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Improved Reliability Testing and Modeling of Electronics with Multi-DOF Vibration in Unmanned Army Ground Vehicles

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ABSTRACT

The functionality of the next-generation Department of Defense platforms, such as the Small Unmanned Ground Vehicles (SUGV) and Small Unmanned Arial Vehicles (SUAV), requires strongly electronics-rich architectures. The reliability of these systems will be dependent on the reliability of the electronics. These electronic systems and the critical components in them can experience extremely harsh thermal and vibrations environments. Therefore, it is imperative to identify the failure mechanisms of these components through experiments and simulation based on physics-of-failure methods. One of the key challenges in re-creating life-cycle vibration conditions during design and qualification testing in the lab is the re-creation of simultaneous multi-axial excitation that closely mimics what the product experiences in the field. Currently, there are two common approaches in the industry when testing a prototype or qualifying a product for multi-axial vibration environments. One approach is option is to use sequential single-axis excitation along each of the three axes, via a single axial electrodynamic shaker. The second approach relies on repetitive shock shakers that produce simultaneous multi-axial vibration but with uncontrolled power spectral density (PSD) profiles. Consequently, the dominant failure modes in the field are sometimes very difficult to duplicate in a laboratory test using the options stated above. The US Army Materiel Systems Analysis Activity (AMSAA) is currently collaborating with the Center for Advanced Life Cycle Engineering (CALCE) at the University of Maryland, to develop test methods that better capture unforeseen design defects in the prototyping and qualification stages, by better replication of the multi-axial life-cycle vibration conditions. This effort has led to the use of a novel multi degrees of freedom (M-DOF) electrodynamic shaker to ruggedize designs for fatigue damage due to random vibration. The PSD profiles can be controlled on this shaker simultaneously along all six DoF (three translation and three rotational).

This paper discusses the merits of vibration testing methods with a M-DoF shaker and the cost savings associated with such an approach. The M-DoF shaker may detect critical failures earlier in the development cycle than have been traditionally possible with existing shaker technologies; and therefore produce more cost effective and reliable systems for our warfighters.

INTRODUCTION

The increasing complexity of electronic equipment, especially in low volume and highly sophisticated and dense electronic systems, such as autonomous military platforms, has resulted in an increased need to understand the failure mechanisms due to dynamic loads. Figure 1 is an example of an electronically dense SUGV. Typically, these types of systems are subjected to various complex loadings, including shock and vibration, during their life-cycle. These loads may impose significant stresses on the printed circuit board (PCB) substrate, component packages, leads and solder joints [1-2]. These stresses can be a combination of bending moments in the PCB and/or inertias of components. These stresses may lead to several failures such as delamination in the PCB, solder joint fatigue, lead fracture or components structural damage.

When conducting Physics of Failure (PoF) analysis of electronic systems, the large variety of package types is perhaps one of the main challenges to consider, since failure may occur due to one of several failure drivers. For example, interconnect failure in heavy components with large center of mass can be predominantly due to inertial loads while in light low-profile Surface Mount packages the dominant stress source can be due to flexural board deformations. Both of these failure drivers may compete in heavy and large electronic components such as inductors and transformers. Depending on the architecture of these components, they can also potentially alter the local vibration response significantly. It is common to increase the board stiffness to reduce the overall response of the PCB. However, increasing the board stiffness may increase local bending moments.

Figure 1: SUGV

Typically, the PoF approach may employ a simplified two-dimensional (plate of shell) finite element method (FEM) of a PCB. The mass and stuffiness of the components are "smeared" over their PCB footprints to reduce computational time and cost [3]. A simple example of transforming a three-dimensional PCB model to a smeared FEM is shown in Figure 2. In this example, the PCB contains six large components which were smeared using two dimensional cell elements. This technique assumes that the board component mass and stiffness can be approximately represented by simply increasing the mass and stiffness locally under the footprint of each component (where the mass and stiffness effects are included by locally increasing the PCB's density and Young's modulus, respectively). Unfortunately, such an approach does not address the inertias of large components [4]. In the case where inertia is significant, a traditional three- dimensional FEM might be necessary.

