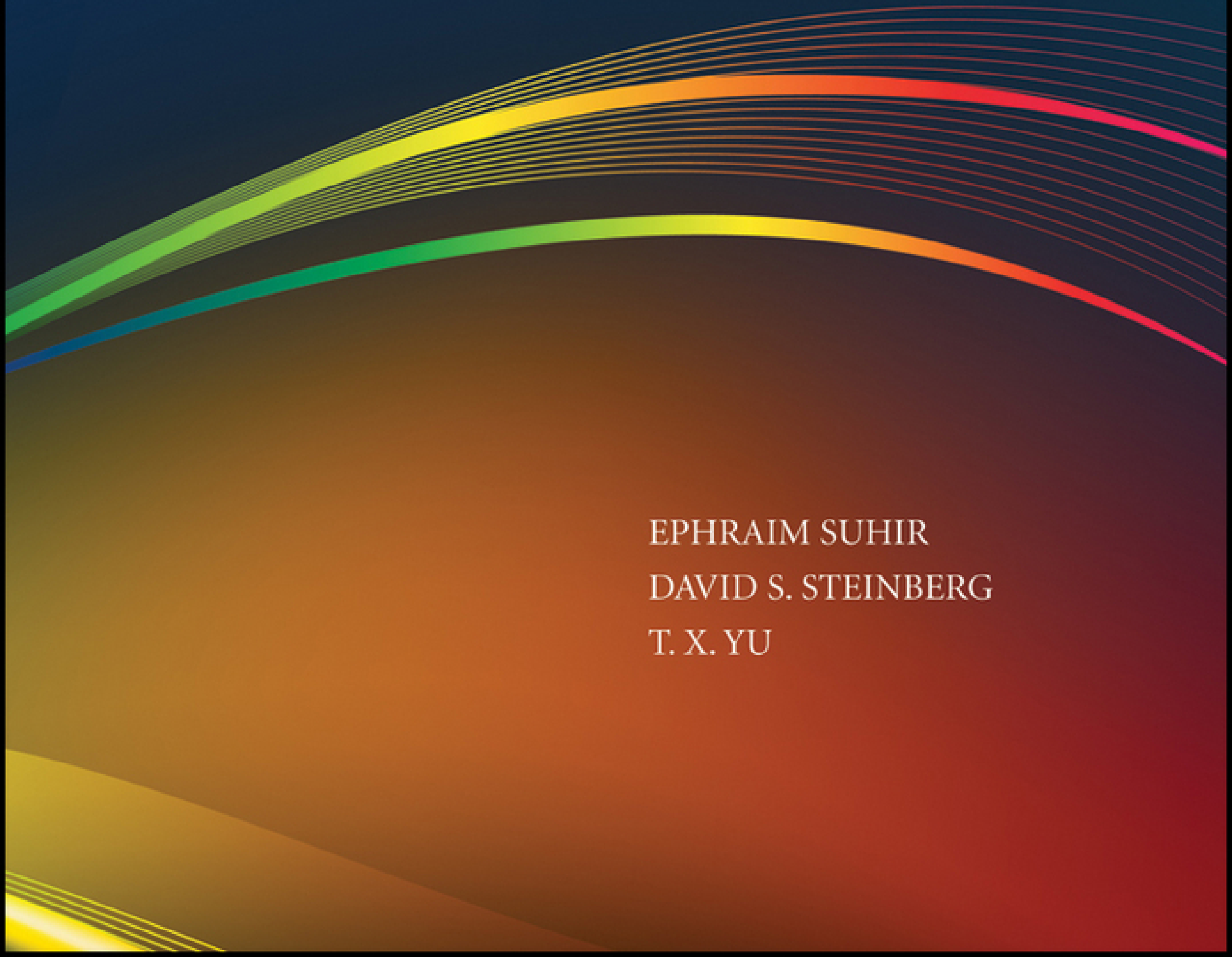
Structural Dynamics *of* Electronic *and* Photonic Systems



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Edited by
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Preface

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 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 day for the qualification tests arrived. One of the customers selected one chassis assembly to start the vibration 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 did not know was that most viscoelastic materials are extremely sensitive to temperatures. At room temperatures and lower, these materials work very well and can provide good damping. However, at higher temperatures these materials can lose almost all their damping properties and are almost useless. Since all the prototype fabricated test models were tested at room temperatures, the loss of damping at higher temperatures was not observed. No one in the expert group thought of the heat that can be generated when the electronic system was in operation. All the existing finished assembled units ready for delivery were now scrap, a whole new system had to be developed and put into production as quickly as possible, and the new system would still have to survive the severe environment. The company had a contract to deliver a large number of systems at a predetermined price. They had two choices. Go bankrupt or go ahead with a new design and production to meet the contract with their cost of about \$25 million. They chose to redesign the unit and to meet the contract with their own money.

