Vibration Test Replication of Operating Environments

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Mercury Marine has successfully implemented a product durability test program using actual recorded data that is replicated in the laboratory. A brief history of environmental vibration testing and field vibration replication techniques are reviewed in this article.

Since the early days of piston-engined, propeller-driven aircraft, vibration testing has evolved to match the changing requirements and improvements in instrumentation technologies. Since the vibration environment in piston-powered aircraft is primarily tonal, sine testing and swept-sine testing provided a good simulation of the actual vibration. More importantly, sine testing was possible with the technology of the time. As jet power replaced the pistons, requirements for vibration testing changed dramatically. Jet powered aircraft fly at higher speeds where aerodynamic forces cause primarily broadband vibration.[1]

As the vibration environment changed from tonal to broadband, new testing techniques were developed. New technologies such as the Fast Fourier Transform (FFT) analyzer became commercially available. With the FFT analyzer, Power Spectral Densities (PSDs) could be taken directly either in the laboratory or from field data taken with tape recordings. The PSD spectra could then be converted into a random profile, often by tracing the envelope of the spectrum on a transparency, for use in closed-loop random vibration controllers.

Sine testing continues to be used to test objects where there are strong tonal components, including:

- Low performance propeller-driven aircraft
- Jet-powered turboprops and helicopters[2] with their large propellers and rotors
- Mounting locations directly on the engine[3]
- Vibration caused by gunfire[4]

In addition, some standards such as MIL-STD-167-1 Mechanical Vibration of Shipboard Equipment still use sine testing because it was the technology available when the standard was written.

Random Vibration Tests

A random vibration test is described by a test profile defined in terms of a Power Spectral Density (PSD). The PSD magnitude at each spectral line is the RMS^2, or mean-square output value of an equivalent 1 Hz wide band-pass filter centered at each spectral line. The PSD spectrum has magnitude units of g^2/Hz, where the 'Hz' dimension is the noise bandwidth of the filters actually synthesized by the FFT. The noise bandwidth is the nominal frequency resolution ($\Delta f = 1/n\Delta t$) of the n-point FFT multiplied by the shape factor of the window function used in the FFT. The window function most commonly applied to a random test is a Hanning window, which has a *shape factor* of 1.5. The PSD spectrum is a good representation of the power in the total signal. *The square root of the area under this curve closely approximates the RMS value of the total signal.*

The trick, or art, is how to turn the field data into a random test profile that represents the actual environment. Two methods commonly used to produce a random test profile are the "average method" and the "peak method."

To develop a test profile, the time history is divided into short time segments, and the PSD is computed for each of these segments. For the "average method" of random test profile generation, all these PSDs are averaged together. For a given frequency line, the average method represents the average power of the entire time history. For the "peak method" of random test profile generation, find the maximum of any of these PSDs at each frequency line. For a given frequency line, the peak method represents the maximum power seen at that frequency in the entire time history.

Damage caused by vibration can be the result of either long-term fatigue or short-duration exposure to high levels of vibration. The "average method" is used for representing energy related to fatigue while the "peak method" is considered better for characterizing the damage caused from short duration events or transients. These assumptions have been tested on actual data for constant RPM and run-up/run-down cases.

Constant RPM. Figure 1 shows a section of the acceleration time history for an engine at a relatively constant RPM. These steady state conditions are often seen in the automotive and aircraft industries when the vehicle is in an idle or cruise configuration. The RMS and the peak accelerations from the actual waveform are compared to random test profiles generated using the 'average' and 'peak' methods described above. The random test peak acceleration levels were measured over a 60 sec test period with sigma clipping turned off on a nonresonant structure. (Instead of discussing whether sigma clipping should be used, it was simply turned off to maintain consistency.)

As expected, the average method RMS acceleration of 1.97 g is close to the actual RMS acceleration of 2.03 g, and the peak method acceleration of 9.74 g is close to the 9.27 g peak acceleration of the actual waveform. The peak method acceleration (3.83 g RMS and 18.7 g peak) are too demanding by 90% and 100% when compared to the actual measured acceleration.

Run-up and Run-down. Figure 2 shows acceleration measurements for an engine during run-up and run-down. These operating conditions are often seen in automotive and other industries with variable speed rotating elements. Although transient events like run-up and run-down typically represent a small percentage of total operating time, they often have the highest absolute levels. The random test peak acceleration levels were actual levels measured over a 60 sec test period without sigma clipping.

