Vibration Screening Custom Tailored for Electronics

Temperature cycling and vibration are commonly used stress screens, but vibration can be more effective and cause less damage. The trick is to create the vibration screen with an understanding of the product at point of failure level.

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Environmental Stress Screening (ESS) exposes hardware to environmental loads aimed at preventing infant product failures, but it creates stress cycles that lead to fatigue damage. This can precipitate flaws to failure, and every load cycle uses some portion of available product life. Two commonly used environments for screening are random vibration and thermal ramping, which can be used jointly or individually. Either way, they should be understood individually, but there are differences between the two.

Thermal loading, or cycling between temperature extremes, creates high stresses everywhere. Failure can occur after relatively few thermal cycles. Each thermal cycle applied takes significant life out of *every* component. On the other hand, vibration can be the most effective screen if it is developed to match the needs of the particular product. Also, vibration has the advantage of applying many cycles of low stress, which is amplified by the presence of flaws, resulting in an accelerated rate of failure that's more controllable.

Vibration, however, can seem complicated. While thermal cycling stress is relatively independent of location on a card, vibration stress is extremely dependent on position. Vibratory cyclic stress depends on modes that highly load a few components while isolating many others, and the large variations in component device dimensions, materials properties and their fatigue characteristics make vibration testing a challenge. The good news is COTS vibration stress screens can now be optimized through the product understanding gained using desktop computer power coupled with automated vibration analysis software, and this understanding can result in huge savings.

What is the Ideal Screen?

For any type of ESS, if the screen is too intense, it uses too much of the product's life and can cause early service life failures. If the screen is too mild or invokes the wrong profile to effectively screen flaws, a flawed product can "pass", only to fail early in field use. An effective screen creates enough damage at risk locations to turn flaws into detectable failures.

Tailoring vibration screens to a product is difficult and the questions are many: How to attach the product to the shaker? What Power Spectral Density (PSD) vs. frequency profile should be used? These are difficult questions and are usually resolved by the process of developing a screen and adjusting it to compensate for failures known to occur in service life. But shipping an unreliable product can affect a company's reputation, and field replacement is costly. It seems obvious, but the best screen is neither too mild nor too severe.

Navy vibration screening guidelines were published in 1979. Though these guidelines clearly stated the need to customize screening to the product, many adopted the suggested "starting point" vibration profile directly from the document (Figure 1). Many still use it today,

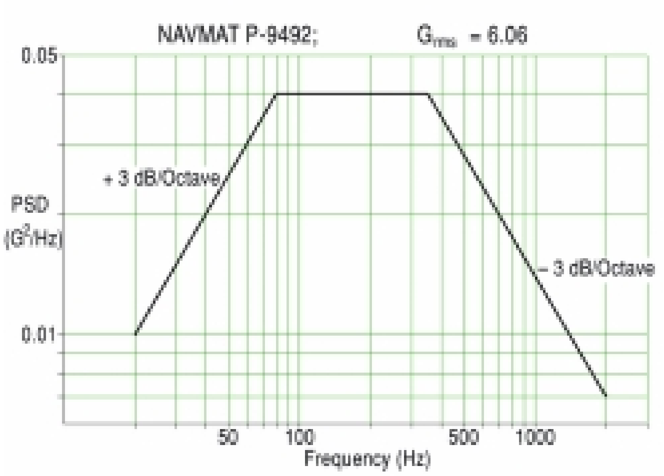

Figure 1

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not knowing how or why it should be modified. Is this the optimal screen for all products?

Back then there were no screen-optimizing tools for electronics. Screen optimizing could have been accomplished with early test analysis support, but in 1979 this was very expensive. It required analysis experts, few of whom fully understood what was needed or could present usable information to screen developers.

To create the ideal customized screen, a detailed understanding of how the product responds to vibration is required. Damage from vibration should be evaluated and fully understood *at the point where failure occurs.* Only then can knowledge accumulate and ultimately lead to screen improvement.

