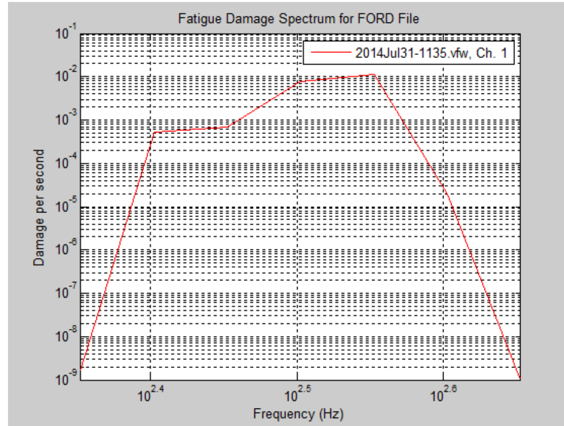


Figure 4: FDS plotted (one fatigue value per frequency bin)

Figure 5: Collective FDS plot for a FORD data file

How to Accelerate Random Vibration Test Using Fatigue Damage Spectrum

Test engineers want to be able to accelerate their vibration tests. One way of doing so is to use the Fatigue Damage Import feature in a random vibration test. In the following example we use a simulated recording from FORD of their Laguna Head across the frequency range of 243-423 Hz. The simulated recording was approximately 3.5 minutes of data (Figure 6).

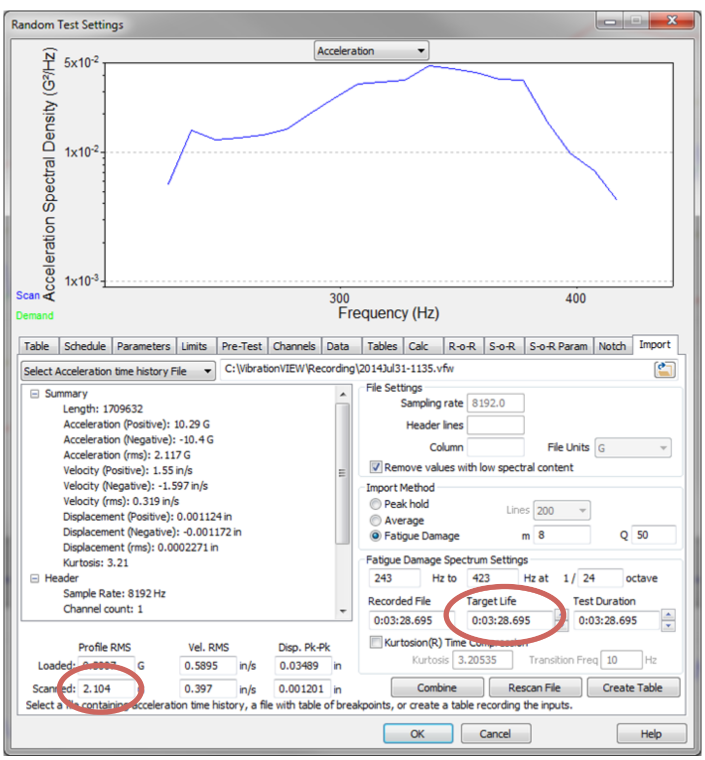


Figure 6: The PSD and GRMS of a recording of a FORD fuel-rail test using the FDS import.

In order to simulate an end-use environment, test engineers need to set the Target Life value to some realistic value as seen on the field. In this example, FORD utilizes a minimum durability standard of 2.1 GRMS for 120 hours for their fuel rails (Figure 7).

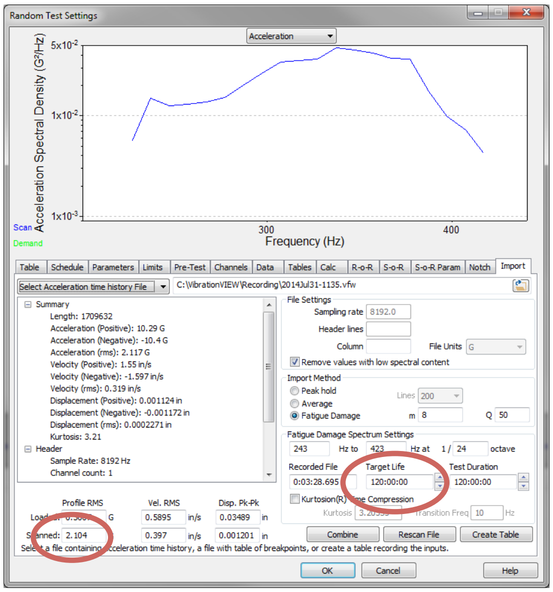


Figure 7: The PSD of a recording of a FORD fuel-rail test using the FDS import, with Target Life and Test Duration set for 120 hr.