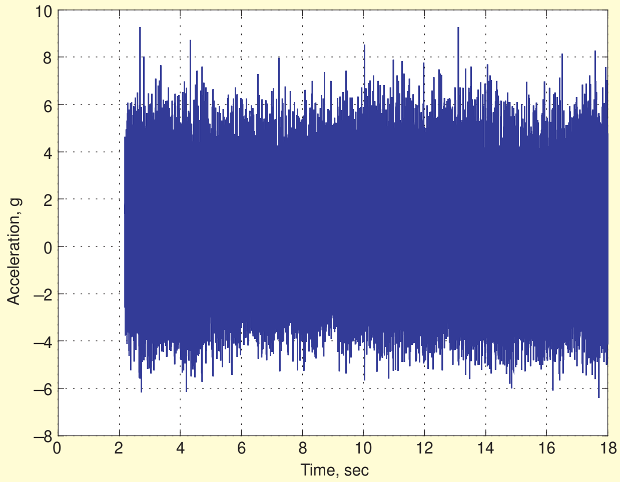
Note that neither the average method nor the peak method accurately represents the actual vibration levels of the engine as shown in the actual waveform. As expected, the average method produces the same RMS acceleration levels as the actual waveform. However, looking at the peak acceleration levels, the average spectrum is too conservative by approximately 40% and the peak spectrum is too demanding by 160%.

Transient operating environments such as this are where random vibration control begins to diverge from real world conditions. For some transient events, such as a drop test, earthquakes and other short duration events, techniques such as shock- and shock response-spectra (SRS) have been applied.

The problem with vibration test replication is simulating longer transients such as engine run-up or gunfire. Various combinations of random, shock, SRS, sine-on-random, and random-on-random test environments have been applied to the gunfire-testing situation.[5] Advances in digital signal processing (DSP) and storage devices have improved techniques for simulating longer transients.

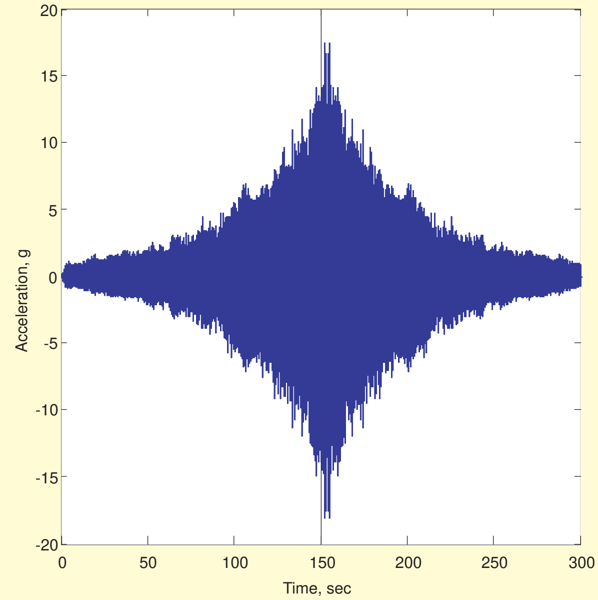
Field Data Replication

The goal of vibration testing has always been to make the test



	Peak Acceleration	RMS Acceleration
Actual Waveform	9.27 g	2.03 g
Average Method	9.74 g	1.97 g
Peak Method	18.7 g	3.83 g

Figure 1. Engine vibration levels for a constant RPM condition.



	Peak Acceleration	RMS Acceleration
Actual Waveform	18.2 g	1.73 g
Average Method	8.05 g	1.73 g
Peak Method	48.1 g	9.86 g

Figure 2. Vibration levels for an engine during run-up/run-down condition.

as close to reality as possible while maintaining repeatability. The direct reproduction of vibration data recorded on site has become practical because of rapid advances in computer technology. This technology has now progressed to the point that it is possible to calculate a transfer function for a shaker and fixture in real-time, while simultaneously streaming the recorded data to the shaker system. This allows test technicians to control vibration that exactly matches data recorded in the field; hence the name “Field Data Replication.”

