

Potential Uses for the Fatigue Damage Spectrum (FDS) in Test Specification and Health and Usage Monitoring Systems (HUMS)

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Abstract

The Fatigue Damage Spectrum (FDS) is a frequency domain representation of fatigue damage, calculated using an acceleration time-waveform which accounts for both the magnitude and duration of the signal. The FDS can be generated using either time-domain based methods or can be calculated directly from frequency domain signal representations, such as Power Spectral Density (PSD) plots. The FDS's primary use case is in specifying and comparing vibration tests for mechanical vibration testing; however, it also has potential in comparing the damage potential of various signals, as well as edge processing and data reduction at the source, where storing time-domain data is impractical or unfeasible. The main barrier to the adoption of FDS based practices comes from both resistance to change in the industry, and the complexity of adoption of these methods. This submission presents a literature review on the rationale of adopting the FDS, as well as an overview of a newly developed software package that seeks to overcome some of the obstacles to adoption. The literature clearly shows that FDS methods are superior in developing test profiles from mixed-terrain input data. Combined with well-designed software, the FDS offers potential benefits to industries relying on vibration testing, by way of an increase in accuracy and reduction in conservatism compared with default severities listed in defence standards.

Keywords: Fatigue Damage Spectrum, FDS, Shock Response Spectrum, SRS, Vibration Testing, HUMS, Aquila.

Introduction

The use of mechanical vibration testing is commonplace in both defence and civilian applications, and is primarily used to reduce the risk of in-service failures due to vibration. A robust test profile is derived from measured data collected from environments representative of those which the test article will be exposed to in service. To achieve this, a wide range of vibration data is required across both platform types and mission terrains. A repeatable and accurate method for data conversion is also required, to allow for appropriate vibration profiles to be developed for programming into mechanical vibration test equipment. The challenge in achieving these aims, means that test specifiers often turn to default severities (for example those listed in defence standards), which can be unsuitable due to their generic nature. To challenge these existing practices, both an efficient method of data acquisition and a repeatable method of converting this data into test profiles is needed. Software which leverages the FDS, both as a method to create damage equivalent tests, and as a method of data reduction, would allow for organizations to adopt more robust test strategies developed from a wider range of platforms.

Background

Producing vibration profiles which can be used in mechanical vibration testing, typically involves the conversion of either frequency or time domain data into a PSD and test duration. The goal of developing the profile is to accurately replicate the environment of the engineering item being tested, as far as is reasonably practicable, often with an element of conservatism. Many of the methods to convert measured data to PSD test profiles are outlined in DEF-STAN 00-035 Part 5 Issue 5 [1].

Defence standards such as DEF-STAN 00-035 and MIL-STD 810H [2] also include default severities (pre-made profiles). They provide an alternative to developing vibration profiles using measured data. While the use of these profiles offer a simple solution, they are designed for situations where measured data is unavailable, and a degree of conservatism can be accepted. While there is often no transparency on the way these default profiles are created, it can be deduced that they are likely developed using enveloping methods, which have limitations that may cause unrealistic damage to payloads under test [3]. Conservatism from the use of these profiles can be extreme when compared with a measured data profile (up-to ~63000x depending on material parameters) [4].

A misconception in the interpretation of standards is that testing equipment using default severities (particularly for MIL-STD-810H and DEF-STAN 00-035) is thought to 'meet' the standard. These defence standards provide guidance to test specifiers, and test service providers, to produce repeatable and accurate tests, however, for the most part, they are non-prescriptive in terms of test severities and duration. Test severities should vary depending on the mission profile of the item under test. Despite the standards clearly stating the benefits of using measured data, there are barriers to its adoption. These include:

- Technical complexity of the methods required to convert time-series data to PSD test profiles.
- The requirement for engineering judgement in selecting material parameters, data conversion methods and statistical methods to combine profiles.
- Desire for repeatability, even at the expense of accuracy.

While various methods exist for the specification of PSD profiles, and programming of shaker controllers to recreate vibration environments, the accuracy varies substantially. Research conducted using a full-scale vibration test with a complex payload, showed that compared to other methods, the FDS provided the most accurate method of combining multiple mission terrains, and was able to conservatively adjust for non-stationary, and non-gaussian signals where other methods were not [4].