To accelerate the test, the test engineer needs to adjust the test duration to a reasonable value. In this example, the test duration was set for 16 hours (Figure 8). Decreasing the test duration results in a higher GRMS value for the test. This will bring about a life-time dose of fatigue for that particular test more quickly than if the test ran for the 120 hours.

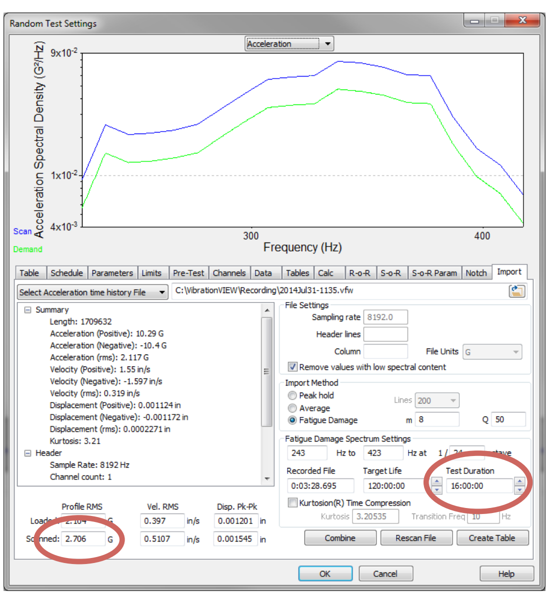


Figure 8: The PSD of a recording of a FORD fuel-rail test using the FDS import, with Test Duration set for 16 hr. Notice the increase in the GRMS value (from 2.104 (see Figure 7) to 2.706 GRMS)

Interestingly, the Fatigue Damage Spectrum does NOT change as the Test Duration setting is changed. Regardless of what the FDS Test Duration is set at, the total Fatigue Damage remains the same. This makes sense, as 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 the simulated FORD data file with test duration set at 120 hours versus 16 hours (Figure 9 and 10).

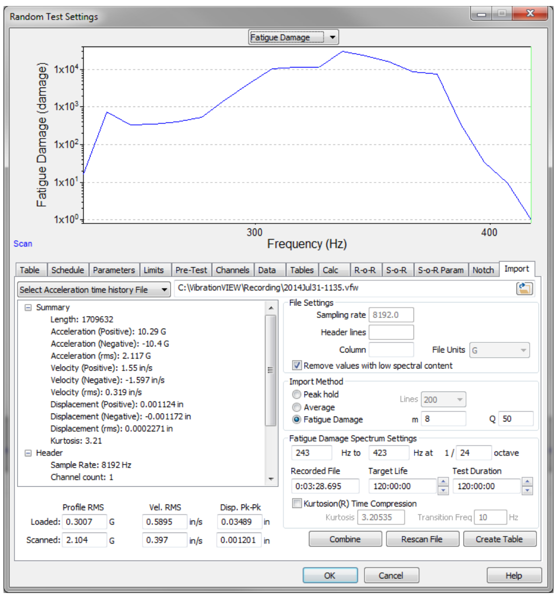


Figure 9: The FDS of a recording of a FORD fuel-rail test using the FDS import, with Test Duration set for 120 hr.

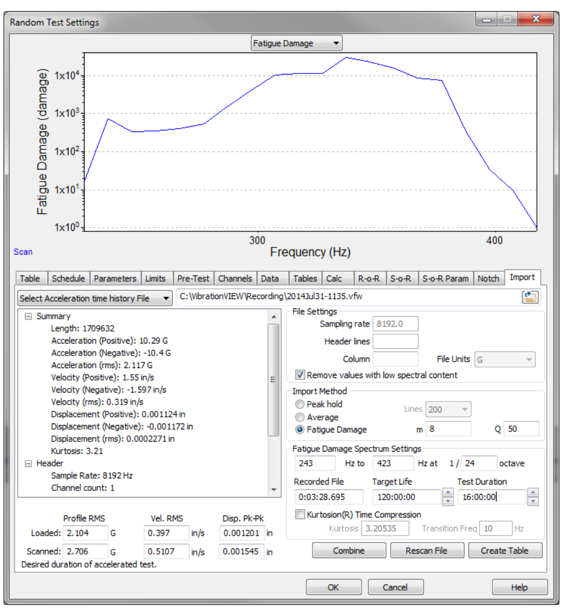


Figure 10: The FDS of a recording of a FORD fuel-rail test using the FDS import, with Test Duration set for 16 hr. Notice that the Fatigue Damage Spectrum is the same as the 120 hr case (compare to Figure 9).

