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Vibration Test Goals: Efficient, Effective and Valid

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Even the most rigorous and thorough test methods can miss their mark, without proper understanding and analysis of the test results.

Commercial industry often uses Design of Experiments (DOE) for development of reliable electronics. DOE applies statistical analysis to develop a product in as few experiments (tests) as possible. Electronics life capabilities can be greatly influenced by power cycles as well as thermal, vibration and shock environments. For high-production commercial products, multiple destructive tests can be run due to low product cost. However, DOE tends to be product unique and is not very efficient.

Many common methods for designing electronics for harsh military environments use field experience to determine vibration/shock capability and reliability. Products can be obsolete prior to being understood. A lack of understanding can result in an inadequately designed or unreliable product. Methods that depend on field failure experience to improve products are not very effective.

Military and aerospace companies can rarely run multiple destructive tests required for DOE approaches, since circuit cards can cost tens and even hundreds of thousands of dollars each. Developing high cost systems requires detailed understanding of the product and of the fundamental details of tests. When the product is understood, development of rugged, reliable electronics is greatly simplified. Nearly every product is thermally designed for heat dissipation through detailed analysis. Simple analysis can similarly cover shock and vibration.

A Valid Combination

There are indications that test understanding often falls short. As an example, the validity of Highly Accelerated Life Testing (HALT) is questioned by many, but few question the validity of qualification testing of a single unit. When coupled with product understanding, HALT and Qualification Tests are valid. The HALT process has the step “determine root cause of failure.” This requires understanding the fundamental details of the failure. If this is properly performed for the product and for any design improvements when necessary, HALT is valid. When vibration tests and the tested products are understood, the tests are valid.

Qualification Tests are Accelerated Life Tests (ALT) that apply equivalent environmental exposure in a compressed time period. In vibration, this is accomplished by vibrating the product at higher excitation than those expected during service life. The time compression used in the test is based on the fatigue properties of the parts of the product. Equivalence of life means equal damage accumulation. Figure 1 illustrates the high cycle fatigue properties of a typical assembly part.

Time compression for qualification tests is often based on an average fatigue slope, which is an over-test for some parts and under-test for others. A qualification test is rarely questioned when passed, but is the test valid if it is an under-test for the weakest parts?

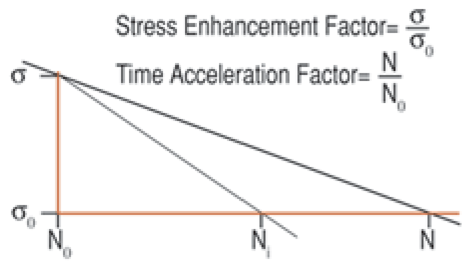


Figure 1

Time Compression of ALT requires a "factored" amplification of applied stress. The high cycle fatigue curve is represented by a log σ - log N plot. For any specific product, the number of applied stress cycles, N, is directly proportional to the duration of vibration. Compressing the test time by the ratio N/N_0 is accomplished by increasing the amplitude of vibration by the stress ratio σ/σ_0. The time compression is material-dependent. For a material with a different fatigue slope (Ni curve), the stress ratio σ/σ_0 would result in an equivalent time compression of N_i/N_0. The N/N_0 time compression test would be an under-test for any material with a larger fatigue slope (as in the N_i curve) and an over-test in any material with a smaller fatigue slope.

The ideal time compression should be based on the fatigue slope of the weakest parts, requiring an in-depth understanding of the product at root cause of failure level. Root cause understanding is critical to all effective vibration and shock testing.

Root cause understanding requires detailed analysis but does make the testing efficient and effective. It also defines failures in terms that are transferable across designs. Without root cause, every product is unique because failure is related to test measurements by parameters that hold only for the design tested.

Vibration Failure

Circuit card assembly failures from exposure to vibration are usually from accumulated fatigue damage. "Damage" is not a negative term. It is a mathematical means of describing exposure to stress cycles. Fatigue failures are dominated by high stress cycles because there is an exponential relationship between the damage caused by a stress cycle and the amplitude of the stress cycle. The highest stresses occur at structural resonance responses. These responses can be the modal vibration of the component itself or of the card assembly.

Decades ago, components used for military applications had their life capabilities specified in Gs and cycles of exposure. Most modern components are not fatigue dominated by inertial stress. They are dominated by stresses developed from forced component distortion imposed by matching the local mode shapes of the assembly at resonance. When stresses are dominated by mode shape of the assembly rather than the component itself, the correlation between stress cycles and measured response is unique to the product. Measurements cannot be used to predict expected life unless analytical models are used to relate response to damage. No simple conversion of acceleration or displacement or velocity relates to stress cycle damage accumulation for component stress dominated by assembly response.

Response Measurements Versus Stress

Attempts to correlate different designs to one another with combinations of exposure time and integrated measurements will fail, since they do not directly relate to damage. Two identical components with identical vibration exposure and measured responses can have drastically different life capabilities.

