# Vibration Analysis Study of Spacecraft Electronic Package: A Review

**K.P. Subramanya, Jiwan Kumar Pandit, C.S. Prasad, M.R. Thyagaraj**

*Abstract*- ***This paper briefly describes the vibrations coming onto the spacecraft electronics, which will always be quite harmful to the functioning of the components and the Printed Circuit Boards (PCB's) during launch of the spacecraft and its journey to the space. Vibrations experienced by electronic package of a spacecraft during its launch phase can damage its function unless precautionary measures are taken. This paper describes the strength and stability requirements of electronic packages to withstand launch environment. As space based applications such as communication and navigation depends on reliable operation of electronics, means of vibration isolation are also discussed to prevent mechanical failure of electronic components due to vibration induced loads, during operation and throughout its life cycle, which will ensure the accuracy in space based navigation providing a reliable mission.***

***Index Terms—electronics packaging design, vibration, Spacecraft electronics, vibration induced failures, printed circuit boards.***

## I. INTRODUCTION

During a spacecraft launch, very harsh and high intensity vibrations are transmitted from the launch vehicle into the spacecraft structure; wherein the severity of these vibrations can be much strong enough that damages electronic components and may cause spacecraft failures[1]. Electronics packaging design is a process that requires optimized solutions based on multidisciplinary designing trade-offs, which usually have complex relationships among multiple design variables.

Rigorous numerical analyses combining electrical, thermal, and thermo mechanical, among others, which have made the multidisciplinary design and optimization process more challenging because of their time-intensive modeling and computation. To ensure that the failures do not occur during the mission, all spacecraft electronics are subjected to stringent pre-flight qualification tests. These tests are intended to make failures occur on the ground instead of during the launch. In terms of preventing mission failure totally on the electronic package (Fig 1.0), the design should be modified before launch and ensure that vibration related mission failures virtually never occur. However, in terms of the overall design process this method is inefficient, as each failure and subsequent design iteration may take hundreds of man hours and push back deadlines by several months. Fortunately, the majority of designs pass the qualification test first time, but it is the reduction of the few occasional failures and the consequential costly design iterations - that is the primary focus of this paper.

Fig.1.0: Typical Electronic box

A study on hardware failure rates of military aircraft electronic systems, show that 40% of failures are found in electrical connectors, 30% are found in cables and harnesses, 20% are related to electronic components and 10% are due to other factors [2]. Another study based on environmental failure rates shows that thermal, vibration, humid and dusty environments are the major reasons of environmental failures [2]. Distribution of these failures is shown in Fig.2.0

This paper discusses failure of electronic packages due to vibration and thermal effects. For electronic equipment, generally, the launch survival is the major mechanical design driver. From mechanical failure point of view, 80% of the failures are due to thermal stress levels and 20% is due to severe shock or vibration. In 1970's, NASA showed that 45% of the first-day spacecraft failures were due to damage caused by vibrations during launch [3]. At the time, several studies looked into the problem of the harsh vibration environment experienced by Printed Circuit Boards(PCB) during launch, and various solutions were proposed,[3] [4].

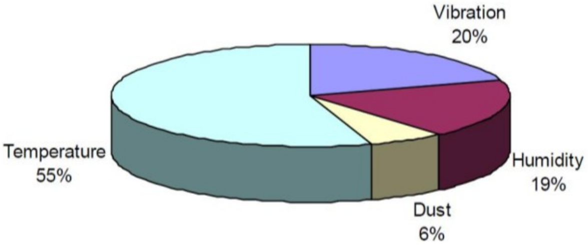

Fig2.0: Failure mode distribution

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## II. WHY VIBRATION ANALYSIS REQUIRED FOR ELECTRONIC PACKAGING?