Vibration Screen Decisions

Tailoring involves modifying controllable parameters to optimize screen efficiency. The two primary variables within the control of the screener are:

1) fixturing—how the test item is supported
2) vibration profile and duration

The first question is should the product be attached (fixtured or supported) to the shaker in the same manner as in-service or in some other manner? A screen is intended to be a "stimulation" and not a "simulation" of expected field environmental exposure. Creating a screen that mirrors the in-service attachment is more likely to find flaws that could become failures in service life under the same type of excitation. To do this requires product understanding at the component level to define when and how support variations (and fixturing) should be considered. The goal is to sufficiently "damage" all components to find flaws without using excessive life of any components. (Note: "Damage" is not a negative description; it is a mathematical means of describing usage due to the stresses of normal service life use.)

Concerning the second primary variable under the screener's control, the proper intensity and number of applied stress cycles depends on component details. Every component's damage exposure must be compared to its life capability. If all manufacturers built all components to identical cyclic bending capability, an ideal screen would bend all components equally. If nothing was known about the product, a reasonable goal would be to minimize the range of component bending (minimum component to maximum component).

Complex Damage

The concept of "damage distribution" is important when creating and evaluating vibration screens. To introduce damage distribution, results in this article are first presented for components of equal capability. Once damage distribution is understood, support conditions

Factors on Life

The size of each red area in Figure 2 depends upon the fatigue properties of the material at risk. These plots use a fatigue slope corresponding to a 1.2 factor on stress resulting in a 10 times reduction in cycles to failure. The 1.2 factor describes the slope of the fatigue curve for the material at point of failure and is representative of the exponential relationship between stress and cycles to failure. The 1.2 factor is within the expected range for electronic parts. A different value would result in a similar profile but different numerical life range. Consider a change to 1.26, which corresponds to some solders. A stress factor increase from 1.2 to 1.26 would reduce the 10,000-life range to 1445.

New Life Range—Calculation Details:

A 10,000-life factor is four powers of 10. Since each power of 10 on life corresponds to a 1.2 factor on stress, a 10,000-life factor corresponds to a four powers of 1.2 on stress. The total factor on stress for four orders of magnitude on life:

$1.2^4 = 2.07$ factor on stress.

If the fatigue curve had a slope of 1.26 (typical of some solders), the 2.07 stress factor is a lower number of powers of 1.26 ($1.26^{3.16} = 2.07$). Since the stress power on 1.26 is equal to 3.16, the same 3.16 is the power used for powers of 10 on life. For a material like this solder, the power on life would be $10^{3.16} = 1445$ life factor. The RED area in the plots would represent approximately a 1445 life factor (minimum to maximum).

and/or the vibration profile can be tailored. Using advanced COTS software and technology to visualize damage greatly eases the process of optimizing a screen. CirVibe, a purpose-built software package for vibration test fatigue damage, is used in the following analysis.

A circuit card is a complex distributed mass-spring system. Over a range of forcing frequencies (field or test lab), a basic set of mode shapes (circuit card flexure) will occur. These mode shapes depend upon dimensions, thickness, frame, stiffeners and support conditions. Adding components to the circuit card modifies the set of modes by adding component mass and stiffness. Mounted on a circuit card, the life capability of a component is primarily defined by its ability to survive flexure cycles.

Random vs. Sine

Some engineers say "random vibration is more damaging than sine", but the truth is that either will excite the vibration mode shapes of the card. Random vibration excites all modes simultaneously, and damage calculated for the response in one mode shape of vibration for random excitation underestimates the damage actually occurring. Why? Because of the added stresses from other, simultaneous, vibration modes. Even when these additions are smaller, the exponential relationship between life and stress causes a large increase in damage.

Fatigue damage from sine or random vibration can be evaluated with current PC computational power, as opposed to requiring supercomputer-like horsepower, and damage does not have to be approximated with decades-old formulas. Damage can be numerically defined at every component for any support mode and vibration profile. And numerical results can even benefit other tests. For instance, the level of damage that will precipitate a component flaw to failure can be defined and this information is transferable across design configurations. The following calculated results achieve detail down to the level of component/board solder connections.

Concept of Damage Distribution

If all components were identical in terms of their flexural (bending) life, an ideal screen would flex all components equally. But components are not identical in capability, so effective screen development requires an understanding of design needs at component level.

