Physics of Failure for Portable Electronic Devices in Military Applications

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SUMMARY & CONCLUSIONS

In military applications electronic devices play a vital role in the success of a mission. These devices which provide control, guidance, communication, and reconnaissance are critical components in modern unmanned vehicular applications. The current trend is to provide a human interface to control theses systems via portable devices. This trend in modern warfare has increased the complexity of electronic equipment, especially in low volume, highly sophisticated, and dense electronic systems. These modern devices take advantage of the remarkable advances made in low cost commercial electronics. This current movement of using commercial-off-the-shelf (COTS) electronics and devices for military applications has led to concerns about their reliability in harsh battlefield environments. The increase in the use of COTS components lead to the need to improve the reliability of these components by understanding the failure mechanisms due to thermal loads, dynamic vibration, and shock through Physics of Failure (PoF) analyses.

Unfortunately, current military standards do not provide an adequate approach to analyze, design, or test for those types of complex portable electronic systems. In some cases, the loading profiles may be over-conservative and in others under–conservative and not representative of the operational conditions. In this paper, a PoF approach is provided to understand the failure mechanisms experienced by these devices during their life-cycle. In this study, the life-cycle of portable handheld electronic device was modeled. The life-cycle included thermal loading from diurnal cycles and power cycles and vibration loads due to transportation.. The transient response of electronic assemblies to mechanical loading encountered in drop and shock conditions was simulated. These loads may impose significant stresses on the Printed Circuit Board (PCB) substrate, component packages, leads, and solder joints. Explicit finite element analysis combined with computational thermal analysis and analytical models have been utilized to uncover potential failure modes. To reduce the computational time and cost, modified shell elements were used to model the circuit card assemblies (CCAs). Failure modes predicted by the modeling and simulation were utilized to assess the overall reliability of the portable device.

This study demonstrates how a PoF approach may provide an understanding of the loads experienced by the electronics and how they affect the reliability of the device. This is critical to developing and acquiring more reliable systems as the DoD begins to utilize more advanced portable electronics systems.

1 INTRODUCTION

The increasing complexity of electronic equipment, especially in low volume and highly sophisticated and dense electronic systems, such as military, aerospace, and automotive applications, has resulted in an increased need to understand the failure mechanisms due to dynamic loads. Typically, electronic systems are subjected to various complex loadings, including vibration, during their life-cycle. Further complexities are involved when the systems are handheld or portable, opening up a world of unique operational environments. Electronics systems have traditionally been mounted to vehicles or other large platforms; be them ground vehicles, aircraft, or ships. These platforms quite often have specifications for what operational environments they must survive and what storage conditions are required. Vibration profiles are well known or can be fairly easily measured at the points where these systems are mounted to the main frame. With handheld or portable systems, the operational environment is not as easily defined or measured. Due to a wide array of human factors it is difficult to develop a prediction of how the device will be handled in the field.

Furthermore, many military vendors encounter design challenges in products subject to high strain-rate life-cycles such as drop and blast events and random vibration loads. New design iterations invariably bring new unexpected failure modes under such loading and costly trial-and-error design fixes are often necessary after the product is built. Designers have long sought to address these effects during the design phase, with the aid of computational models. However, such efforts have been difficult because of the nonlinearities inherent in complex assemblies and complex dynamic material properties. The goal of this paper is to provide and illustrate the computational approach to capture the transient response of portable devices under various dynamic and thermal loads as well as combined loads. Ultimately, the model results can be used to perform early design iterations so as to anticipate and minimize costly trial-and-error and design-and-fixes later during qualification testing or after the product design has been finalized.

2 CURRENT CHALLENGES

While operational profiles and specifications are often available for platform mounted systems, they are often undefined or under defined for handheld and portable systems. To determine the reliability and life expectancy of handheld electronic devices the first step is to understand the operational environment and stressors on the system. Critical stressors include vibration, daily temperature cycling, power cycling, shock and drop. Vibration and temperature are often seen as primary stressors in more conventional rack mounted electronics. However, in handheld devices the primary stressors stem from the high strain rate induced on the systems from drop events, which are extremely challenging to model due to nonlinear effects such as contact stresses, large deformation, and complex dynamic material properties. Currently, engineers mostly use finite element models to study the local effects under the assumption of simple deformation at the contact areas at the time of impact. Unfortunately, designers tend to neglect the nonlinear effects to simplify the analysis, leading to erroneous results and inferior products. The common argument is that a portable system should not be dropped, thus designing for it is outside of the scope of its intended use. However, failures due to drop are common place in the battlefield and must be accounted for.