The FDS was first introduced by the French Atomic agency, and is referenced in DEF-STAN 00-035 under General Vibration Methodologies for mechanical vibration testing. DEF-STAN 00-035 includes the FDS as a method to convert measured frequency domain accelerometer data. MIL-STD 810H also refers to the FDS, however, it is primarily concerned with the combination of various PSD based field measurements into a single PSD to be used in testing. Computationally, the FDS has evolved from a purely frequency domain-based method into a method which can be applied to raw time-domain data. One of the primary benefits of the FDS is that it incorporates duration in its calculation and outputs a comparable dimensionless damage estimate, which can be used to compare vibration exposures, and inverted to create test severities and durations. This means that the amount of judgement required by the test specifier in combining test profiles is minimised, provided that the software package is well designed, and can incorporate the test item mission profile.

For time domain calculations, the FDS relies on a Single Degree of Freedom (SDOF) response calculation (typically in displacement but can be calculated in velocity and acceleration also), followed by a rainflow cycle counting process, and finally the application of a modified linear-damage approximation, utilizing a fatigue exponent. A full derivation is beyond the scope of this document, however, background information is available in the literature [5] [6]. A flowchart of the method used to convert time-domain data to the FDS and the subsequent inversion of the FDS to a test PSD is shown in Fig. 1.

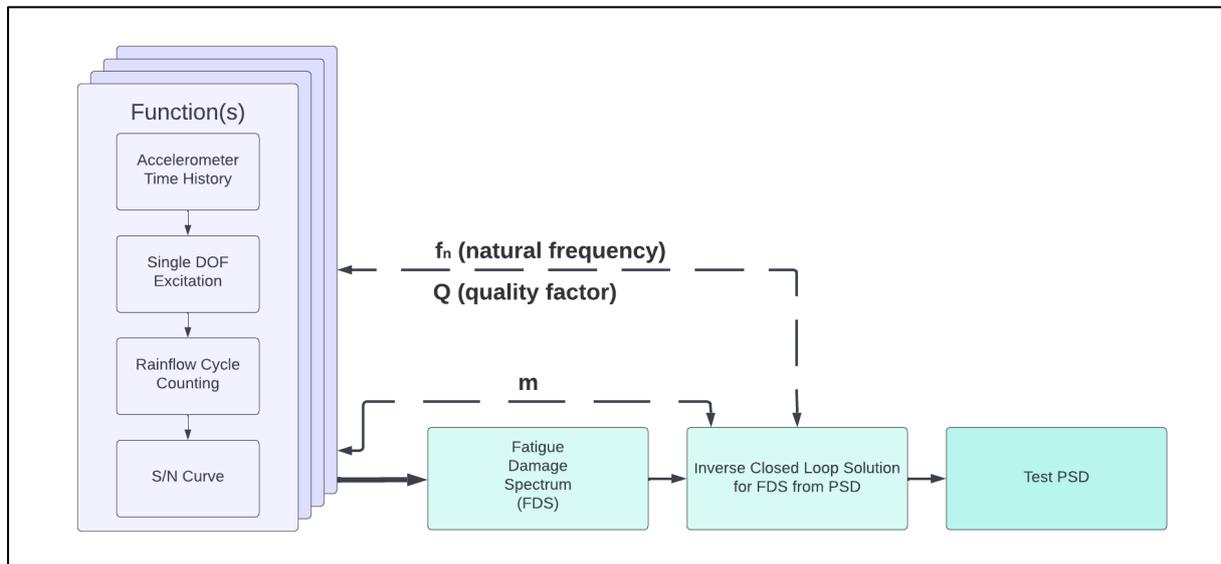


Figure 1 – Fatigue Damage Spectrum (FDS) Flowchart

While software solutions exist in the vibration signal processing space which utilize the FDS, none of them offer a simple, discrete option which allows for an automated test profile creation using the test item mission profile as the primary input. The Aquila Vibration Profile software package was developed to fill this gap in the market. It offers a mission profile centric design that matches and automatically accounts for the units and duration of the measured data, and associates each entry with a portion of the mission profile. The software also allows for real-time, test duration calculations so the test intensity can be quickly adjusted to account for shaker limits, and recommended test amplification limits, set to standards such as DEF-STAN 00-035 etc. The software is designed to be easy to learn, while still offering flexibility for tests to be appropriately tailored.

