What Results from Vibrating Electronic Systems?

Detailed analysis is no longer too expensive to use. Not using it can be disastrous.

John Starr, Engineering Consultant,
CirVibe
and
Wayne Tustin, President,
Equipment Reliability Institute

For many electronic systems, vibration is part of the qualification test requirements. "Qual" test vibration is intended to accelerate the damage anticipated during a life of service use. Military and aerospace companies often must develop systems for use in severe life environments using Commercial-off-the-Shelf (COTS) boards or components. Vibration is also often used in post-production environmental stress screening (ESS) programs. Here, operating products are exposed to various environmental conditions (particularly random vibration) to expose infant mortalities resulting from part and workmanship flaws. Many organizations have found exposure to vibration to be the most efficient means of finding flaws.

But design efficiency, development, testing and screening including HALT, HASS, ESS, ALT, and Qual requires full understanding of how the product responds to vibration (Table 1). Screening requires avoiding damaging fragile areas while at the same time adequately exposing risk regions. In the past, maintaining this delicate balance was difficult.

The reason is that vibration of electronic systems is very complex. Tests are expensive and they provide very little information. Worse, little more is gained by applying mere empirical analysis. However, modern computer technology now provides the opportunity to greatly expand the understanding of vibration of electronics, thereby greatly expanding the test results. This expanded knowledge shows in improved product reliability at lower cost.

Physics of Failure

Whenever a failure takes place during ESS, HALT, HASS or other test, it is essential to identify the root cause of the failure. When vibration is understood at the root cause level, design changes to *avoid* that failure can be implemented with the greatest probability of success and at the lowest cost. Physics of Failure (PoF) analysis is the application of engineering, science and mathematics for product evaluation at point of failure level, considering all contributions to that failure.

Both commercial and military companies are incorporating PoF for developing more reliable products while at the same time reducing costs. Defining damage under vibration is key to developing products that meet design requirements. PoF analysis can translate test measurements into numerical definition of component fatigue damage. PoF is also key to optimizing ESS.

Tests…or Results?

It's clear that testing is required, but what's the efficiency of a test? Tests are run for "results". But, measurements are not results. Rather, new product knowledge is a result; a failure is a result. Analyzing PoF measurements provides results and greatly expands knowledge and efficiency.

Tests can determine fragility limits of test samples, but few tests supply

Test		Description
ALT	Accelerated Life Test	Tests performed at high intensity for the purpose of defining fragility limits of a system
ESS	Environmental Stress Screen	Products are exposed to various environmental conditions (particularly random vibration) to expose infant mortalities resulting from part and workmanship flaws
HALT	Highly Accelerated Life Test	ALT at higher intensity optimized for ALT Test process costs
HASS	Highly Accelerated Stress Screen	ESS at higher intensity optimized for ESS process costs
Qual	Qualification Test	Tests performed at higher intensity to create damage anticipated during a life of service use

Table 1

Life test and stress screen acronyms and descriptions.

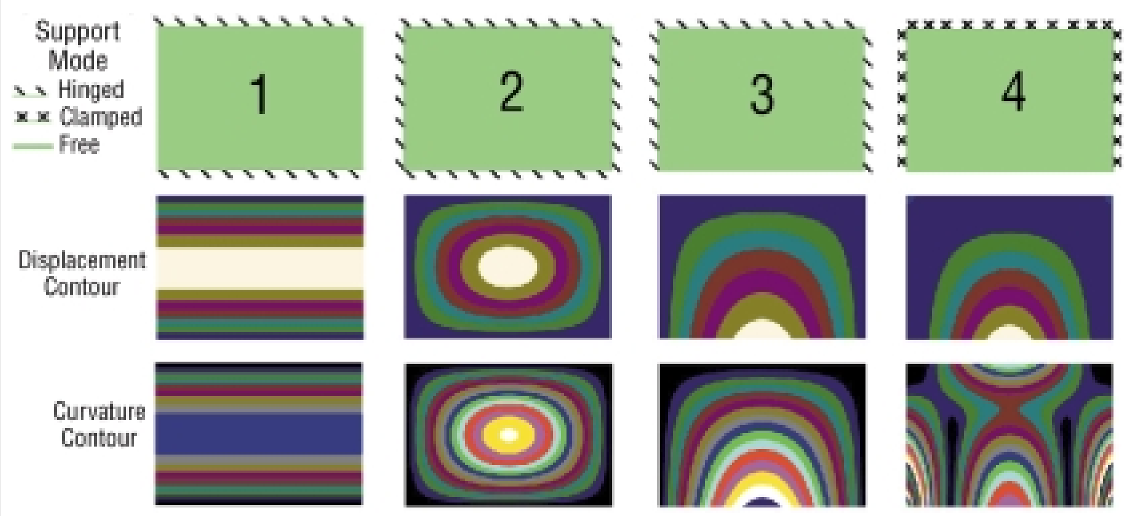

Figure 1

This figure displays the displacement and curvature plots for the first vibration mode shape for uniform plates with sets of ideal support conditions. The first row displays the support configuration; the second row displays displacement contour plots (lines of equal displacement); and the third shows curvature contour plots. Curvature is representative of local bending. These plots illustrate the ideal conditions often assumed to exist in the analysis of circuit card vibration life.