To illustrate this, Figure 2 shows two components on a very stiff circuit card. The card is very stiff relative to the components so the components do not significantly affect the mode shape. If this circuit card is vibrated at its first natural frequency, the component on the diagonal will fail first, even though the measured responses of the components are identical. For repeated repair and tests to failure, the mean life capabilities between the populations of failure for the two components can differ by over 1000, because failure occurs due to stress, not due to acceleration. This illustrates how the alignment of the component with mode shape can change product ruggedness. Mode shape is controlled by support conditions and other design parameters. A small shift in position of the weakest component can easily change the assembly's capability for vibration exposure by a factor of 100 MTBF.

Component life is also influenced by the flow of stress from all surrounding components and other design features. Understanding complex assemblies requires detailed modeling. Detailed damage analysis, coupled with test experience can numerically determine ruggedness and reliability for all electronic assemblies.

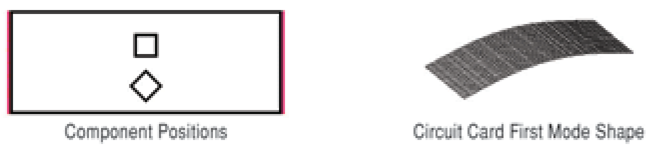


Figure 2

This simple circuit card illustrates component life capability is not proportional to measured response. The left side shows two identical components positioned at the center of a circuit card with "hinge" supports along the short ends. The right side shows the first vibration mode shape (displacement exaggerated). If the circuit card is much stiffer than the components, the two components have identical curvature and measured Gs response. If vibrated to failure, the component at 45° will fail first. If replaced, it will continue to fail first since leads in the other component are at much lower stress levels. Measurements in terms of displacement, velocity or acceleration are not a measure of failure for most modern components.

Resonances: Exponential Stress Damage

Response to vibration excitation is enhanced at structural resonances of the circuit card assembly. Stresses are much higher for resonance responses, but not every resonant cycle under random excitation is equally damaging because of stress response distribution. The exponential relationship for stress cycles can be illustrated with a simple plot. Figure 3 shows the response distribution and damage distribution (for a typical solder) for stress peaks for a single response mode.

The response distribution of acceleration and corresponding stress peaks is the Rayleigh distribution. The damage distribution shows the shift associated with the damage relationship to stress amplitude. The damage plot shows that responses below 1.0 sigma response at resonance contribute little damage. This is also an indication that non-resonant responses are insignificant for damage accumulation. For the damage accumulation plot shown, curve 3 in Figure 3, 1.1% of the response cycles cause 70% of the damage.

Isolation, Few Parts at Risk

The same stress/life relationship that makes vibration ALT efficient also eases understanding of electronic assemblies. Due to this exponential relationship, only high stress components are at failure risk. Since most modern components are stress dominated by resonances of the assembly, only those components in high

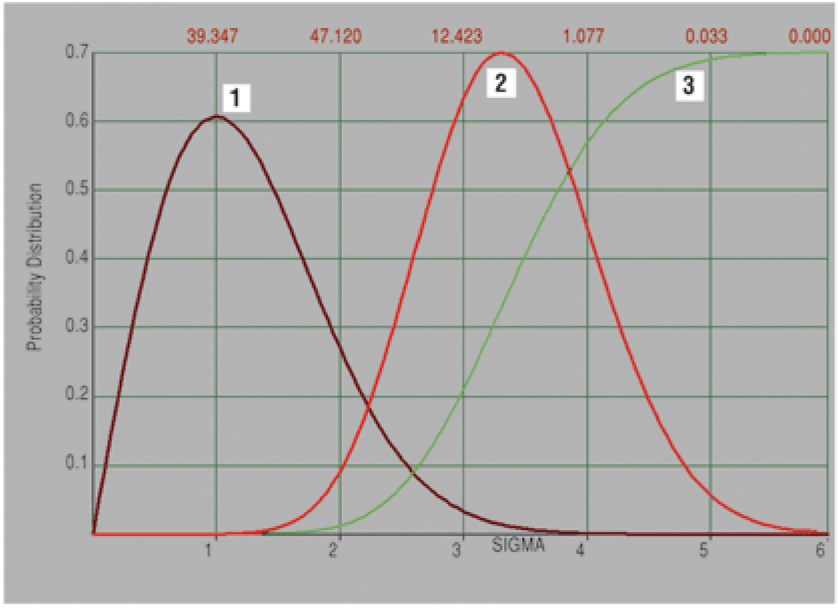


Figure 3

This graph compares vibration response distribution and damage distribution. Random vibration response distribution (the distribution of peaks of response cycles at resonance) is shown with curve 1. However, damage accumulation for each response cycle is dependent on the response amplitude, with higher responses causing more damage than lower responses. Curve 2 represents the distribution of damage of all the response cycles (consistent with the fatigue properties of many solders). Curve 3 is an integration of the damage distribution curve 2. The 1.1% of all response cycles (those above 3 sigma) cause 70% of the damage.