Electronic devices used in control, guidance and communication systems are among the most important parts of modern avionic systems. Common aim in the aerospace industry is to design and produce systems which have a life of at least 20 years with high reliability levels [5]. The electronic assembly consisting of three parts, the components, PCB and the electronic housing, requires special attention in order to meet the expectations of the aerospace industry. In terms of preventing mission failure, an analysis will be needed to find the natural frequencies of each part, and also for the assembly and the electronic housing. Each part will have its own-dynamic response, however, the combined assembly of the PCB and the enclosure will have a dynamic response different than the two independent responses. Mass, CG and the response of electronic packages are used to analyse package installation, layout design and local assembly analysis [6]. More importantly, it must be determined if the two parts will couple dynamically, i.e. each part affects the dynamic response of the other. It is generally the practice to find deflection of the package enclosure at PCB mounting locations by analysis. Hence, the deflections of the board will be considered to be acceptable for reliable design.

## III. VIBRATION OF ELECTRONIC ASSEMBLIES

Electronic assemblies are formed by electronic components attached to the PCBs which are mounted onto the mechanical housing. Therefore, vibration analysis of an electronic system is usually handled at three main levels:

1. Electronic components.
2. Printed Circuit Board (PCB's), and
3. Mechanical Housing/ Electronic box for electronics.

Excessive deformations and accelerations of PCB's result in damage to the electronic housing, electrical interfaces and mounted components solder joints, as well as the circuit board itself. Basic failure mechanisms due to the combination of thermal, shock and vibrations coming from different aspects of the spacecraft can be specified as follows.

1. Electronic components.
   i) Connector contact fretting corrosion
   ii) Loose hardware
2. Printed Circuit Board (PCB's)
   i) Solder joint fatigue failure
   ii) Excessive deflection
   iii) Lead wire fatigue failure (Figure 2.0)
3. Electronic box/ Mechanical Housing for electronics.
   i) Structural failure due to vibration
   ii) High stress level failures
   iii) Thermal stresses

Reduction of vibration and shock loads experienced by spacecraft during launch would greatly reduce the risk of its damage and would also allow more sensitive equipment to be included in missions. As the severe launch environment also accounts for much of the expense of designing, qualifying, and testing spacecraft components, significant cost can also be saved if dynamic responses seen by the spacecraft are reduced. The launch events include low frequency dynamic loads such as liftoff, motor excitation, buffet, motor starts and shutoffs. Spacecraft are also subjected to shock loads in the several thousands of G's level during their trip to orbit. These high shock loads usually result from some separation event, such as staging, spacecraft separation, and fairing separation [7].

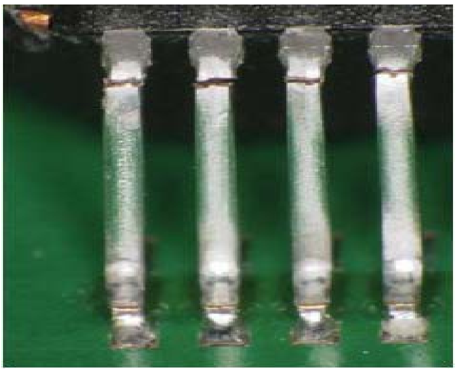

Fig.2.0: Ruptured lead wires due to fatigue [15]

Shocks or vibrations on electronic packaging in turn affect the soldering of components on PCB. Soldering is inevitable during mounting processes of electronic components overprinted circuit boards. High solder reliability is required since failures of solder joints and lead wires directly result in failure of systems. Main failure mode of solder joints under vibration loading is fatigue failure. High cycle fatigue, in addition to heat and vibration causes crack growth in solder joints and excessive stresses in lead wires [8].

Electronic box design is based on protection of internal components from environmental conditions. In case of vibration loading, the electronic box should ensure structural integrity of the system [9].

Electronic box design has many important issues resulting from vibration loading such as mounting and isolation of the box, connector fixing to the box, attachment of PCB inside the box and cover mounting.

## IV. BATHTUB RELIABILITY CURVE

The classic bathtub reliability curve (Fig3.0) [2] shows that failures can be divided into different time-frames, namely infant mortalities, useful life and `end of life' wear-out failures [10].