information beyond pass/fail. Why? Because test measurements can't fully describe failures. All too often, attempts are made to define hardware capability, but only in vibration response measurement terms, such as Gs or Gs_{rms}.

Failures under vibration are typically fatigue failures that occur due to stress cycles at a *point* in the assembly. As an example, a circuit card can fail from a solder joint crack. It is impossible to conduct a test and measure the accumulated fatigue damage to every solder joint and every other possible failure type. Tests miss most of the valuable failure-related information that nowadays is readily available.

Therefore, it's critical in electronics to understand the impact of expected product variations that can determine life capability. It's really the iterative process of understanding what the test is trying to accomplish coupled with analyzing the results that yields useful information and makes the test beneficial.

Analyzing Tests with COTS Software

In the '70s and '80s, relatively simple empirical equations such as the Steinberg rule were developed to predict vibration life capabilities of circuit cards. These equations often looked at products in only one dimension and to only first-order parameters, such as circuit card and component lengths, as well as component position on the card. They were developed because few companies could afford that era's high-speed computer systems and the technical expertise needed to analyze vibration.

Those methods, still used by many, provide guidelines that only sometimes work. In any complex field, it is easy to establish a simple design rule. A simple rule does not attempt to define strength or margin, and it is an application without understanding. If an adequate design margin exists for all products when that rule is applied or if failures experienced are not costly, there is no need to look for a better design method. Unfortunately, all too often such guidelines for electronics fail outright, causing great expense.

But since the time when the formula was first developed as a substitute for detailed computer analysis, the cost of high-speed computer power has dropped at a rate of about 50% per year. The compounded cost savings of the mid '80s high-speed computer is over 99.99%. That means that now, every company can afford high-speed detailed analysis tools in support of its testing and product development. One of the best kept secrets of a large company's ability to produce reliable products at low cost has been its ability to fully understand vibration of electronics through detailed analysis.

Empirical Methods vs. COTS

Every test performed without detailed post-test analysis throws information away and wastes money. Rather than throw it away, information can be captured and used to save many design and production problems. The money saved is the cost of failed electronics that far exceeds the cost of tests. Examining the differences between results provided by empirical tests and COTS-based analysis can be startling.

Early methods were very crude. When designs failed, the methods gave little help in understanding why. Over the years, understanding of product vibration capability has been limited to what little knowledge could be extracted on a limited testing budget.

More than twenty years have passed since those analysis methods were developed. The following examples illustrate the mathematical view of circuit card vibration as viewed by a simple empirical approach and a detailed analysis approach. Previously, circuit card vibration life evaluations required detailed Finite Element Analysis (FEA).

Instead, PC-based COTS software such as CirVibe are purpose-built for electronic circuit cards fatigue analysis. Even better, CirVibe is an automated analysis package that eliminates the need for FEA expertise. Models created in minutes provide valuable information on component vibration damage distribution across any circuit card under single or multiple environments.

Simple Plate Vibration Example

As shown in Figure 1, an empirical equation approach must look at a circuit card as if it is the simplest form possible—a flat plate without any complexity. It must also look at a component in the simplest form—how much is it bent? Figure 1 illustrates mode shapes (displacement and curvature) in flat plates. But even three of these simplified systems are too complex for empirical methods.

Empirical methods were simple but not representative of mode shapes of real cards. Components are sensitive to magnitude of curvature as well as direction of curvature (curvature is a numerical definition of component bending). Figure 1 shows the first vibration mode shape of four simple plate configurations. These mode plots are for plates of uniform thickness and stiffness.

The top row illustrates the support mode for each column. The first three configurations have two to four hinged supported edges. A "Hinged" supported edge has displacement held to zero. The last (number 4) has three clamped edges. A "Clamped" edge has both displacement and slope (the rate of change of displacement) held to zero, like the "Fixed" end of a cantilever beam.