Through Physics of Failure (PoF) modeling and simulation, the impact of dropping the device can be thoroughly examined. Testing drop scenarios can be time consuming, costly, and data and information can be missed. The challenge comes in accurately modeling the electronics and their housing or chassis. While MIL-STD-810 cites vibration profiles and drop requirements for systems, they do not necessarily apply to handheld electronics [1]. In past PoF analyses MIL-STD-810 or the system specifications and environmental requirements often provide vibration profiles that the system must survive, these are not as applicable for handheld and portable electronic systems. The vibration profiles in MIL-STD-810G Method 514.6 are designed for systems and devices mounted to vehicles and other platforms at known, specific locations. Handheld devices, while subjected to vibration during transport to and from theater and within the mission usage, are not likely subject to such relatively harsh vibrations. Likewise Method 516.6 of MIL-STD-810G designates shock values for safety of systems within vehicles and provides a standard for how to conduct a transit drop test, letting the device hit on all 26 corners, edges, and faces. While these tests are valid and useful for boxed, vehicle mounted electronics, they are not as applicable to portable devices.

3 PHYSICS OF FAILURE IN ELECTRONIC SYSTEMS

Electronic component stress failure is the primary concern in aerospace, automotive and military vehicles due to the extremely harsh environmental conditions [2], [3]. These operating conditions can instigate failure modes such as open electrical leads and changes in the operating parameters that are outside the specification limits. These failure mechanisms are phenomena that either occur instantaneously or develop over time. The effect of the stresses can be manifested as degradation in performance or as a gradual loss of durability of the elements in the product. Accumulated damage is another measure of degradation that often cannot be directly detected by performance loss. Damage can occur and accumulate during the life phases and affect the reliability of the electronic hardware [3], [4].

With the remarkable advances made in commercial electronics, it is becoming progressively more beneficial to use such components in military applications for improved computational performance, reduced cost, on-demand availability, to address obsolescence, and to maintain state-of-the-art capabilities. The use of commercial-off-the-shelf (COTS) electronics and electronic packages for military applications has lead to overwhelming concerns about their reliability in harsh battlefield environments.

It is understood that one of the more predominant failures in electronics is due to solder joint fatigue. Analysis of solder joint stresses associated with vibration is widely seen in the literature [3-5]. In assessing the solder joint fatigue failure under vibration, it is important to understand the dynamic characteristics of the electronic system and the mechanical behavior of the individual components. This may involve observing failure of solder joints experimentally and incorporating a solid joint mechanical behavior into analytical and numerical models. Computational models coupled with analytical models may provide a reasonably fast and accurate identification of the parameters of interest in vibration and drop analyses. Among the available analytical models are those by Suhir [5], developed to assess vibration induced failures in electronic packages. Barker *et al.* [6] developed analytical models for vibration induced failures in surface mount components. In Surface Mount Technology (SMT), the reliability of solder joints is extremely critical, since the solder joint provides electrical and thermal continuity as well as structural integrity [7]. Habtour *et al.* [8] provided a coupled 3D with 2D approach to account for the stiffness of large electronic components.

4 HANDHELD AND PORTABLE SYSTEMS PHYSICS OF FAILURE METHODOLOGY

4.1 *Identifying the Life Cycle Stresses*

The authors in this paper performed PoF analyses for a portable smart LCD handheld device developed by iRobot, shown in Figure 1. The objective of this device is to provide the human interface between the soldier and several manned and unmanned platforms. The most critical step in performing this PoF analysis is to understand the operational life cycle of the system. It is important to consider all elements of the life cycle: production, transportation, operation, etc. Typically, operational conditions are harshest as it may involve handling and interaction by soldiers and exposure to environmental conditions. Other potentially hazardous stresses include shock and drop during transportation and thermal cycling when in storage where temperatures can reach 71℃ as stated in Army Regulation 70-38 (AR70-38) [4].