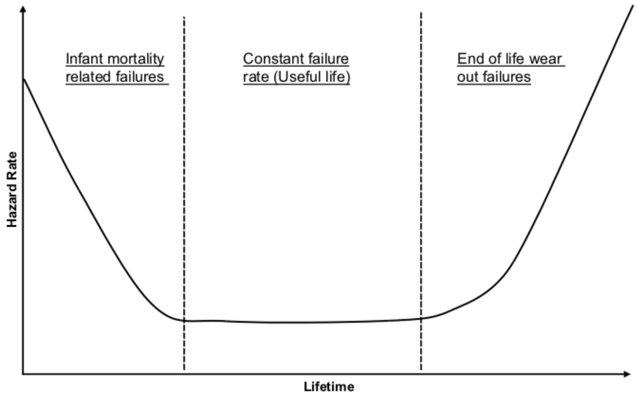

Fig 3.0: Bathtub curve showing failure probability v/s time

The infant mortalities are attributed to manufacturing defects within components or manufacturing processes causing failures during the start of the components operating life. The useful life is a period of a low constant failure rate, with the few failures that do occur possibly attributed to temporary events outside the expected operating conditions. The wear-out failures are caused by the accumulation of damage in components and joints until they are sufficiently damaged to fracture under the normal loading conditions.

There is also another case of failure in which the component only survives a few thousand vibration cycles before failure (within a few seconds of launch environment), this type of failures are akin to a classical over-stress failure and is distinct from manufacturing related failures as it is not directly attributable to a manufacturing defect, but poor design or a gross under-estimation of the operating environment [11]. After the common locations of vibration failures are identified, the analysis then progresses to discuss the physical mechanisms causing these failures, in terms of how the stresses act on the components causing the above mentioned failures.

The exact determination of the dynamic load that the equipment will experience on the spacecraft is partly due to random characteristics, the phenomena which generate the vibrations and in part due to the fact that the vibration level at the equipment-spacecraft interface depend strongly on the characteristics of the various equipment [3].

Knowledge as to whether an equipment failure is caused by an infant mortality, constant rate failure or a wear-out failure is useful, as it suggests either poor manufacturing in the case of infant mortalities or an underestimation of the stress (or environment) in the case of premature wear out failures such as mechanical stresses, thermal de-bonding and thermal fracture which are among many of the possible breakdowns of electronics components. Mismatch of the thermal coefficient of expansion between two different materials, especially at the interface conditions, could result in the separation of interfaces and bonds between different parts in a module at higher temperature [18]. In addition fatigue in the solder connections and cracking in substrate are common failure in electronics components when operating at off-limit temperatures.

### A. Physical Cause:

This section considers the actual forces that act on the components to cause them to fail. Ultimately, it is always stress/strain that causes any component to fail, but it is very difficult to measure these stresses within the component, so it is much more convenient to define the variables (board displacement or bending, acceleration and displacements causing impacts) that correlate with failure, as they are easier to measure and identify.

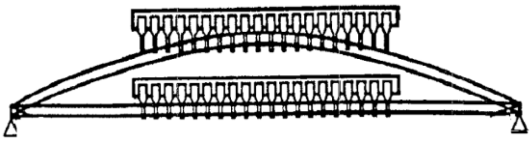

Fig.4.0: Diagram illustrating how bending of PCB causes greatest strain in the leads furthest from the center of the component[12]

### B. High Board Bending/ curvatures:

When a PCB is subjected to vibration it bends periodically, some of this bending moment is resisted by the components that are attached to the PCB. This means that there must be forces transmitted through the component leads; therefore stress must be present in the leads. Bending failures of PCB’s occur most often at the corner or end leads of a component package, where the stresses are the greatest [10] (Fig 4.0). It has also been shown that bi-directional curvature (i.e. a PCB that is curved in both the x and y axis) causes greater damage than uni-directional curvature. Bending stresses are significant failure drivers for components which cover a large area and thus for a given curvature experience greater relative displacement at their edges. Heavy components are less susceptible as they are usually stiff enough to reduce the PCB curvature.

### C. High Acceleration:

During resonance, the PCB and the soldered components experience very high inertia forces. As a result of the component's mass, large inertial forces are transmitted through the component leads. The greater the mass of the component the higher these axial forces become. Additionally, the accelerations may excite internal resonances of smaller sub-components which are within the package. High acceleration is defined as $20G_{rms}$, although accelerations of higher than $100G_{rms}$ are often observed in spacecraft electronics, causing non-identifiable failures [5].