How to Predict Life-Expectancy of UUT: A Ford Motor Company Case-Study

History:

Lab technicians at a Ford Motor Company (FORD) testing facility were struggling with tests performed on their 5.0 L and 6.2 L BOSS engines (Figures 11 and 12). The part under concern was the fuel rail. In the testing facility, laboratory tests were producing failures in the fuel rails that were never before observed on the field (Figures 13 and 14). Such results naturally created some concern. Would these failures occur in the field? Or was the laboratory test simply over-testing the fuel rail?

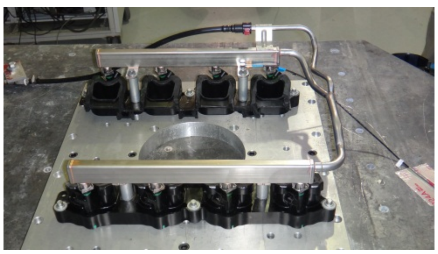


Figure 11: FORD Boss Fuel-Rail System

Figure 12: FORD Boss Fuel-Rail System on a shaker

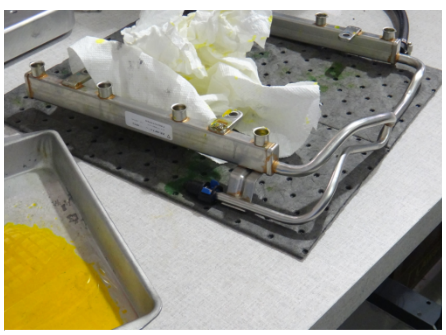


Figure 13: Fuel-Rail System leak after vibration test

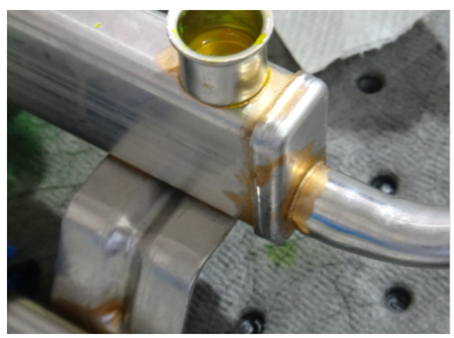


Figure 14: Fuel-Rail System leak

Test engineers wanted to know whether or not their laboratory tests were over-testing the fuel-rail or not. Secondly, if they were over-testing the fuel-rail, they wanted to know whether there was a more realistic test that could test the unit in an efficient manner.

Of all the data that was provided by FORD, it became apparent that the Engine Head (Z axis) was going to be most profitable for our study (Figure 15). This is because:

- It provided the largest GRMS values
- It appeared to be putting the energy into the “Crossover” for its resonance.

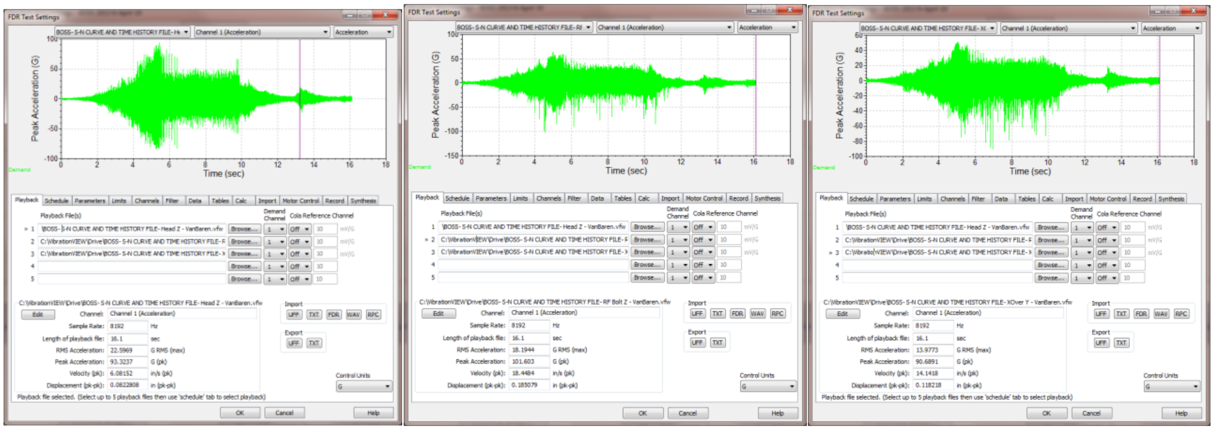


Figure 15: Three components of Fuel-Rail System: Head (Z axis); Left-Front Bracket; "Crossover". Head (Z axis) has significant GRMS.

