Structural Dynamics of Electronic and Photonic Systems
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Electronic, optoelectronic, and photonic components and systems often experience dynamic loading. In commercial electronics, such loading can take place during handling or transportation of the equipment. In military, avionic, space, automotive, and marine electronics, dynamic loading, whether deterministic or random, is expected to occur even during normal operation of the system. On the other hand, random vibrations are sometimes applied (in addition to, or even instead of, thermal cycling or environmental testing) as an effective and fast means to detect and weed out infant mortalities. In addition, the necessity to protect portable electronics from shock loading (typically, because of an accidental drop) resulted in an elevated interest in the development of theoretical and experimental techniques for the prediction of the consequences of an accidental shock, as well as for an adequate shock protection of portable products. Development of new shock absorbing materials is regarded equally important. Finally, owing to numerous optoelectronic and photonic technologies emerged during the last decade or so, the ability to evaluate and possibly optimize the dynamic response of various photonic devices to shocks and vibrations is becoming increasingly important.

The following objectives are pursued in this book:

- familiarize the readers with the major problems related to the dynamic behavior of electronic and photonic components, devices, and systems;
- examine typical failure modes and mechanisms in electronic and photonic structures experiencing dynamic loading;
- address the basic concepts and fundamentals of dynamics and vibration analysis, including analytical, computer-aided, and experimental methods, and demonstrate how these methods can be effectively used to adequately approach the above problems;
- discuss and solve particular problems of the dynamic response of electronic and photonic systems to shocks and vibrations, and
- suggest how to choose the appropriate mechanical design and materials to create a viable and reliable product.

The reader of the book will become familiar with the mechanical, materials, and reliability related problems encountered in systems experiencing shocks and/or vibrations and will learn about the theoretical and experimental methods, approaches, and techniques which are used to solve these problems. This will enable those in the field to enhance their knowledge and skills in their profession and will teach those not in the field yet how to apply their background in mechanics, materials, and structures to this exciting and rapidly developing area of “high-tech” engineering.

The book is unique: it is the first time that a book of such a broad scope is written. The content of the book covers some of the most important mechanical, materials, and reliability aspects of the dynamic response, stability, and optimal design of electronic and photonic components, devices, and structural elements experiencing dynamic loading. The book contains 23 chapters written by leading specialists in the field. After getting familiar with the book’s chapters, readers will better understand the reliability problems in, and mechanical behavior
of, typical microelectronic, optoelectronic, and photonic structures subjected to dynamic loading, as well as be able to select the most appropriate materials for, and geometries of, such structures. Some of the design decision could be made based on simple and easy-to-apply formulas which will be provided in the book. These formulas indicate the role of different materials and geometrical factors affecting the mechanical behavior and reliability of a structure and can be effectively used prior to, and quite often even instead of, computer-aided modeling or experimental analyses.

The technical emphasis of the book is on the application of the basic principles of the dynamic structural analysis to understand, analyze, and improve the dynamic behavior and reliability of microelectronic and photonic structures operating in dynamic environments. The book will enable a design and reliability engineer, who did not work before in the field of electronics and photonics, to apply his/her knowledge in dynamical analysis to this new and exciting field. At the same time, physicists, materials scientists, chemical or reliability engineers who deal with “high-technology” components and devices for many years will learn how methods and approaches of mechanical and structural engineering can be effectively used to design a viable and reliable product.

The book is written with the emphasis on the physics of the phenomena. No in-depth knowledge of the mechanical, materials, or structural engineering is required. The needed information is given in the book chapters, when appropriate. Nonetheless, some knowledge of the basic calculus, strength of materials, and theory of vibrations is desirable to better understand the contents of the book.
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CHAPTER 1

SOME MAJOR STRUCTURAL DYNAMICS-RELATED FAILURE MODES AND MECHANISMS IN MICRO- AND OPTO-ELECTRONIC SYSTEMS AND DYNAMIC STABILITY OF THESE SYSTEMS

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1 PHYSICS OF ELECTRONIC FAILURES IN VIBRATION AND SHOCK

Modern electronic equipment is being used in a very large number of different areas that range from simple applications, such as automobile keys and temperature control devices, to very complex applications, such as airplanes, space exploration vehicles, and optical scanning medical devices. It is probably safe to say that virtually all electronic systems will be exposed to some form of vibration or shock during their lifetime.