From a testing and evaluation perspective, failure mechanisms due to dynamic loads can be studied via accelerated vibration testing of electronic systems. This offers great potential for improvements in reliability life testing while reducing test time and cost. Unfortunately, difficulties encountered in accelerated life testing have limited its application and acceptance. Some of these difficulties can be traced, in part, to a lack of understanding of the actual failure mechanisms and sites in accelerated testing. To understand a particular failure mechanism by means of testing, it is important to simulate actual vibration conditions, which can be accomplished with a PoF approach utilizing a M-DOF shaker.

In the beginning of this study the initial assumption was that there would be an abundance of research performed in the area of multiaxial vibration testing since most mechanical and electronics products are universally subject to accelerations in all DoF. It was recognized that there is a literature on single and sequential uniaxial vibration testing. However, research performed in multiaxial vibration testing using electrodynamic (ED) shakers is extremely limited due to cost constraints associated with multiaxial vibration shakers [5]. Published standards requiring multi-axis vibration testing are almost nonexistent. The most common standards for vibration testing for military devices are published in MIL-STD-810F and NAVMAT P-9492 which contain both single and sequential testing but no mention of simultaneous multiaxial excitations. Therefore, for the past several decades, single-axis electrodynamic shakers have been the predominant vehicle for conducting random vibration testing of electronic and mechanical systems including unmanned vehicles. Nonetheless, it is important to point out that sequential uniaxial testing does not provide a true manifestation of the actual operating environment of a test device [6]. It may provide misleading results due to the two competing mechanisms of coldwork and vibration fatigue. This means that while an article is excited vertically, hardening due to coldworking may delay the crack initiation. This may potentially give the false impression that the article is robust.

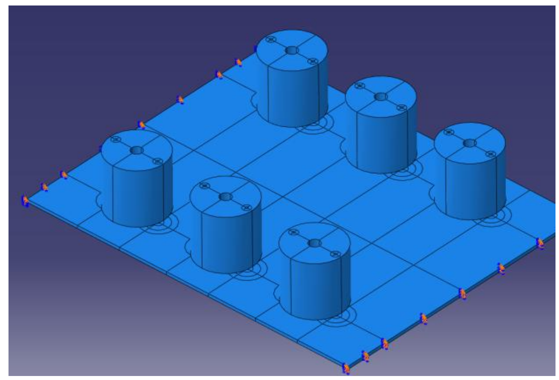

Figure 2-a: CAD model of PCB with large components

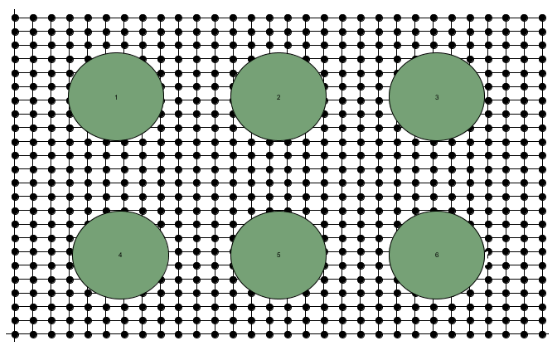

Figure 2-b: Two dimensional FEM using smearing method

CURRENT CHALLANGES

While several different schemes are widely used to test devices sequentially in the various axes, it is understood that they are rough approximations to the ideal simultaneous M-DoF testing. Uniaxial excitations are applied to test objects even though most mechanical application data show that devices are subject to a multidirectional environment such as a spacecraft launch, a military ground vehicle deployment or a computer operating an automotive engine. Therefore, serious compromises must be made in the prototype design to perform meaningful tests on a single DoF ED shaker. For example, to simulate M-DoF vibrations in military applications, MIL-

STD-810F recommends performing the vibration tests by sequentially applying uniaxial excitation to a test object along three orthogonal axes (X, Y and Z). This is accomplished by exciting the test asset vertically then repeating the procedure two more times after rotating the article 90° each time. Figure 3 is an example of a sequential multiaxial Acceleration/Power Spectral Density (ASD/PSD) profile for composite two wheeled trailer vibration according to MIL-STD-810F.