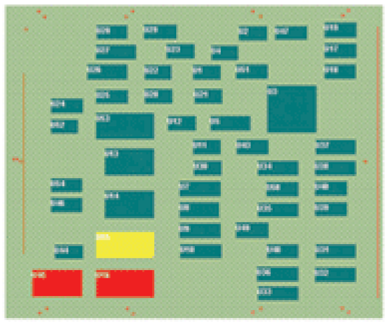
stress positions are likely to be at risk. Other components experience no significant damage under vibration. How do you determine which components are at highest risk? Figure 2 demonstrates that test measured responses do not describe component capabilities (unless they are stress driven by their own natural frequency). Parts at risk can be determined by performing detailed Finite Element Analysis (FEA). Since circuit cards use a limited number of general component configurations, FEA can be automated to perform analysis efficiently and accurately.

CirVibe software, a PC-based purpose built package for electronic circuit card assembly fatigue analysis, is used to illustrate component risk for damage. For any circuit card assembly, only a few components will be at highest risk of failure. An advantage of CirVibe is that it is highly automated, not requiring FEA expertise. Interfaces with electronic CAD programs allow models to be created in minutes, providing valuable information on component vibration damage distribution. Figure 4 shows results of a CirVibe analysis of a circuit card tested to failure.

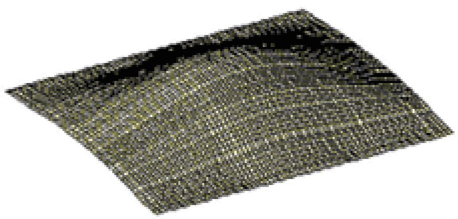
The analysis determined that the red components would fail first due to the high stress levels. These were the first to fail in a vibration step stress fragility test. The tests carried on to higher damage levels and additional component failures agreed with analysis results. The analysis provides numerical definition of the failures in damage terms that are transferable across designs. The weakest components in this design were at locations of low measured response.

Finding Failures Early

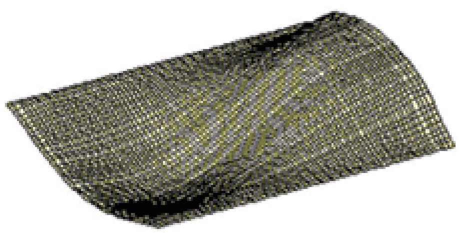
Environmental Stress Screens (ESS) expose hardware to environmental loads in order to prevent infant mortality of the product in the field. Vibration screens, when optimized, can be very efficient at finding production-related problems. ESS applies stress cycles that can find failures prior to product shipment. Detailed understanding is required to determine what level of stress can be applied without damaging the product and lowering its life expectancy. The same “root cause” understanding needed for all tests also defines damage in every component under the vibration screen. At levels of vibration that will not damage the weakest



Component Fatigue Damage Plot



Resonant Mode Shape 1



Resonant Mode Shape 2

Figure 4

This circuit card model response isolates most components from high stress—only a few components are at highest risk for failure. The two components in this Figure shown in red are at slightly over 100% life usage for the support condition, test profile and duration. The yellow component is at about 25%. All other components are at less than 1.0%—most far below 1.0%. The stress amplification accelerates the rate of component damage. Stress reduction by isolation protects most components from risk of failure. Detailed analysis determines components at risk. An interesting detail on this circuit card: the components that failed were at high stress, but at low "Gs response" locations.

component, the level of damage applied to all other components can be defined. Definition of the damage distribution defines the screen effectiveness.

When a product is designed for ruggedness, i.e., no excessively weak part, higher screen vibration levels can be used, which increases the ability to find flaws making the screen more effective. A fragile part, placed in a properly isolated position is not a weak part of the assembly. Being able to define damage experienced in a screen for each component through analysis allows understanding of screen effectiveness on a point-by-point basis.

Detailed Analysis is Key

The connection to root cause of failure under vibration requires a numerical definition of damage accumulation. This cannot be determined by test measurements alone but requires detailed analysis of the assembly. Understanding the product is critical for developing reliable hardware for harsh environments.

The most useful tests of electronics are tests to failure. Whether by HALT or other step stress means, creating a failure gives a true point in the distribution of failure. Validity of tests to failure can be measured by what is done with test results.

All decisions on test and product are eased when the product and test are numerically understood at the component level. This includes decisions on design layout, support modes, test acceleration factors, fixturing, duration, when to improve the design, how to improve the design, margin on requirements, how to combine multiple environments (Random and Sine), equipment control, vibration profile, test process, product design detail variations, etc. It is applicable to ALT, Environmental Stress Screening (ESS), Highly Accelerated Stress Screen (HASS), qualification testing, HALT and Step Stress Testing. Building quality requires an understanding of what quality is. Damage analysis provides the numerical definition of failure that makes vibration testing efficient, effective and valid.

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