The vibration and shock exposure may be due to the operating environment experienced by an airplane or an automobile. The vibration and shock exposure may also be due to shipping the product across the country by truck or train. Electronic systems that are required to operate in a harsh shock or vibration environment will often fail. If a failure occurs in an automobile temperature-sensing device or a fuel gage, it may be inconvenient for the owner, but the chances of someone being injured or killed are small. If the electronic failure happens to occur in the flight control system or navigation control system of an airplane or a missile, several hundred people could be injured or killed.

Many different types of materials, for example, metals, ceramics, plastics, glass, and adhesives, are being used today to fabricate and assemble a wide variety of electronic systems for commercial, industrial, and military applications. Many types of sophisticated electronic component parts are now available from a large number of manufacturers for specific applications and functions that did not exist only a decade ago. These components are often soldered to multilayer printed circuit boards (PCBs). PCBs may have from 6 to 12 internal layers of thin copper ground planes and voltage planes to remove heat and to provide electrical interconnections. The PCBs make it easy to assemble, remove, and maintain complex sophisticated electronic equipment at reduced costs. The PCBs must also protect the electronic components in storage, shipping, and operation in severe vibration, shock, thermal, and high-humidity environments. A wide variety of special plastics and metals are available to fabricate cost-effective and reliable electronic systems for special conditions.

The soldering process must be carefully controlled because solder is often the major source of early failures in the field. Good solder joints usually require the use of paste and flux to obtain a reliable connection. The paste and flux must be carefully removed from the PCB to prevent electrical malfunctions in sensitive systems after several months of operation.
2 Dynamics-Related Failure Modes and Mechanisms

in harsh environments. The normal procedure is to mount the electronic components slightly above the surface of the PCB, so that there is a small gap under the components. This makes it easy to flush out any paste and flux accumulated under the components. A thin protective coating should be applied to the PCB after cleaning to avoid the growth of dendrites, which can degrade the electrical performance of sensitive electronic systems operating in humid conditions. Dendrites are thin semitransparent plastic whiskers with a high electrical impedance that will often grow between electrical conductors in the presence of a chemical residue such as paste and flux and moisture exposed to an electrical current. Extended exposure for periods of several months can produce such a large mass of these whiskers that it will change their electrical resistance to an extent sufficient to cause malfunctions and even short circuits in the electrical system. Several thin protective coatings are available that can effectively prevent the growth of dendrites on PCBs. Materials such as paralyne, solder mask, polyurethane, epoxy, and acrylics can be applied to the clean PCB surfaces using different methods such as spray, brush, dip, and even vacuum processes. One of the best materials for protection is paralyne, which can be applied as a vapor. However, it is expensive and very tough. It is difficult to remove from the PCB if repairs have to be made and can often create new failures while trying to repair the old failures.

PCBs are often enclosed within a box or housing for easy transportation and handling. The housing can also protect sensitive electronic components from hostile external environments, such as sand, dust, sun, humidity, rain, insects, mice, and birds. Very small insects often make nests inside the warm interior of the electrically operating system. Their residue can build up inside the housing and cause bridging across multiple pin connectors, resulting in short circuits with early electrical failures. Electronic systems that will be required to operate in open outside areas must be fabricated and assembled to prevent small insects from entering the housing and making nests. Removable covers must have a very close fit or gaskets must be used to provide a good seal.

The PCBs are normally attached to the inside walls of the housing to help conduct away excessive internal heat to the outside ambient, where it is carried away. This also prevents the PCBs from impacting against each other and causing damage in vibration and shock conditions or the PCBs may have a multiple pin or socket connector added to one end of each PCB with a mate on the housing, so that each PCB can be plugged into the housing for electrical operation. Side wedge clamps can be used on the PCBs or the housing to improve the internal conduction heat flow path to the outside of the housing to reduce internal hot-spot temperatures. Reducing the internal hot-spot temperatures will usually increase the fatigue life of the electronics. The use of wedge clamps also helps to support the sides of the PCBs, which increases the PCB stiffness and natural frequency.