Ideally, the systems specifications and requirements outline the life cycle for a system and the environments in which it must survive and operate. A system's Operational Mode Summary/Mission Profile (OMS/MP) attempts to provide the information necessary to construct a life profile. The OMS/MP provides the expected operating hours and power cycles for a given period of time. It will also detail what percentage of the operational life the system is expected to be in what climatic conditions and percentages of time the system (if vehicular) will spend on various degrees of terrain. Operating hours combine with expected mission profiles can be utilized to develop power cycles to predict thermal fatigue of the solder joint connections on the circuit boards. The expected climatic conditions can be used to identify the temperatures the system should experience in operation and can be used similarly to look at thermal fatigue. The operational conditions defined in the OMS/MP can be used to develop vibration profiles based on what vehicle the system is expected to be used in conjunction with and what terrain it will be in.

Figure 1 –Handheld Electronic Device Developed by iRobot

While MIL-STD-810 and AR70-38 define ambient temperatures and radiation levels for different climates; conducting environmental testing with those values can yield accurate results of what temperatures the system itself may experience during its life. Additionally, lab testing should be done to record the temperature rise across the circuit boards when the system is powered on. The ramp times up and down from the powered on temperatures should also be recorded as they can be incorporated into a thermal analysis investigating solder fatigue.

The system can also undergo vibration testing to determine the dynamic response at the operable frequency range that might be experienced by the circuit boards. The vibration profiles commonly found in specifications or MIL-STD-810 are for the overall system, not the location at which the electronics, specifically the circuit boards, are mounted. Exciting the system, as dictated in the specifications, with accelerometers on the boards should determine the dynamic response and subsequently the stresses. If testing is unfeasible due to costs, schedule, or artifact availability, dynamic finite element modeling may be utilized as an alternative to identify the response of the electronics chassis due to the system excitations.

These techniques may aid in developing and understanding the various stresses the system might experience over the life cycle. The stresses identified are used as inputs into the failure models to determine the accumulated damage and the expected life.

4.2 *Building the Circuit Card Assembly Model*

The circuit card assembly (CCA) can be modeled in a simple first order model designed specifically to analyze reliability of electronics. It is important when modeling the CCAs to incorporate all key material properties (mechanical and thermal) of the substrate materials, components, and solder used [3]. The component packages constraints and properties are incorporated into the model; material densities, elastic and viscoelastic materials properties, temperature limits, number of leads and package configuration and type. Any connectors or other through-hole components are modeled such that they improve the stiffness of the board at their respective locations. The model should smear the inertial and stiffness properties of the components, substrate, and solder joints across the elements in their respective locations [8]. These shell elements create a two-dimensional model of the CCA with its relevant properties for analysis. The modified shell elements model is then utilized to perform the thermal, vibration, and drop analysis.

4.3 *Thermal Analysis*

Data gathered from the life cycle analyses and testing are used to determine the temperature gradients that electronics could experience. In the absence of test data, it is possible to conduct computational fluid dynamics (CFD) analysis. The CFD analysis provides the temperature gradients and distribution the board may experience under given environmental and operating conditions, as shown in Figure 2. The CFD model also provides optimal cooling schemes for given conditions.

AR70-38 data for both the diurnal cycle for the expected climate conditions are utilized for predicting the power endurance of the device. Overstress and fatigue are two of the driving failure mechanisms in thermal analyses of electronic systems. The thermal solder-joint fatigue assessment model can provide a life estimate of the component interconnects (solder-joints) across the board. Because the PCB substrate and the components are made of differing materials they have dissimilar coefficients of thermal expansion (CTEs). As a result they could expand and contract with changes in temperature at dissimilar rates, creating stress on the components' interconnects.

There are two well established failure models for thermal fatigue; Engelmaier's and Steinberg's. Englemaier's Fatigue model is a modified version of the Coffin-Manson low-cycle fatigue equation and Morrow's strain-energy relationship that accounts for stress relaxation, creep, of the solder through a fatigue ductility exponent [4]. Englemaier's Fatigue Model can be applied to both leadless and leaded components to calculate damage. Steinberg's Failure Model equates the load in the wire to the load in the solder, solving for the stress in the solder and then determining the number of cycles to failure based on the solder's S-N curve [4]. Both models can be used to determine damage accumulation and life estimates of the solder joints due to thermal fatigue.