### D. Large Displacements Causing Impacts:

If the PCB has very large dynamic displacement and it has very small clearance with nearby objects, then it is possible that the PCB or components may impact these nearby objects.

## V. TIME TO FAILURE

Time to failure gives information about how and when these failures are occurring, and is relevant when it comes to the final discussion on the operable reasons of failure. Aside from failures that fall within the wear-out failure category, there is very little literature available on this topic. This is because all other types of failures are seen primarily as an issue within the manufacturing design process, and are too difficult to remedy except by improving manufacturing tolerances. Practically all of the references in the previous two sections (physical cause and failure location) fall under the heading of wear-out failures.

With reference to the bathtub curve (Fig.3.0), the different possible times to failure are [15] [18].

### *A. Infant Mortalities:*

This type of failure occurs within a relatively short time of the load being applied and it is attributed to manufacturing defects and material variability. Infant mortalities can be differentiated from other failures in that it is unlikely an identical board subjected to the same environment also fails in the same location. The electronic components are at a higher risk because of the large number of soldered joints and thus represent a higher risk of manufacturing defects. In terms of spacecraft electronics, infant mortalities are usually not a problem as they can be found during the acceptance test and then re-worked; although, this is only true if the acceptance test is severe enough to prompt them to occur.

### *B. Constant Rate Failures:*

This type of failure is a flat failure rate over the entire life of the equipment, these randomly distributed failures are because of inaccurate or incomplete specification of the loads imposed upon the equipment. There may be an element of fatigue in each failure, but the predominant cause is still poor specification of the loading environment.

### *C. Wear-out Failures:*

The probability of this type of failure increases beyond equipment’s useful life unless the working stress is below the fatigue threshold. These wear-out failures do not pose a problem unless the probability of their occurrence during the mission is high. Therefore, the onset of wear-out failures should be estimated and ensured to occur after the required life of the equipment.

Wear-out failures can be a difficult problem in terms of pre-flight acceptance tests for the following reason: The tests are necessary to highlight infant mortalities, but during this process some of the useful fatigue life of the component is used up. If the acceptance test is too severe, it may use up too much of the fatigue life, with insufficient component life remaining to survive the launch phase. Fortunately, this can usually be avoided by considering the length of time before the failures occurred in the earlier and more severe qualification tests.

### *D. Instantaneous Over-stress Failures:*

These types of failures are not considered in the bathtub graph (Fig.3). They normally occur almost immediately after being placed under stress, without significant fatigue damage ever occurring. Over-stress failures can be distinguished from infant mortalities by their repeatable nature, that is, similar equipment subjected to similar loads show similar over-stress failures, whereas infant mortalities show a large amount of variability. These failures generally occur from the stresses on the components being very high, because of either massively under-predicting the stress or over-predicting the component strength. Similar to infant mortalities, over-stress failures should not cause mission failures as they would always be detected during the pre-flight qualification tests; however, it can sometimes be difficult to distinguish them from infant mortalities.

## VI. OPERABLE CAUSE FOR FAILURE: DESIGN

Poor design is one of the foremost under-lying root causes of failure, thereby demonstrating that improving the design process is the most effective way to reduce the failure probability. In terms of design related failures, either the PCB vibration response will be too harsh or the components durability too small. Where the PCB vibration response concerns everything that determines the local environment experienced by the components (i.e. physical causes of failure as defined in section II) and the components durability concerns its ability to withstand these intense vibration environment [14]. However, although the discussion has considered too harsh vibrations and too weak components, until this point it does so in vague terms without giving specific values. This is the topic of discussion in the final part: looking at the design tools that currently exist to give a value to both the PCB response and component durability.

The mechanical requirements placed on equipment design are set by the authority incharge of the overall spacecraft development. These requirements aim to ensure that the equipment can withstand without failures the mechanical environment produced at the equipment location during launch. This environment consists of low frequency dynamics and steady accelerations, combined with random vibrations, acoustic loads and shocks.