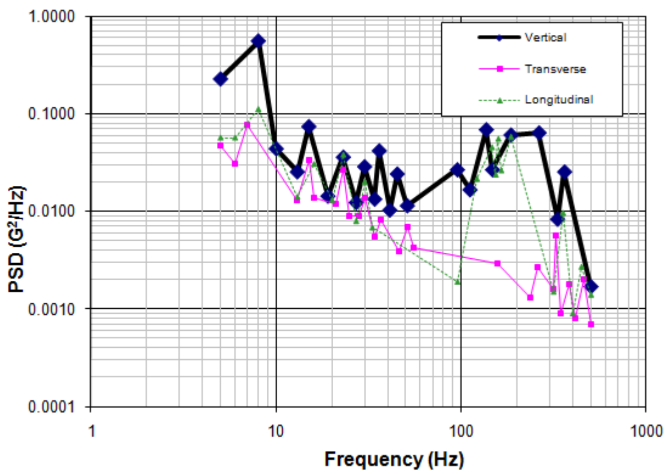

Figure 3: Composite two-wheeled trailer vibration profile

In SUAV platforms, the majority of vibrations, shocks and acoustics can be multiaxial in nature. One of the most critical and persistent design problems in SUAV design is the survival of high precision, sensitive and expensive electronics systems. Johnson *et al.* states that the acceleration levels input to aircraft are over a wide frequency range from about 30 Hz to 2000 Hz or higher [7]. To control or mitigate the risk of vibration effects, complex systems and strategies are employed. They may involve sophisticated six-axial vibration isolators and multiple sensors. Such complex solutions can be costly and sometimes unnecessary. This can be avoided if the product in question is studied under multiaxial shakers to produce a clear understanding of the critical failure mechanisms. Such an understanding enables designers to create robust and cost effective components and isolators that can withstand these harsh conditions.

Studies published in the open literature pertaining to single axial and multiaxial vibration testing for aerospace applications are limited. However, the automotive industry provides a plethora of literature in single and multi excitation testing. Components in automotive applications are subjected to fatigue testing to ensure they will not fail during the design life of the vehicle, typically 160,000 km, to meet the warranty obligation [8]. Typically, a test vehicle will be driven over a set of chosen road surfaces under expected driving conditions, while accelerations are measured on the component in question. These data are then brought into the laboratory to replicate the measured accelerations, thereby subjecting the component to the same fatigue conditions it experienced in the test vehicle. Depending on the location and application, a typical automobile component qualification test requires a 2.9 G_{rms} (3.9 for military vehicles) random vibration profile from 5 to 1000 Hz [8].

PHYSICS OF FAILURE IN ELECTROMECHANICAL SYSTEMS

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, addressing obsolescence, and providing state-of-the-art capabilities. This current movement of using commercial-off-the-shelf (COTS) electronics and devices for military applications has led to overwhelming concerns about their reliability in harsh battlefield environments.

One of these reliability concerns is susceptibility to fatigue damage due to vibration. In fact, electronics failure caused by stresses due to vibration is the primary concern in military vehicles due to the extremely harsh environmental conditions [9]. These conditions may instigate failure modes such as open electrical leads and changes in the operating parameters that are outside the specification limits. These failure mechanisms may occur instantaneously or develop over time. The effect of the vibration stresses can be manifested as degradation in performance or as a gradual loss of durability of the elements in the product. Accumulative damage is another measure of degradation that often cannot be directly detected by performance loss. Damage may occur and accumulate during the life phases and affect the reliability of electronics [9].

Another predominant failure mode in electronics assemblies is solder joint fatigue. Analysis of solder joint stresses associated with vibration is widely seen in the literature [10-11]. In assessing the solder joint fatigue failure under vibration, it is important to know the vibration characteristics of the systems as well as the mechanical response of individual components. This may involve observing failure of solder joints experimentally and incorporating a solid joint mechanical behavior into analytical and numerical models. Analytical models can help to quickly identify the parameters of interest in a vibration analysis and are computationally less intensive than numerical models. Among the available analytical models are those by Suhir which were developed to assess vibration induced failures in electronic packages [12]. Barker *et al.* developed analytical models for vibration induced failures in surface mount components [13].

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 [14]. However, in most solder joint reliability analyses, in both industry and academia, the main focus is on the uniaxial deformation behavior when, in reality, the solder joints are subjected to complicated multiaxial stressing and straining. There is a need to measure the basic mechanical properties of various solder alloys under multiaxial loading and at the same time develop a comprehensive constitutive model for reliability and failure analysis. However, the multiaxial constitutive descriptions for solder alloys are very limited, especially the time-dependent constitutive descriptions for lead-free solder alloys.