The Aquila Vibration Profile software allows for the creation of a PSD profile first, by entering the mission profile. Mission profile units can then be selected as generic laps, or specific units such as km or hours. The test specifier then selects time-series data, and assigns units, and a quantity (eg 100km) to each file. The program automatically calculates the FDS for each file, and using the input mission profile and target test duration, provides a PSD that can be programmed into a mechanical vibration test, as well as a comprehensive report. By simplifying the workflow, the test specifier gains greater control over the test data as changes and updates become easier. This means more time can be spent on the quality aspects of the test specification, such as how much data should be used, and how this data is collected. Test profiles created using this method for a specific platform will typically be of a lower magnitude than default severities, as they do not have to account for multiple platforms. In a modern context, where integrating complex and sensitive hardware is a requirement, this is particularly advantageous as equipment can be better optimised for the conditions and platform it is being deployed on.

Shock Response Spectrum (SRS) testing is also useful for discrete shocks which do not contain a random component, eg those caused by live firing, or machinery collisions. The SRS is a data set that can be programmed into a mechanical shock test. The Aquila Vibration Profile also allows for the calculation and combination of SRS values, by performing a series of SDOF responses to the input signal (similar to the FDS). Note that instead of calculating fatigue damage from the resulting cycle counts, it calculates the maximum and minimum shock values of the SDOF oscillator. As with the FDS, this calculation is repeated for a series of SDOF natural frequencies to arrive at the spectrum. Separating random vibration test data, from highly non-stationary shocks (and testing them separately) is recommended in DEF-STAN 00-035/MIL-STD 810H etc. While the FDS can conservatively account for these shocks, it will always be more accurate to test them separately.

Potential Uses in HUMS

Most current solutions to create a mechanical vibration test PSD rely on high quality accelerometer data, measured during field trials. Collecting this data can be expensive and time consuming, and even with a well-designed program, may not be representative of the conditions where vehicles and equipment are deployed.

In theory, Health and Usage Monitoring Systems data could be used to enrich or replace this data. This would provide test specifiers access to a wide range of vibration data, measured during the actual use of a vehicle or test item. HUMS data is not always suitable, however, often due to the limitations inherent in its design. For example, the HUMS system used by the ADF relies on a sampling rate of 10Hz [7], for accurate mechanical vibration test profile creation higher frequencies are often required. DEF-STAN 00-035 specifies that sampling rates for digital data acquisition systems are more typically between 2000 Hz and 20000 Hz, and should be four times the target upper frequency range to account for Nyquist. As a result, 10Hz data is generally unsuitable for reproduction of vibration tests, as it will only be accurate up to approximately 2.5 Hz, and depending on the pre-sample filter may have aliasing present in the final signal. Increasing the sample rate for accelerometer data however, does have its drawbacks. The data storage and transmission rates scale linearly, and this increases the hardware requirements for any HUMS system, particularly if it relies on telemetry. Reducing data prior to transmission or storage (edge processing) can overcome some of these limitations, however, the way the data is reduced can impact the accuracy of the final product.

One option to reduce the volume of data in a vibration signal is to convert blocks of time-domain data to a frequency domain representation. The most basic candidate for this would be a PSD. Guidance on how to produce PSDs are specified in DEF-STAN 00-035. This method typically involves averaging a defined number of overlapping Fast Fourier Transforms using Welch's method [8] to arrive on an estimate of spectral density. This typically results in a PSD generated for a discrete time period, and typically, multiple PSDs for a given time-waveform. These PSDs can then be analysed and combined to arrive at a vibration profile which contains multiple terrains, speeds and vehicle configurations. While this method will reduce the data volume, it does have limitations. For example, this method assumes the signal is stationary, and gaussian, for the period in which the spectral estimate is being made. Furthermore, the methods to combine the PSDs will typically rely on statistical or enveloping methods, which can be unrealistic due to the non-linear nature of fatigue. A PSD will not account for damage caused by highly non-stationary events such as shocks. Finally, for this method to be effective, individual PSDs must be stored for each block of data analysed. For very long-term acquisition

activities, or those with a high number of channels, this may drive a higher data volume or exceed data transmission limits.

Calculating the FDS at the point of data capture, offers an alternative to this method. As the FDS accounts for both the duration and magnitude of a signal (i.e. it is cumulative), the method to convert the FDS back to a vibration profile no longer relies on storing individual PSDs. A single FDS can be stored which accounts for all the vibration measured up to that point. While it would be pertinent to store the FDS at regular intervals, the frequency of this interval is no longer dictated by the duration of data used to produce the PSD. Calculating the FDS does require the system user to specify the fatigue exponent and quality factor, however, due to the reduction in data volume, multiple values can be simultaneously calculated where required. The major downside of using the FDS in HUMS, is that it does have a computational overhead. Modern microprocessors are, however, capable of handling these calculations in real time.