A higher PCB natural frequency substantially reduces the PCB dynamic displacements in vibration and shock conditions. This reduces the stresses in the PCBs, in the components, in external lead wires, and in external solder joints. This increases their fatigue life. Reducing the PCB dynamic displacements also increases the fatigue life of the die bond wires and the ball bonds inside the electronic components. Therefore, by increasing the PCB natural frequency, one could increase substantially the fatigue life of the lead wires, the solder joints, and the ball bonds on the semiconductor components mounted on the PCBs.

The natural (or resonant) frequency of the outer housing must be well separated from the natural frequency of the internal PCBs to avoid severe dynamic coupling and rapid structural failures of the PCBs in the housing during sine vibration. When the natural frequency of the outer housing is excited during exposure to a sine wave, the housing can sharply amplify the magnitude of the input acceleration \((g)\) level, depending upon the damping in the system. As is known from the theory of damping in linear vibration systems, when the structural damping in the system is zero and the system is being vibrated at its natural frequency using
a sine wave, the transmissibility (amplitudes) of that structure will be infinite. This condition is impossible, however, because every real structural system has damping.

2 CASE HISTORY FOR DESIGN, ANALYSIS, AND TESTING OF ELECTRONIC CHASSIS REQUIRED TO OPERATE IN SEVERE SINE VIBRATION ENVIRONMENT AND EFFECTS OF USING VISCOELASTIC DAMPING MATERIAL ON PCBs TO INCREASE FATIGUE LIFE

Failures in electronic systems can occur in many ways, often due to carelessness and lack of experience in handling a new environment or a new material. A large company with extensive electronics experience was awarded a multi-million-dollar contract for a program with a very severe vibration environment. Several other companies no-bid this contract because of the potential problems with the environment and low weight requirements for a system about the size of a shoe box. The company put a team of its top engineers together to solve the problem. This team spent several months investigating different proposals involving different exotic materials and the use of prototype test models to prove their capability to withstand the severe environment. The standard approach for providing reliable operation in severe vibration is to use vibration isolators. However, in this case the equipment had to be hard mounted so that isolators would not work. The team of experts finally selected a fabrication method for the PCBs inside the electronic enclosure that used a viscoelastic material. When this material was bonded to the PCBs, it provided high damping. The prototype vibration test models showed excellent results. The viscoelastic material was very effective in reducing the vibration “G response” levels enough to assure reliable operation in the severe vibration conditions. Reports were written and presentations were made to upper management. The experts’ team was given a green light to proceed with the fabrication and assembly for a large number of production units. Everyone was happy and sure that they had a reliable lightweight design that would survive the required severe qualification vibration tests. Their successful prototype test data were proof their new design would not fail. Their customer was invited to witness the qualification tests. The selection was made from a group of about 40 production units, ready for delivery to the customer. The first part of the vibration sine sweep tests went well, with no problems, so that everyone was happy. The next phase was the nasty 60-min dwell at the primary resonant frequency of the chassis. It was a mess. There were very loud cracking noises and a complete electrical failure of the electronic unit after a few minutes into the resonant dwell. The chassis was removed and the top cover was opened to inspect the condition of the PCBs inside of the chassis. Dozens of electronic components that had been soldered to the PCBs had broken off and were now lying at the bottom of the chassis. It was a major disaster. It was obvious that the design of the chassis did not meet the contract environment requirements. It was also obvious that the other 39 chassis assemblies sitting on the shelf ready to be delivered to the customer were also unacceptable.

An investigation of the failures showed that all the prototype models were tested at room temperature. No one in the expert team had any experience with the properties of viscoelastic damping materials. All the data they had from various sources showed the general material had excellent damping properties. No one in the expert team thought of calling or talking to the various viscoelastic suppliers to get more information on these materials for their severe environments. After all, the expert group had their own test data that showed the viscoelastic material was acceptable for their environment. What else did they have to know? What they