Some of the limited studies investigating the vibration durability of solder were performed by Zhou *et al.* at

CALCE [15]. They examined the vibration durability of Sn37Pb and SAC305 (lead free) solders using a combination of harmonic excitation tests and finite element modeling. The analysis was conducted using a time-domain approach, to quantify fatigue damage caused by harmonic excitation at the first natural frequency of the test vehicle. Zhou and Dasgupta concluded that the SAC305 solder was found to have lower fatigue durability than the SnPb solder under narrow-band harmonic excitation [16]. Furthermore, failure analysis produced in their investigation revealed that there are two competing failure modes, one in the solder and another in the copper trace under the component.

TESTING METHODOLIGES

Repetitive Shock Shaker

The conventional design approach in electronics packaging is an iterative loop, i.e., design-prototype-test-fix. This process requires long cycle times and high expenses related to physical prototyping and testing. The lack of prediction capability of a product's reliability leads to deficiency in its design. This hurdle can be potentially overcome with a Repetitive Shock (RS) shaker or Highly Accelerated Life Testing (HALT) during the prototyping and qualification stages. The idea of HALT is to conduct highly accelerated tests during the design process with the intent to stress the product to failure in order to assess the design robustness and weakness through rigorous root cause analyses. The purpose of the test is to identify design weaknesses that, due to variability, would eventually show up as failures when larger quantities of the product are used within the design limitations. This method is performed by applying accelerated stresses to determine the operating and destruct limits of the design.

Figure 4: RS Shaker at CALCE

HALT testing may subject the test sample to stresses higher than those encountered in the field during shipping, storage, or operation. Because failure of the product during HALT cannot be precisely correlated to lifetime in the field, the rule of thumb is to continue improving the product performance under HALT as far as feasible. As commonly occurring failure mechanisms are accelerated under higher stresses, any improvement under HALT usually leads to improvement in the field [9 and 17]. The test is performed in a HALT chamber which typically has a broad spectrum of vibration energy from 10 to 5,000 Hz and runs from 1 to 150 G_{rms}. The initial stress and order of increase or decrease for the various stress levels are products dependent. Vibration is performed by using pneumatically driven hammers to simulate six-DoF excitations, as shown in Figure 4.

HALT does not provide clear knowledge of the failure mechanisms. This is because it provides mostly a qualitative rather than a quantitative understanding of the failures due to two major limitations [18]. First, the only input that can be controlled during vibration testing is the G_{rms} in the vertical direction (or Z direction). Thus, it is impossible to control the shape of the PSD profile, as shown in Figure 5 [18]. Secondly, since the chamber employs six-axis pneumatically driven hammers, it is impossible to independently control each DoF. CALCE has confirmed that the coherence between the axes is nonexistent, as shown in Figure 6 [18]. Thus, it is impossible to identify the most dominate failure mechanism or the DoF that instigates the most damage to the components. Therefore, it is difficult to establish a quantitative relationship between performance in the field and performance in the test.

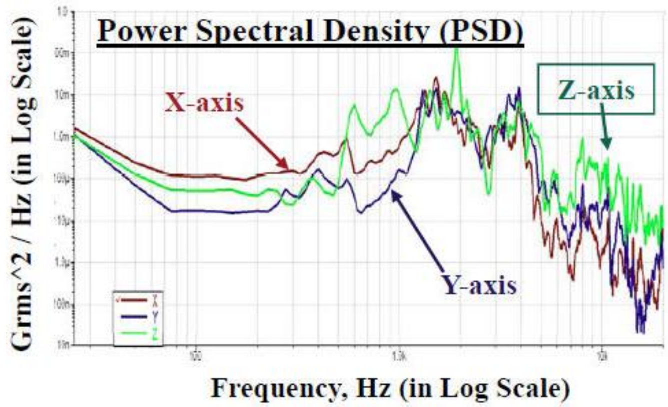

Figure 5: PSD in RS Shaker [18]