The second row shows displacement contour plots, while the third row shows curvature contours. These plots represent the curvature that would be forced on a multi-lead component based on its attachment location. Stresses from curvature normally dominate fatigue life and define vibration capabilities. It's important to note that Figure 1 displays the condition assumed by empirical equations, but that these conditions don't exist in the real world. Here's why.

For many systems the first vibration mode (as in Figure 1) dominates stress-defining fatigue life. Empirical equations were based on one direction of curvature, since consideration of the second direction was far too difficult. This lumped all the vibration into Configuration #1 of Figure 1, with curvature occurring in one direction only. The parallel contour lines show that curvature occurs only in one direction in the plate, since the primary direction of curvature is normal to the contour lines.

For almost any component, curvature in the second direction will change the stress condition and affect life capability. Configurations #2 to #4 are "closer" to typical support conditions, but the mathematically ideal "handbook" conditions of clamped and hinged supports do not occur in real circuit cards. The direction of curvature changes for every position, and empirical predictions will have a different level of error for every component. There is error due to differences in support conditions and error due to the alignment of the component with curvature. Since fatigue life is exponentially related to stress level (Equation 1), there can be huge errors in predicting life capabilities using only empirical predictions.

$$N S^m = C \qquad \text{(Equation 1)}$$

N = cycles to failure
S = alternating stress
m = material-dependent exponent
C = constant

Real World Circuit Cards

Circuit cards are far more complex than the simple plate models discussed previously. Circuit cards can be very flexible or can be stiffened in multiple ways, and components can significantly affect the stiffness. Cards can be supported by standoffs, wedge-locks, connectors, frames and many other means. In addition, stiffeners, screws, standoffs, board cutouts, or other components can act as "stress risers". Under random vibration, stresses from multiple mode shapes combine. All these complexities affect component life.

If we consider the expected error in the ability of a simple formula to predict component stress on a plate from Figure 1, such as using the Steinberg equation (examining card and component length, and component placement), the lowest error would occur in Configuration #1. The formula is based on a single direction curvature and Configuration #1 contains only one direction of curvature.

Configurations #2 and #3 give greater errors due to the two directions of curvature and the stress error associated with the alignment of component and curvature resultant. Configuration #4 errors would be even higher due to the complexity of the mode shape. The curvature contour lines indicate a curvature reversal, illustrated by the contour lines "radiating" from the supports on the ends of the free edge.

Detailed Analysis—Physics of Failure Understanding

The "design life" of any system is defined by its weakest part and the part's local exposure. Since vibration damage of circuit cards is dominated by cyclic stresses experienced at its natural frequency mode shapes, analysis must accurately quantify the stresses experienced in every component. Design life is defined by accumulated fatigue damage. Taking advantage of the speed of today's PC, even companies without prior experience can obtain product understanding.

PoF analysis is detailed analysis beyond the information presented in the main article. Figures 1 and 2 are circuit card level analyses, whereas PoF is a level of analysis higher. It carries the analysis to stresses in components and requires adequate detailed input data in order to be effective.

As an example of the capability of detailed PoF analysis, consider a component that fails a test and the circuit card mode shape critical to the failure of that component. Now select the two components "adjacent" to that component, based on the primary direction of curvature. Replace the adjacent components with much stiffer components. The added stiffness and reduced modal curvature will greatly reduce the stress in the "sandwiched" component.

The sandwiched component, more than likely, will not fail. This is similar to adding stiffeners to the card. A simple curvature analysis approach could not evaluate this situation. Detailed analysis is needed to evaluate every component at this level, based on its individual surroundings for all modes. Coupled with test programs, the knowledge gained is greatly expanded, and this level of understanding is a necessary part of reliable product development and test.