The most recent version of MIL-STD-810F (1 January 2000) added a procedure for direct reproduction of measured material response data to the previous procedures of statistically generated repetitive pulse, repetitive pulse shock response spectrum (SRS), and high level random vibration/sine-on-random vibration/narrowband random-on-random vibration. The standard makes the following comments about direct reproduction:

For single point material response measurements on comparatively simple dynamic material, the method of direct reproduction of in-service measured material response is near ‘optimal.’ The main advantage of this technique is that it permits reproduction of material responses (nonstationary or transient vibration) that are difficult, if not impossible, to completely specify and synthesize for input to a vibration exciter control system. The main disadvantage of this technique is that there is no obvious way to statistically manipulate the measured material response data to ensure a conservative test. However, conservativeness could be introduced into the testing by performing the manipulation at a reduced level of vibration exciter power amplifier gain and then testing at the higher gain. The assumption behind this scenario is that the test item response resulting from the vibration exciter input is a linear function of the power amplifier gain.

Note that MIL-STD-810F actually advocates running open loop control of the shaker. With today’s controllers, it is possible to run the test in a closed loop configuration with an amplification factor to ensure conservativeness and repeatability.

Benefits of Field Data Replication

Multiple Waveforms, Same PSD. Since most analyses of time signals occur on analyzers with averaging turned on, it must be noted that the averaged PSD can hide much significant information. Transient events in a field sampled waveform can completely disappear in the resulting averaged PSD. As these transients could very well be causing damage to the product, any random test profiles generated from this PSD could be missing a major source of product failures, leaving the product seriously under-tested.

Closest to the Real Environment. The goal of testing is to accurately simulate the environment to which the product is actually exposed. Over the years, many attempts have been made to get closer to the actual dynamic environment when testing in the lab. Mixing both sine and random test modes together with “sine on random” testing is a good example of these attempts to reproduce the field environment. With current technology, it is now possible to reproduce in the lab the recorded dynamic vibration signal experienced by a product in the field. This technique allows testing past normal dynamic levels. This can be done by setting the test to run at multiples of the recorded levels, thus increasing the severity of the test while maintaining a very close representation of the field environment.

Oversampling. In any form of vibration testing, the testing sample rate is crucial. In random testing, for example, it is generally accepted that the sample rate should be at least twice the highest frequency in the spectrum. This means that a random profile which goes to 2000 Hz will require a sample rate of at least 4000 Hz. Due to practical filter limitations and to avoid aliasing, random controllers over-sample by 35% or so. For example, a 2000 Hz upper frequency would set the sample rate at 5400 Hz.

While it is possible to generate accurate random tests with a sample rate of slightly over twice the highest frequency, it is not fast enough for accurate data replication. A sample rate of twice the upper frequency limit allows only two data points at the highest frequency on the profile. This does not allow enough data at the high frequencies to maintain signal resolution. Figure 3 shows a comparison of 4× and 65× over-sampling to graphically illustrate this point. Audiophile types maintain that an over-sample of 10× is required to accurately reproduce audio signals, meaning that 2000 Hz data should be sampled at 20,000 Hz. Practically, a 5× over-sample is usually adequate for vibration testing. Though 5× is often adequate, there are still tests, such as MIL-STD-810F Method 519.5 Gunfire Vibration, which call for sampling at 10× the highest frequency of interest to more accurately represent conditions in the field.[5]

Extended Time Histories. Transients can vary from short

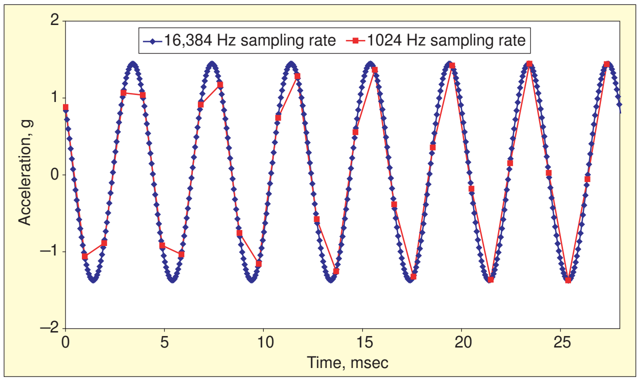


Figure 3. 250 Hz tone at 1024 Hz and 16,384 Hz sampling rates.

events on the order of a few seconds up to very long events lasting hours. To handle long transients, it is important to have a system with "no limit" on time duration of the data. In reality, the current limits are the size of the hard disk drive, sampling rate and file size limitations of the computer's operating system.