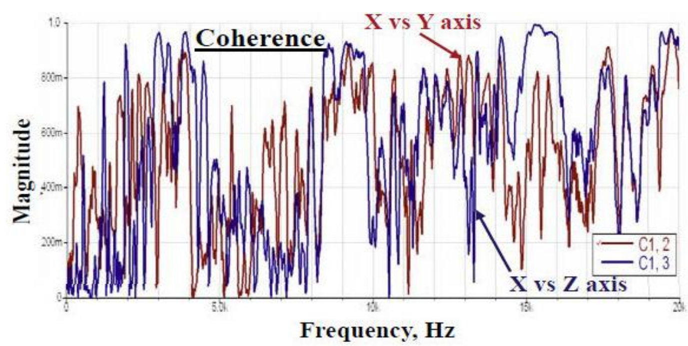

Figure 6: Coherence in RS Shaker [18]

Multiaxial Electrodynamic Shaker

Due to the limitations of uniaxial ED shakers and HALT, CALCE and AMSAA are investigating the possibility of utilizing multiaxial electrodynamic shakers. The objective is to study the differences in failure modes and fatigue life for multi-axis loadings versus single-axis inputs by utilizing multiaxial ED shakers.

The multiaxial ED shaker at CALCE was developed by TEAM Corporation. It consists of eight plane actuators and four out of plane actuators underneath the shaker table, as shown in Figure 7. The twelve ED shakers are mechanically coupled to the table. This architecture allows the shaker to produce a true M-DoF vibration environment. Each axis has four shakers with 200lbf rotation per axis. The excitation limit is up to 30Gs with 0-3000Hz. Unlike other testing methodologies, multiaxial ED shakers will provide a clearer knowledge of the failure mechanisms in electromechanical devices. This is because they provide both qualitative and quantitative understanding of the failures not present in single-axis excitation. The inputs can be controlled for all as demonstrated by CALCE, Figure 8. This is because the twelve shakers can be excited independently of each other. Figure 8 shows excellent control of the shape of the excitation PSD profile. CALCE has also shown that the coherence between the axes is excellent as shown in Figure 9. Therefore, it is possible to identify the most dominate failure mechanism or the DoF that instigates the most damage to the components. This will aid AMSAA in establishing a quantitative relationship between performance in the battlefield and performance in the test.