Figure 2 contains "area" damage plots for three support modes (three columns) and four excitation spectrums (four rows: one broad band and three narrow bands) for a circuit card. The narrow band spectrums were selected to drive individual modes thereby being representative of sine excitation. Area damage plots evaluate position risk by analyzing local curvature on a standard component. The component used here is sensitive to flexure in both directions (an example could be a BGA). Area damage plots are very valuable in comparing screens (support and profile variations) and a great deal of information could be generated quickly—information that's useful in understanding the product for screen detail decisions.

Dynamic responses create component bending and inertial loading. Plots such as Figure 2 result from stresses due to circuit card natural mode shapes. Thus these damage plots depend on (1) component type (including "lead-wire" type and material), (2) support method details, and (3) excitation profile. The plots show some of these variations.

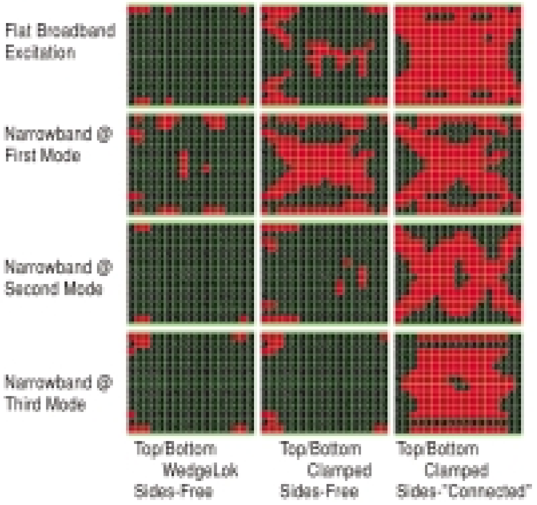

Figure 2

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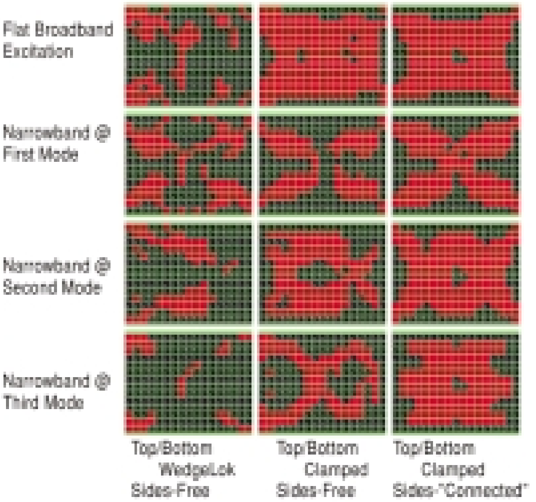

Figure 3

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The plots demonstrate the ability to control applied vibration damage distribution. The range of damage in the red area represents four orders of magnitude of "component" life exposure. A component in the worst position of the red area could experience 10,000 times as much damage as a component in the best position (refer to sidebar: Factors on Life). Since damage is a numerical representation of life fraction used, damage is proportional to the duration of vibration exposure. The four orders of magnitude on damage is similar to comparing vibration exposures of one hour to one year!

The last column of Figure 2 represents a support condition where most of the circuit card falls within 4 orders of magnitude on damage. Four orders of magnitude control may not seem tight, but it is when compared to the first column. If the card is tested in the normal support mode (equivalent to “simulate”), the entire board covers 15 orders of magnitude of damage, and less than 4% of the board area falls in the 4 orders range. With this support one can’t effectively screen a large fraction of the board without overstressing components in the 4% region.

However, a screen with this first support condition could be acceptable if the screen is known to be effective for expected problems. When the product is understood at component level, screens can be properly tailored.

Figure 3 displays damage comparable to Figure 2, but analyzes a component that is sensitive primarily to bending about the “Y” axis, such as a DIP-type component with lines of leads parallel to the “X” axis. The mode shapes for Figures 2 and 3 are nearly identical, but the red areas are very different, illustrating that damage is sensitive to component type.

Application to Design: Understand the Product

Similar plots can be created for the actual components used in any design. When using actual components, it’s important to evaluate damage against individual component strength. This requires an understanding of the components used. What is the vibration “quality” of the component and assembly manufacturing process? Such analysis of actual components is valuable in selecting a screen support and a screen profile.