Live Filtering. Ideally the actual time signal would be reproduced over the entire frequency range. Practically, shakers (electrodynamic or hydraulic) and fixturing have displacement and frequency limits. The displacement and frequency limits affect all test techniques, including sine, random, shock and field data replication.

Currently the longest stroke available from an electrodynamic shaker is approximately 4 in. peak-to-peak. Hydraulic shakers feature larger displacements but lower high frequency ranges. These limitations often cause problems in reproducing the data, which make live filtering crucial. Live filtering allows certain frequencies to be effectively removed from the time history interactively, which is most important for displacement limitations. Live filtering allows test technicians to control the maximum displacement of a test by lowering the minimum frequency until it reaches the maximum displacement available from the shaker.

Shaker-fixture combinations have a maximum frequency limit. A low-pass filter can be used to limit the signal to a frequency that a given shaker and fixture are capable of accepting. Such limits are important because, while data should always be over-sampled by 5-10 times the highest excitation frequency, the shaker should not be driven beyond half the sampling frequency.

Notch Filtering. Notch filtering works very much like high pass and low pass filtering. Instead of removing the frequencies above and below certain points, a notch filter will remove a band of energy from inside the frequency limits of a test. This becomes useful when a particular frequency is suspected of damaging the product being tested, allowing the suspect frequency to be cut out of the signal to see if the problem goes away.

Mercury Marine Accelerated Life Testing

The goal of vibration testing is often accelerated life testing. The damage from a lifetime of operation is compressed to reduce testing cycles and development time. With random testing the common approach is to increase vibration levels to simulate longer operating times. The exchange rate between increased vibration levels and accelerated time is a topic of some debate. Even if an exchange rate is accepted, random testing with evaluated levels can only simulate damage caused by fatigue. If a part sees transient values of 10 g at certain points during its operation, testing the part at amplitudes higher than it will see in operation can lead to over-testing and over design.

Mercury Marine, a division of Brunswick Corporation of Lake Forest, IL, is the world's leading manufacturer of marine propulsion systems. Since the company was founded in 1939, Mercury has consistently emphasized quality, innovation and reliability. Since marine propulsion systems tend to operate over a wide range of speeds, a random profile generated using the average method will tend to under-test the part, while a random profile generated using the peak method will tend to over-test.

Mercury Marine uses the field data replication method to test its engines. First, a time history over the entire RPM range is used to create a peak-hold spectrum, which shows the highest value at all frequencies the engine would see in operation. The highest levels of vibration tend to occur at the higher RPMs of the engine's operating range.

A system being tested must include all fluids, pressure and electrical power components (fuel rails, injectors, vapor separator, hoses, etc.), which will simulate operation of the engine. Whenever applicable, the performance of a component is monitored in real time.

The requirements for successful qualification are 2000 hours of operation with equal running time spread across the entire engine speed range. After successful qualification, the test profile deemed the worst will be accelerated by a factor of two each day until failure occurs. This is done to determine the design limit of the parts. All components and systems tested must complete vibration testing in all three axes without any failures or intermittent operation.

To reduce test time and more efficiently test their product, Mercury Marine looks for that part of the operating range with the most vibration. Starting with the time record from the top 20% of the engine's RPM range, they compare the peak hold spectrum of this range with the peak hold spectrum of the entire RPM range. If the two spectra match, then the 20% time record is used for testing. If the peak hold spectrum of the top 20% range is below the peak hold spectrum of the entire RPM range, the time record is extended to 40% or 60% until the peak hold spectra match.

It is assumed that the engine spends equal amounts of time at all operating speeds during its service life. Using this assumption, test time can be reduced by the percentage of the RPM range used for the time signal. For example, if the vibration for the upper 20% range is found to match the peak hold spectrum for the entire speed range, then 400 hours of testing at the top 20% is equivalent to 2000 hours of testing over the entire RPM range. The actual time of the test will be determined by the acceleration factor(s) applied to the test.

Conclusion

Field data replication is a valuable tool for vibration environments with a mix of sine and random spectra. Examples include:

- Run-up/run-down testing on automobile and marine propulsion systems
- Gunfire testing to MIL-STD-810F

To maintain testing accuracy, make sure to include features like over-sampling, long time histories, and filtering (low pass, high pass and notch) when implementing field data replication.

References

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