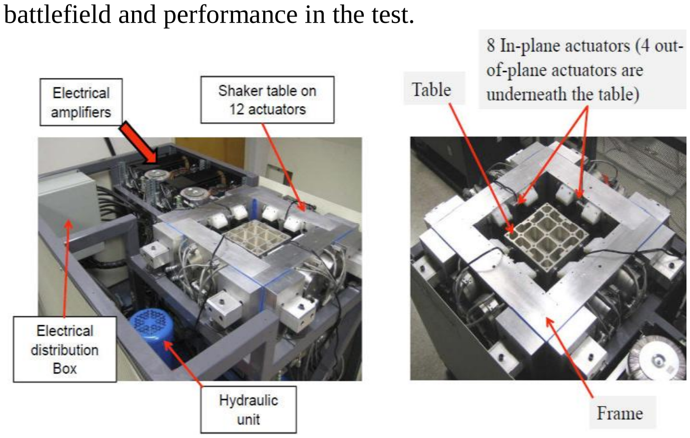

Figure 7: Multiaxial ED Shaker at CALCE

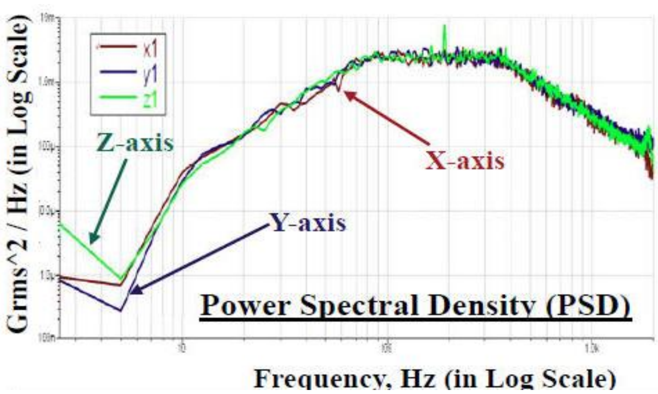

Figure 8: PSD in Multiaxial ED Shaker

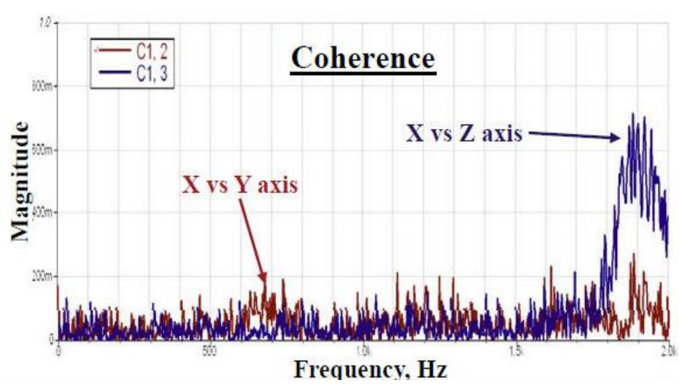

Figure 9: Coherence in Multiaxial ED Shaker

ANALYTICAL APPROACH

When performing electronics PoF for ground vehicles, some researchers have suggested modeling the dynamics response of the vehicle subsystems. This approach, however, can be an arduous task [2]. The main reason for this lies in the fact that the vehicle chassis and body are complex systems. The reaction forces and vibration velocities depend not only on the strength of excitation within the chassis but also on the coupling of the chassis and the auto body. Thus, one has no choice but to count on engineering judgment in estimating the boundary conditions and system inputs. A more practical approach perhaps is using experimental Frequency Response Function (FRF) data to represent the body then combine it with the FEM models. Therefore, CALCE and AMSAA have proposed utilizing the M-DoF ED shaker to excite PCBs, with large insertion-mount components, to levels seen on the battlefield. The FRF experimental data will be combined with the FEM model where the solder fatigue results would be extracted with the aid of FEM. For this approach it was necessary to design an optimal PCB with heavy components that respond to in-plane excitation. Based on the FEM modal analysis, the optimal dimensions of the PWB were 101.6x127 mm^2 and 1.36mm thick with six heavy inductors, as shown in Figures 1 and 2. The inductor dimensions are shown in Figure 10.

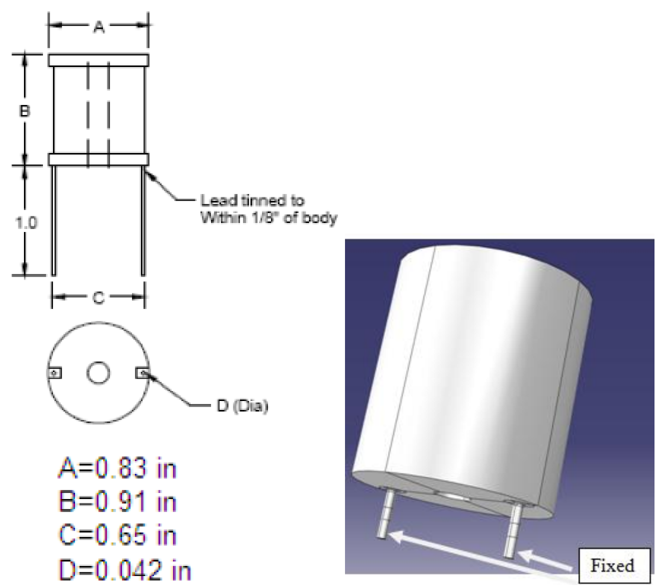

Figure 10: Large inductor used in this study

In this study, modal analyses were conducted for the component individually for various standoff heights as shown in Table II and Figure 11. In this task the component was assumed to be fixed at the leads, as shown in Figure 10. As expected the modal response dropped as the standoff height increased due to the component significant inertia which is typically neglected in the properties smearing technique. Even more interestingly, the modal response of the components dropped significantly when the components were modeled as part of the PCB, where the boundary conditions are more representative of real systems. The PCB was assumed to be fixed along the width of the board as shown in Figure 12.

Thus, the maximum response occurred in the components located at the middle of the PCB. The first mode natural frequencies for the middle components and the component closer to the fixed edges were approximately 69 and 71 Hz. The board natural frequency was 119 Hz. The PCB modal shape is shown in Figure 13.