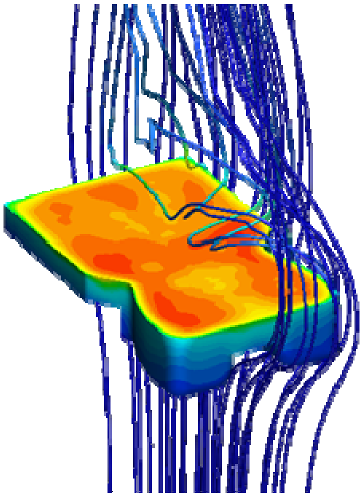
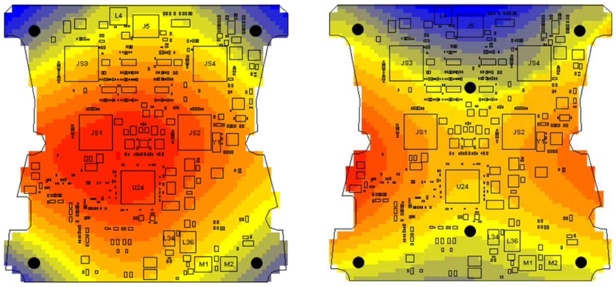


Figure 2 – System Level Thermal Analysis

4.4 *Vibration Analysis*

Although the primary concern with handheld devices is shock from drop events, conducting a thorough vibration analysis is critical. The vibration analysis takes into account the expected transportation and operational vibration profiles. Standard vibration profiles found in MIL-STD-810 are constructed for vehicular applications with exaggeration factors. Thus, using the MIL-STD-810 may potentially provide misleading or overly conservative results as portable and handheld devices are likely not hard-mounted to the vehicles they will be traveling in. On the other hand, not conducting any vibration analysis would overlook potential failures from rough transportation conditions. As such, it is imperative to derive the correct vibration profile for the handheld device.

One of the early stages of vibration analysis is conducting a modal study to determine the natural frequency of the circuit board's modal displacements, as shown in Figure 3. This analysis identifies areas of concern; maximum displacement, curvatures and strains. While many of the new handheld devices are COTS technologies, there are still opportunities to mitigate failures, especially with vibration. Slight changes to the mounting configuration of the boards can result in significant increases in the natural frequency, as shown in Figure 3. Increasing the natural frequency is one of many methods to improve the reliability of the electronics as it will avoid destructive excitation of the board at lower frequencies.



Configuration A – Not Reliable   Configuration B – More Reliable

Figure 3 – Vibration Analysis Example

A key output of the vibration analysis, besides the modal response, is the vibration fatigue life assessment. This provides an estimate of the fatigue life of the component interconnects. The difference in relative curvature of the components and PCB combined with the component local acceleration response may cause significant stresses in the leads and solder joints leading to potential failure of the interconnects. Using Steinberg's empirical approach, fatigue life assessments can be extended to random vibration [4]. The number of cycles to failure can be determined by assuming that the stresses are directly proportional to the out of plane displacement due to the accelerations.

4.5 *Drop Analysis*

A major concern in reliability analysis of handheld devices is electronics endurance to drop events. Dropping an electronically dense device may lead to irreversible damage, or even catastrophic failure. Simply saying that the risk of failure due to drop is mitigated by providing training and documentation instructing soldiers not to drop the device does not substitute the need to design, develop, and produce a robust device that can survive drop events when, not if, they occur.

Finite element modeling can be conducted to determine the device's reaction to drop scenarios and the shock propagation through the case. Once the Computer Aided Design (CAD) is built for the device and imported to a finite element method (FEM) code, the circuit card modified shell elements can be imported as well. As mentioned earlier, these modified shell elements have the electronic components' representative mass and stiffness properties present in their respective locations. Bringing the two dimensional circuit card model into the three dimensional global FEM provides an accurate representation of the PCB and the interaction between the PCB and the case, as shown in Figure 4. It also provides an accurate calculation of the transfer of dynamic loads between the case and the components on the PCB. Finally, the FEM provides an accurate modeling of the transient boundary conditions of the PCB; meaning the boundary conditions of the PCB are no longer static.