The data received from FORD had a broad range spectrum of 10-3200 Hz. The GRMS for that range was 18.9 GRMS. This was too large of a GRMS for the available shaker. Therefore, a particular frequency band was found that would work on the available shaker and would provide sufficient resonance and damage to the product. It was determined that the 243-423 Hz range produced the most damage in the "Crossover" component of the fuel-rail system (37 GRMS), while demanding a small GRMS from the shaker (2.2 GRMS) (Figure 16).

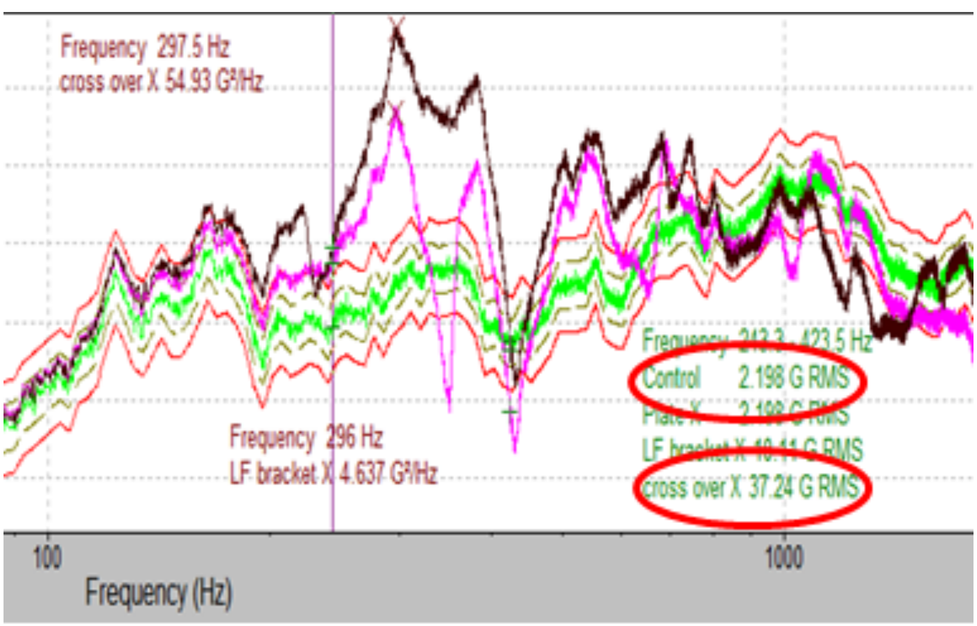


Figure 16: GRMS values for components of Fuel-Rail System at Frequency Range of 243-423 Hz.

The data from tests on FORD's fuel-rail system helped make an S-N curve for the fuel-rail system (Figure 17). The first five data points came from actual data from tests on the fuel-rail system, while the second set of five data points were estimations made to extend the S-N curve.