Table I: Inductor modal response for various standoff heights

Standoff Height (mm)	Mode I (Hz)	Mode II (Hz)	Mode III (Hz)
0.5	108	1733	3266
1.0	102	1657	3161
1.5	98	1560	2682
2.0	94	1430	2200

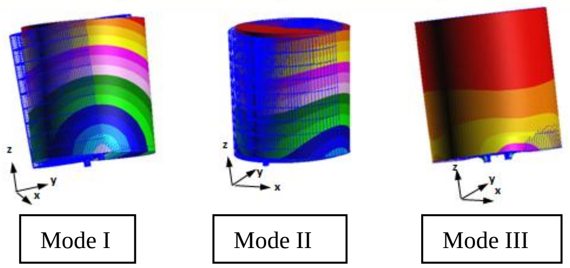

Figure 11: Inductor modal shapes when fixed at leads

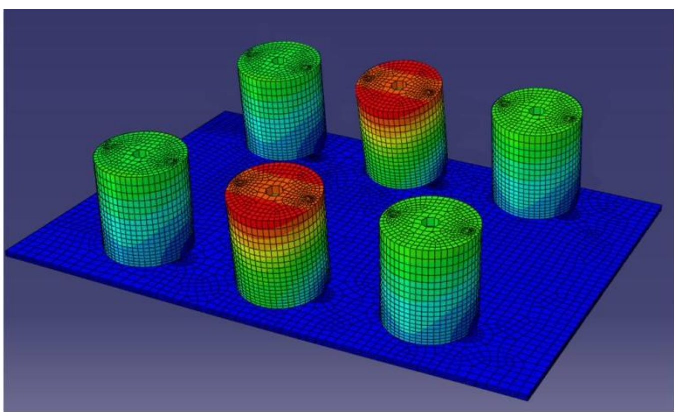

Figure 12: Middle Inductors first modal response in PCB

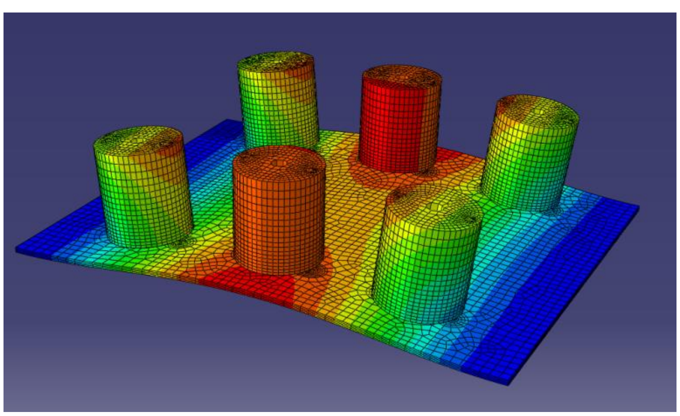

Figure 13: PCB first modal response

The next step that CALCE and AMSAA will undertake is to fabricate test specimens (PWC with heavy through-hole inductors) for M-DOF vibration durability test on the M-DoF ED shaker. Vibration durability tests will be conducted on the M-DoF ED shaker for various orientations: out-of-plane, in-plane, simultaneous in-plane and out-of-plane excitation and sequential out-of-plane and out-of-plane excitations. Subsequently destructive physical analysis of failed specimens will be preformed. The final step will be to develop a PoF modeling approach for vibration durability under random, multi-modal and M-DOF excitations

OUTCOMES

It can be concluded that it is essential to understand the structural characteristics of electronic devices in order to correlate the defects with the dynamic responses. As mentioned above, the main challenge in electronics packaging is the prediction of the reliability and lifetime of the critical components. Therefore, it is imperative to identify the failure mechanisms of the components through experimental analysis. However, the experimental approach has to emulate the real world operational conditions, which includes simulating M-DoF dynamic loads. This involves experimentally measuring the transient in-plane and out-of-plane displacement responses which can be accomplished with the aid of a multiaxial shaker.

There is a need to update MIL-STD-810G to include enhancements to simultaneous multiaxial vibration standards. CALCE will investigate the fatigue damage in circuit card assemblies due to multi-axial excitation encountered on the battlefield. The goal is to capture unforeseen design defects and to ruggedize military devices for fatigue damage caused by unexpected synergies between modes excited by different axes. This investigation will then be utilized to enhance and improve MIL-STD-810G Method 527 through lessons learned. The study will also provide a means to validate and improve existing physics of failure models.

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