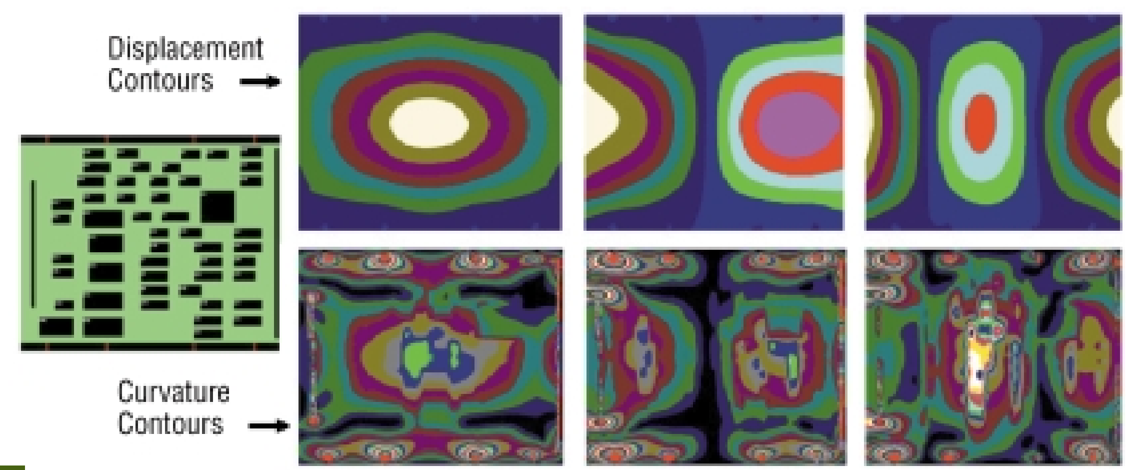

Figure 2

This figure displays the displacement and curvature contour plots for the first three vibration mode shapes for an actual circuit card (left) with wedge-lock edge supports at top and bottom and left/right connectors. The displacement contour plots show smooth shapes, similar to those experienced in the uniform plates of Figure 1, but the curvature plots show large disruptions due to the rapidly changing stiffness locally from connectors and components. These rapid changes in curvature and local concentrations are the reasons for the frequent failure of simple equations to predict vibration life.

How much error could be expected when empirical equations are applied to real world circuit cards? *Figure 1 curvature plots do not occur in real circuit cards,* because of component stiffness and the stiffness of all surrounding "structure". In contrast, Figure 2 shows displacement and curvature contour plots for the first three vibration mode shapes of a real circuit card having wedge-lock edge supports. It also shows an illustration of the circuit card layout, with wedge-locks on the top and bottom of the card, and a short stiffener on the left side and a longer stiffener of the right.

Displacement plots show smooth contours, but the curvature plots show many localized effects. The curvature plots show high stress regions at the clamping points of the wedge-lock (these were 5-segment locks) and at the ends of stiffeners. The wedge-lock concentrations occur in this design due to the concentrated clamping on a flexible card. Stiffener end curvature occurs as stiffener loads are distributed into the circuit card. Similar high stress points can occur with standoffs or cutouts.

The greatest difference between real circuit cards and mere plates can occur in "curvature". Added stiffness changes the vibration mode shape. On the other hand, displacement contour plots are smooth for flat plates as well as real circuit cards. Curvature occurs due to flow of bending moments in the continuous "plate" structure. If we consider adding a component that triples the stiffness locally, the local curvature would to be cut by a factor of three. But that curvature cannot be cut by three without a mode shape adjustment throughout the whole card for structural continuity. All "stiff" parts affect and contribute to defining each mode shape. Curvature contour plots tend to "box" around the component stiffnesses.

The curvature contour plots show this shift. The curvature is disrupted by combined board and component stiffnesses and this disruption is mode shape dependent. The smooth contour lines of Figure 1 do not exist when components are added to the system unless component stiffness is insignificant relative to the board stiffness (refer to the sidebar: Detailed Analysis—Physics of Failure Understanding) .

Figure 2 illustrates why detailed analysis using COTS tools is so necessary when developing reliable hardware. The complex curvature of a circuit card makes any simple formula prediction inadequate for product understanding. Vibration life predictions must include allowances for the statistical variations associated with (1) random vibration and with (2) fatigue failure. Since empirical methods attempt to describe component stress levels with a single curvature, it is not surprising that the methods often fail. Stress estimations are far more accurate with detailed analysis.

Step stress testing incrementally increases vibration testing to establish a designs fragility level. In step stress testing of the circuit card illustrated in Figure 2, the two components predicted to be weakest by detailed analysis failed first. On this circuit card, with further step stress testing, many additional failures agreed with the detailed analysis results.

In contrast to using COTS tools—using either no detailed analysis or just using empirical predictions—the test engineer still has the knowledge that these components broke and are the weaknesses, but there is no way of extrapolating the data for components substitution. Even worse, there's no way to use this expensive test information in other designs or to use past information from previous tests in the initial design of *this* product.

Predictions by the empirical Steinberg equation were not helpful in understanding this circuit card. These failed components were not considered to be the card weakness by this empirical method. There were many components that failed prior to reaching failure for the component predicted to be the fragility point. This is not intended to impugn the empirical methods of the past; rather, the methods met the needs of the time considering the resources available to most. But it's time to use modern tools to analyze and interpret test results. ▮▮

CirVibe
Plymouth, MN.
(763) 559-5166.
[www.cirvibe.com].

Equipment Reliability Institute
Santa Barbara, CA.
(805) 564-1260.
[www.equipment-reliability.com].