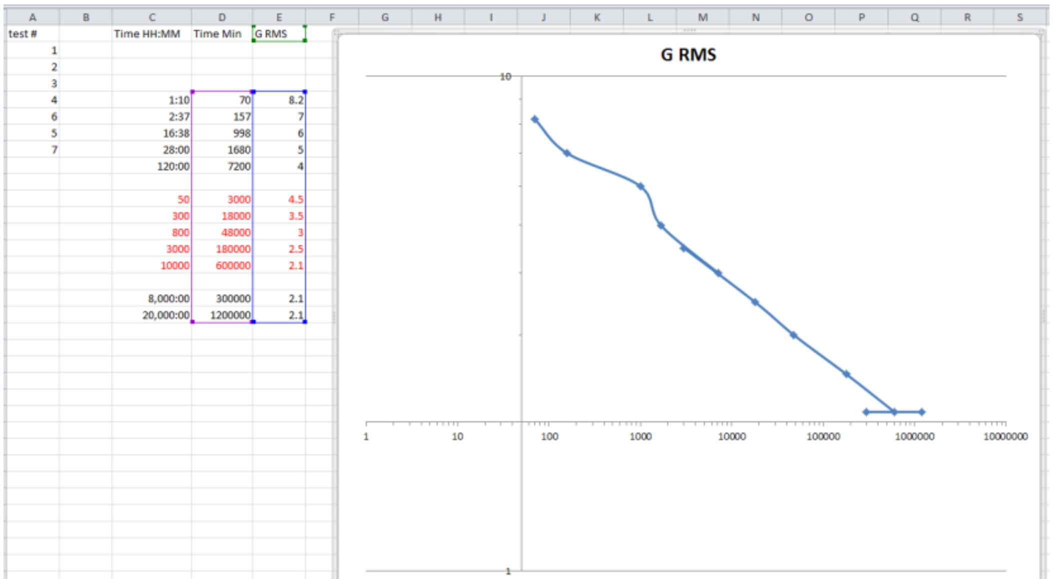


Figure 17: S-N curve for Fuel-Rail System as tested at various high GRMS with estimated values at low GRMS levels.

FORD's Over-testing Situation

Based on the data received from FORD and the construed S-N curve, it is clear that the Dyno that was used by FORD to test the fuel-rail system *significantly over-tested* the product. The data shows that if the fuel-rail system vibrated at 2.1 GRMS for the 243-423 Hz range (which was FORD's minimum GRMS standard for survival of the fuel-rail system), it would have required some 10,000 hours before failures would occur. But FORD was finding failures in the laboratory during its 240 hour durability standard test which ran at the 2.1 GRMS level. The fuel-rail system was failing under these conditions – indicating that FORD must have been significantly over-testing its fuel-rail systems.

Determining a More Realistic/Efficient Test and Predicting Life-Expectancy

In search for a better test than the over-testing situation, the technicians considered whether to run a series of sine tests at various known resonances or to run a random test across a known frequency range.

Due to the significant resonances at a number of key locations, test engineers considered the possibility of testing with a series of sine tones with large amplitudes at the key resonant frequencies observed in the engine and fuel rails. The problem with this proposed solution was that the engineer was saddled with several sticky questions, including, which sine tone and at what level of amplification should be used. In addition, the possibility of the resonances on the fuel-rail changing when it was mounted to the engine, would make it difficult to test the true resonances of the fuel-rail. Due to these concerns, the sine test option was not a favorable option, and therefore, was not used.

Since the sine test was not a favorable option, FORD lab technicians considered running a random test across a known frequency range. They used VRC's random vibration Fatigue Damage Spectrum import test to help predict the life-expectancy of the fuel-rail system.

In the VibrationView software, the Target Life parameter was adjusted until a RMS value of 2.1 was obtained (Figure 18). The Target Life parameter was set to a value to produce a RMS value of 2.1 because that RMS value corresponded with one of the estimated S-N curve data points of the 243-423 Hz range of the Engine Head (Z axis). In addition a GRMS level of 2.1 also corresponded with FORD's durability standard for the fuel-rail system. With this test setting, the fuel-rails would be vibrated at 2.1 GRMS across the 243-423 Hz range for 120 hours. This would give the fuel-rails a life-dose of fatigue that they would experience on the field. Therefore, if the fuel-rails would survive this test they should be expected to survive in the field.