## VII. WAYS TO PREVENT FAILURES.

A good design and analysis is a prerequisite for the safe and reliable functioning of an electronic package of spacecraft. The analysis needs thorough knowledge of the mechanical properties of the material and the boundary conditions applicable to the package. The electronic package that accommodates several PCB’s should be designed with high precision and accuracy. Extensive thermal and structural analyses should be performed to ensure that the package is capable of surviving and functioning during launch, travel to space, and in orbit.

The following are the practical methods which can minimize the time in iterations and also give a quality of work to prevent the vibration and shock loads coming over the package are discussed in this section.

### *1) Use of Vibration Isolators:*

Protecting satellite from these harsh loads by whole spacecraft vibration and shock isolation systems are now in practice. The basic concept of whole-spacecraft isolation is to minimize the entire spacecraft from the dynamics of the launch vehicle [2]. Typical vibration isolation systems work by connecting the isolated structure (payload) to the base structure (launch vehicle) by means of a single resilient mount or number of mounts. The resilient mounts have low relative stiffness as compared to the base and payload, and some degree of structural damping. The stiffness of the resilient mounts is tuned so that the frequency of vibration of the supported payload on the resilient mounts is a specified value (isolation frequency). Damping in the resilient mounts reduces the amplitude of response of the payload at the isolation frequency when the system is under external excitation [7]. The patented SoftRide MultiFlex (Fig 5.0) whole-spacecraft vibration isolation system is intended to reduce dynamic launch loads that are both axial and lateral in nature.

Fig 5.0: Typical SoftRide MultiFlex Vibration isolator

### *2) Use of sensors:*

Sensors can also be used in the vibration and thermal isolation, by mounting different types of sensors on the package and by interconnecting them by the networking of sensors. These networked sensors, send the appropriate signals to the processors, by which a corrective action takes place. By this, if vibration of the component exceeds the specified reliable value, the on-board sensor senses the amount of vibration coming out of the package, and then a corrective action will be taken by the processor, to isolate the unwanted vibration.

### *3) Use of shape memory alloys:*

Shape memory alloys are metal alloys that recover otherwise permanent strain when heated [14]. Shape memory alloys have two properties, the shape memory effect and the pseudo-elasticity effect. The shape memory effect occurs when a shape memory alloy in martensitic state is deformed by a load and then heated to austenitic form where it recovers its original shape.

Examples of variable stiffness elements are shape (or smart) memory alloys magnetohydrorheological elastomers and piezoelectrics [15]. Stable phases of shape memory alloys include a low-temperature phase referred to as martensite and a high-temperature phase known as austenite. The pseudo-elasticity effect occurs when a load is applied to shape memory alloys in austenitic state, which under proper conditions can induce a phase change to martensitic form. When the load is released, the material is transformed back to austenitic form and recovers its original shape [16].

### 4) *Use of smart structures:*

The technology of smart materials enables an unprecedented level of integration of sensors, actuators, and structures. This integration provides the opportunity for new structural designs that can adaptively influence their surrounding environment. To date, several demonstrations have been conducted to mature these technologies. Making use of recent advances in smart materials and structures technology like, microelectronics, Micro-Electro Mechanical Systems (MEMS) sensors, and Multi-Functional Structures (MFS), will enable programmable and flexible vibration control of spacecraft precision payloads [17].

## VIII. CONCLUSION

A crucial step to improve the equipment design is the accurate prediction of the vibration response of the electronic package (i.e. populated PCBs), to the vibration environment experienced during launch. The study briefly describes about the vibrations coming on the electronic package, which are harmful for the PCB's and their components for the operation.

Also the paper briefs about the failures occurring due to the combined thermal, shock and vibration loads, which are responsible for the failures due to fatigue, deflection of PCB's and cracks of the soldered components, and also for the structural failure of the electronic package / housing. Finally, different methods, as discussed can be attempted for the isolation of the vibration and thermal effects, so that the electronic package as a whole can be safe and function properly during the launch and meet the specified mission requirements reliably.

## IX. ACKNOWLEDGEMENT

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