Vibration screen development is greatly eased when the product is understood and when damage experienced by every component is known. Figure 4 shows damage plots for an actual design with support conditions matching those from Figures 2 and 3. These three life plots were determined by analysis using actual components, all having the same vibration requirements and screen profile. Components must be capable of being screened, plus they must have enough reserve life to meet design vibration requirements.

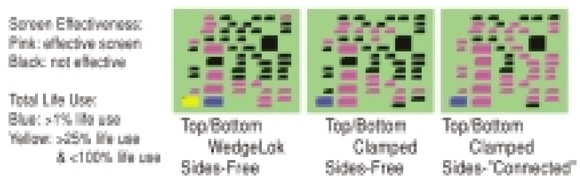

Figure 4

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There is no perfect screen; there is only the question of evaluating the adequacy of the screen to find the system production flaws. The plots show which components can be considered to be effectively screened. Screens can be optimized for any support condition and if an adequate portion of the board is screened—including areas of greatest concern—no adjustments are required.

Analysis provides data that defines screen effectiveness at the component level. These values are best defined in terms of damage, since damage is transferable across design configurations. Damage accounts for applied stress and number of cycles, and damage values in

Numerical Definition of Failures is Key to Understanding

Analysis of any support and excitation condition provides a numerical definition of damage for all components. Analysis translates that information for use in further development of this product and future products. On the other hand, tests to failure generate product information. With tests to failure, the damage at that point of failure is a numerical definition that works for that component.

Consider a common situation: no previous experience exists for numerical definition of either fragility limits or effective screen thresholds at the component level. The product should be tested to failure to define fragility levels for as many components as possible (as tested in their positions in this design). Each design has a “weakest” component for a defined support condition and excitation profile. Testing of a single unit might have failures of components in a different sequence (relative to risk) due to overlapping failure distributions. Numerical definition of component expectations allows a better understanding of component failure risk.

If a unit is very expensive and testing to failure is considered too costly, vibration has the advantage of causing high damage in a small number of components. Replacement of these few components after testing to failure can make this unit as good as new and allows testing to full vibration life requirements without failures. In the worst support condition of the design shown in Figure 4, only two components had “life use” above 1% when the first component failed.

If screen thresholds are unknown at component levels, a first screen profile could be set at a damage level of 1% maximum life for the design’s weakest component. Analysis of the design’s exposure to the screen provides numerical definition of damage at seeded flaw locations. For flaws found, the calculated damage defines initial damage thresholds for effective screens at component level. Screen threshold values are refined over screen life or screen development of other units. The damage threshold values will define the areas where the screen is effective. The resulting screens can find flaws in “low damage” regions of the board, but the flaws found would be expected to be of different types or more severe than those missed in the seeded testing.

With analysis support of screens, it is possible to use any profile or support condition and understand what it can and cannot do.

one design are useful in other designs of comparable component types. When damage is understood at the component level, vibration is understood for both screens and for field vibration.

Tailor the Screen

But, vibration cannot provide an effective screen everywhere. Screens can find flaws in all areas, but damage required to bring a flaw to failure depends on flaw severity. If a flaw is small, a particular screen may be inadequate at that flaw location. A screen can be considered to be effective in an area if its level of damage is adequate to find a flaw that might otherwise fail in service life. In “seeded flaw” tests, flaws that are missed can be attributed to local damage level short fall.

Screen effectiveness is determined by the ability to obtain a proper level of exposure at all possible locations of risk, without using excessive (component) life anywhere. When production risks can be predefined through knowledge of the product, the screen can be tailored to address risk. If risks are unknown, the screen can be set at a small life fraction of capabilities but tailored for uniform damage distribution.

If a region of interest must be screened, determine which mode shape contributes most to damage in this region; increase the profile in the frequency band that stimulates this region. The total damage from all modes to the most susceptible components will of course limit this increase.

Solder joint quality can be considered to be screened if adequate damage is applied in risk regions. If the solder process is uniform in nature, a solder failure anywhere can evaluate overall solder quality. But if solder quality may be bad in only one area on the board, damage distribution becomes important.

Support conditions can be selected based on the screening needs for specific areas. A fragile component can be isolated from excessive damage, while effective vibration is applied at other areas. The ability to numerically define (see sidebar: Numerical Definition of Failures is Key to Understanding) the screen at the component level allows early development of effective screens. ▮▮

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