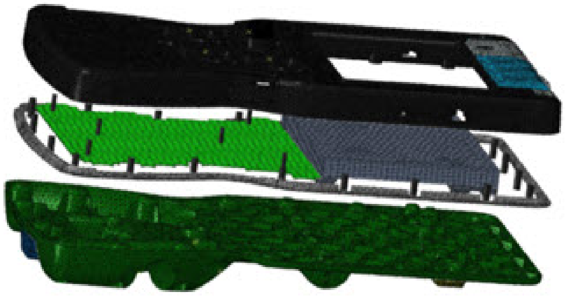


Figure 4 – Finite Element Model with CCA Model

Developing the requirements and thus inputs for the drop analysis is not always well defined. The MIL-STD-810 defines a transit drop that can be interpreted for use for portable devices. The requirements of the transit drop can be used to develop drop simulations to investigate the reaction of the electronics when dropped on various corners, edges, and faces. Testing can be done with accelerometers to validate the model and ensure accurate representation of the device's behavior. The accelerations experienced at the board supports and across the board can be modeled and measured.

Data from the system level drop can be used in analyzing the components and interconnects at the PCB level. Software packages designed to specifically look at circuit card reliability can be fed information from the drop simulation to develop life predictions and damage estimates. Information such as the acceleration of the supports, displacement of the board elements, curvature of the CCA, shock response spectrum or strain across the board can be utilized, as shown in Figure 5.

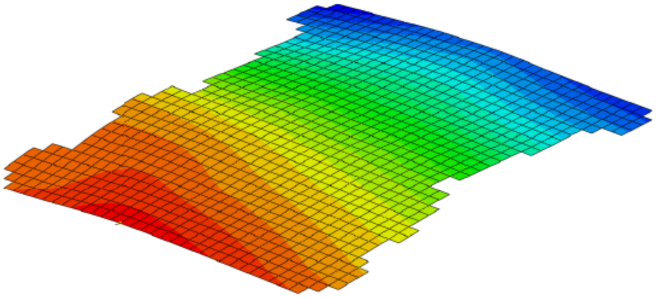


Figure 5 – CCA Displacement Due to Drop

Using the data from the finite element analysis may provide more realistic results than using predetermined shock values that were initially intended for testing vehicles and vehicle mounted subsystems. Simply applying the shock values given in MIL-STD-810 may provide a misleading assessment. The values given for functional and crash shocks only go up to 75G, whereas drop simulations for the handheld device in Figure 1 have shown a potential acceleration at the mounting points of upwards of 1100G. There is a difference of multiple orders of magnitude between the two, showcasing the need for a thorough PoF drop analysis.

The drop/shock PoF analysis yields which components and interconnects are expected to fail or suffer damage in the event of a drop. Comparisons can be done of the various drop orientations and scenarios to determine the worst case scenario for a drop impact of the device. Efforts can then be focused on mitigating the risks of the device falling in such a manner. Engineering changes can be made to how the circuit cards are mounted inside the device if it is still early in the design process. Conversely, for COTS systems changes can be made to the exterior of the device to include bumpers or a protective case tailored to absorb energy from impacts in the worst case orientations, mitigating the risk of a failure. While not all drops will result in catastrophic failure of the system, they will likely damage the system and increase the probability that the next drop can cause a total system failure.

5 OUTCOME & RECOMMENDATIONS

Assessing reliability is a challenge for all electronic systems. This challenge is due to the complexity of microelectronics that exhibit nonlinear geometric and material behaviors directly dependent on the dynamic and thermal conditions. The current standards and procedures for testing the reliability and environmental survivability of military systems are more tailored to vehicular systems and vehicle mounted electronics with linear assumptions. Utilizing these procedures may lead to inaccurate reliability assessments. In the handheld device case discussed above, the vibration analyses conducted with the profiles outlined in MIL-STD-810 yielded over conservative results, predicting higher damage and shorter life expectancies than would potentially be experienced. On the other hand shock analysis using the predetermined values from MIL-STD-810 lead to under conservative results, predicting little to no damage to the electronics as a result of accelerations orders of magnitude less than what would be experienced due to a drop of the system.

As the military moves forward, smaller, more portable handheld electronics are becoming more common for communications, control of unmanned systems, IED detection, and other uses. Tests and procedures put in place to assess systems need to be updated for the new generation of military devices. These devices are subject to unique loads and stresses over their life cycle. It is critical to identify what these handhelds could experience in transportation and operation to develop accurate models. The same underlying physics that is used in tradition PoF analyses for mounted systems can be applied to these systems as long as the loads are accurately identified and applied to the models. There is no one size fits all model for PoF of handhelds but robust procedures should be developed and followed to ensure that we are putting reliable equipment in the hands of the soldier.

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