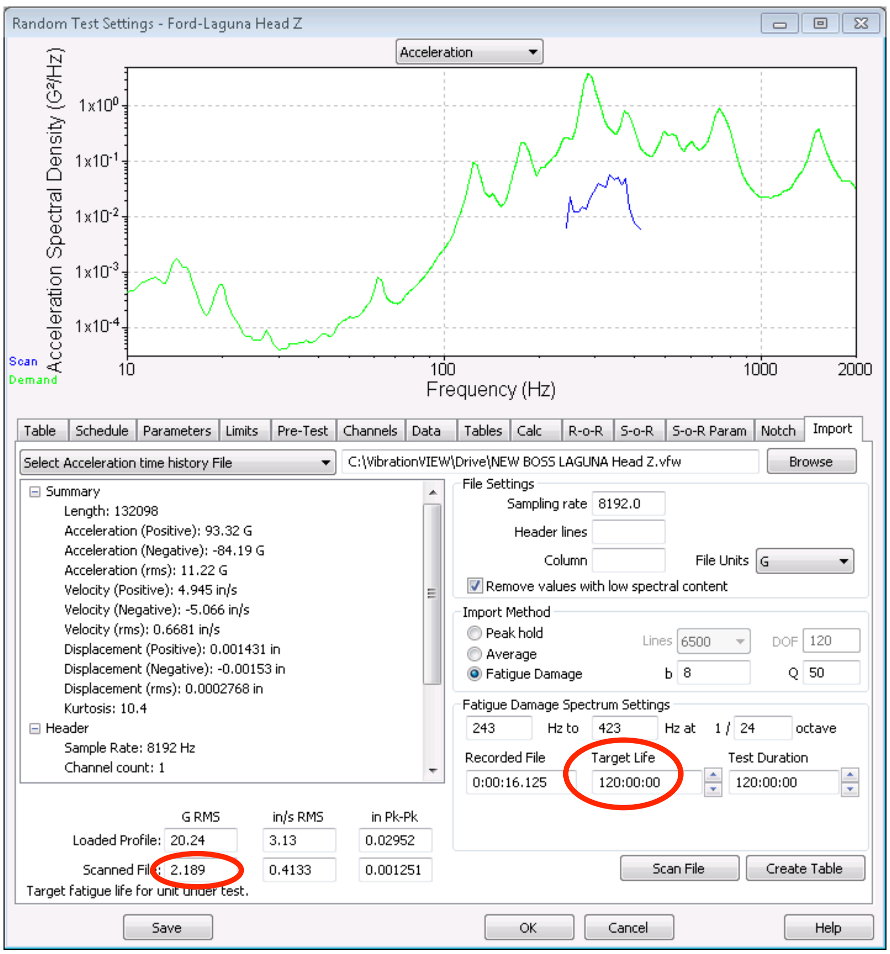


Figure 18: FDS import of Head (Z axis) data for Frequency Range of 243-423 Hz. GRMS of imported file is 2.1 GRMS for the Target Life of 120 hrs, with B=8 and Q=50.

Case-Study Conclusions:

By use of the S-N curve, it was predicted that the fatigue life expectancy of the fuel-rail to be in the range of 8,000 to 20,000 hours for a vibration test at 2.1 GRMS. FORD utilized a standard that required the fuel-rail system to survive a disastrous waveform test for a minimum of 120 hours, based on the kind of environments experienced by the engine in real life. FORD also utilized a durability standard requiring a product to survive 240 hours of similar testing. When using FORD's S-N curve data ("Predicted Life" of 8,000 to 20,000 hours), the life expectancy for the fuel-rail system was more than **30 times longer** than the maximum required 240 hour durability tests. Consequently, the previous FORD laboratory tests were significantly over-testing the fuel-rail systems.

In addition, by using VRC's Fatigue Damage Spectrum test, a new test for the fuel-rail was developed that would realistically apply a life-dose of fatigue to the fuel-rail system. It was determined that a Target Life of 120 hours could produce the necessary 2.1 GRMS durability standard for FORD's fuel-rail system. If test engineers wanted to adjust this test to a shorter test duration, the FDS test could be adjusted to accomplish this without over-testing the product. (To learn how to accomplish this read VRC's paper "A Primer on Fatigue Damage and Fatigue Damage Specta").

FORD's fuel-rail system failures in the laboratory were addressed by this study. They learned that they were over-testing their fuel-rails and how to use VRC's Fatigue Damage Spectrum to produce a realistic and efficient test that would realistically predict the life-expectancy of the fuel-rails.

Fatigue Damage Spectrum Conclusions

The Fatigue Damage Spectrum is based upon Miner's Rule of Damage which teaches that fatigue damage accumulates for a product until a life-dose of fatigue for that product has been achieved. With FDS a test engineer ***can simulate*** the end-use environment for a UUT (Figure 7). Once the end-use environment is simulated, the test engineer ***can accelerate*** a test to a desired test duration value (Figure 8). In addition, as illustrated in the FORD case-study, a test engineer ***can predict the life-expectancy*** (Target Life) of a product by adjusting the Target Life to produce a desired RMS value for a test (Figure 18). Fatigue Damage Spectrum is an innovative tool to simulate end-use environments and to accelerate the life-expectancy of a UUT.

References

[1]Henderson, George R., and Piersol, Allan G., “Fatigue Damage Related Descriptor for Random Vibration Test Environments,” *Sound & Vibration*, p. 21, October 1995.

[2]VanBaren, John, and VanBaren, Philip VanBaren, “The Fatigue Damage Spectrum and Kurtosis Control,” *Sound & Vibration*, p. 10, October 2012.