Edge processing also allows for sorting of data and storage of important events, such as non-stationary events (shocks). A well-designed HUMS system should be able to identify shocks, and these events can either be stored in the time-domain or converted to Shock Response Spectrum (SRS). A stored SRS (or the statistical combination to create a single spectrum) can be reproduced in a mechanical shock test, allowing for this data to be accurately recreated in testing without the need to store high fidelity time-series data for each shock.

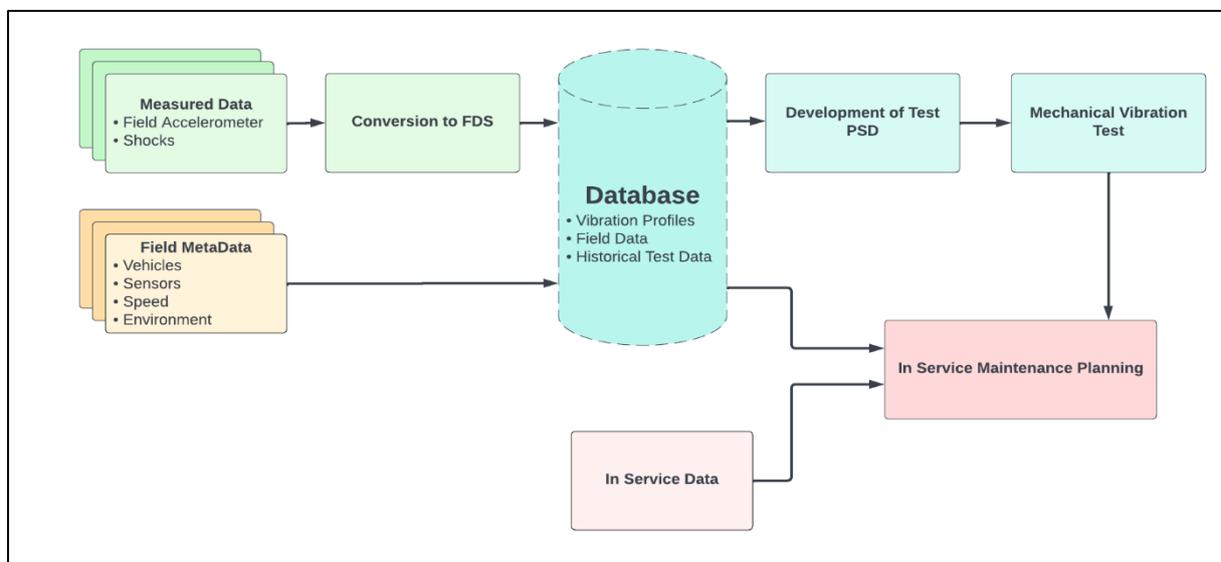


Figure 2 – HUMS Concept

The FDS and SRS may also have applications in life monitoring of equipment, and other areas such as driver training and driver feedback systems, or in the prediction of in-service failures. Due to the FDS being cumulative, alarms can be designed when the FDS reaches certain thresholds, and vehicle to vehicle comparisons can be made easily. These alarms can be triggered on baseline system testing, or reliability data gathered from other vehicles, prompting maintenance or inspection. Furthermore, the derivative of the FDS may be useful for ascertaining the rate of damage (or damage potential) of a given environment, operational profile or even operator. Smart systems which track and monitor the equipment location, operator, and speed could be used to identify operational conditions that cause a high rate of damage. Future systems could also incorporate this information into real-time updates to the operator (or perhaps driverless system controls) to reduce the overall damage to the system. During reliability trials this data could be used to ensure repeatable results, and may offer

insight into degradation of road surfaces, or other changes to the test conditions. A concept on how this system might work is shown in Fig. 2.

Conclusion

The use of measured data in creating mechanical vibration test profiles offers many benefits, primarily in ensuring that the test profile is fit for purpose and tailored to the device under test. There are barriers to achieving this, as the process to convert measured time series accelerometer data to a test PSD can be complex, and often requires a high level of engineering judgement. A new software program, Aquila Vibration Profile, offers access to advanced vibration profile creation techniques (such as the FDS), overcoming these barriers.

Incorporating well designed data reduction techniques using the FDS, offers significant benefits to HUMS systems. These benefits include a significant reduction in data throughput, a more robust and representative test program, potential new insights for condition based monitoring and more effective maintenance planning programs.

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