The company searched for other engineers that had the knowledge and experience to meet the contract requirements. The new engineers were asked if they had ever used viscoelastic damping to improve the reliability of electronics in severe vibration. Their answer was that their experience showed that damping does not work very well, so they prefer not to use those techniques. Instead, the new engineers recommended the use of snubbers to reduce the dynamic displacements of the PCBs in severe vibration and shock conditions. Snubbers are usually made from epoxy fiberglass dowel rods, 0.25 in. in diameter. When several plug-in types of PCBs of the same size are inserted in parallel groups, the dowel rods should be epoxy bonded at the center of every PCB on both sides.

The dowel rods on adjacent parallel PCBs should be facing each other with a small gap about 0.005–0.010 in. between facing dowel rods. These snubbers can reduce the dynamic displacements of the PCBs in severe vibration and shock conditions. This then reduces the forces and stresses acting on the electronic components mounted on the PCBs, which substantially increases the fatigue life of the equipment (see [1], Fig. 7.7, p. 160). Snubbers are successfully used in PCBs for air dropping electronic sensors in the ocean at an altitude of 1000 ft. Shock levels of 1000*g* are produced under these conditions with very few failures.

3 WHAT HAPPENS WHEN 20 PLUG-IN PCBs ARE TIED TOGETHER, THEN INSTALLED IN A CHASSIS THAT IS SUBJECTED TO A 5*G* PEAK SINE VIBRATION INPUT LEVEL?

Another case history that demonstrates types of electronic failures that can be hard to predict involves an electronic enclosure about the size of a shoe-box. It operates in a 5*g* peak sine vibration environment. Several different types of prototype models were fabricated using different methods for mounting plug-in types of PCBs supported on four sides of their perimeter. Rapid failures occurred with every system that was tried. A single PCB with a bolt added through the center of the plug-in PCB was tested and that worked. The fundamental resonant frequency of this PCB with the center bolt was 425 Hz. The problem was how you clamp the center of 20 plug-in PCBs. The best idea was to drill a quarter-inch-diameter hole through the center of each PCB. A hole was also drilled at both ends of the enclosure. A long steel rod with a slightly smaller diameter could then be inserted through each PCB, so that the rod extended through the holes at each end of the enclosure. The clearance between each PCB was measured, so that a spacer the length of each measured clearance could be cut from an aluminum tube with a hole slightly larger than the steel rod. Each spacer has to be located between each pair of the PCBs. Spacers were also required between both inside end walls and the end PCBs. The steel rod can be inserted through each spacer, each hole in the PCB, and the holes at each end of the enclosure. Both ends of the steel rod have screw threads cut so that nuts can be added and tightened. The centers of all the PCBs and the two end-housing walls are now locked together to form a very stiff structure. There are a total of 20 PCBs in the housing, each with a weight of about 1 lb, for a PCB weight of about 20 lb. The enclosure housing was fabricated by using aluminum plates 0.090 in. thick that were dip brazed to form the outer enclosure. The 5*g* peak sine vibration environment with a resonant dwell at the natural frequency was considered to be severe. Therefore, an extra stiff belly band was brazed to the outer housing that extended 1.0 in. around the perimeter of the housing with 0.38 in. thickness (see [1], Fig. 14.29, p. 374). Vibration tests were run with the system bolted to an oil film slider plate. Before the tests were run, several engineers had questions regarding the safety characteristics of the PCBs all clamped together with spacers. There is a lot of vibration data on PCBs that were free to vibrate at their own individual natural frequencies. There was very little data, however, on vibration of many PCBs with spacers all bolted together. Very few people have experience with the large amounts of damage that can be generated by large masses all vibrating at the natural frequency. Accelerometers were located on PCBs inside the housing, on the outside surfaces of the housing, and on the oil film slider plate. The vibration tests were run in a direction perpendicular to the plane of the PCBs in the housing. The 5*g* peak sine vibration test was started using a slow sweep and increasing the frequency. Everything appeared normal as the frequency was slowly increased to 100 Hz, then to 200 Hz, then to 300 Hz. At this point the noise level was starting to increase slightly. As the frequency was increased more, the noise level also increased, but at a much higher level, and the people standing near the vibration machine began to back away. As the forcing frequency approached the 425 Hz resonant frequency, it sounded like a railroad train running through the environment test area followed by an explosion as pieces of the aluminum housing split apart. It should have been obvious that when a large number of heavy components are bolted together they will all have the same natural frequency. A large mass vibrating at its natural frequency will have a high kinetic energy that can cause a lot of damage even to a strong structure. A very massive structure has to be designed and fabricated to prevent this type of failure. This type of system should not be used on structures subjected to high vibration and shock because they can have a high failure rate. Properly designed snubbers can be very effective for high vibration and shock levels when used properly.

4 CONSIDER USING SNUBBERS TO INCREASE FATIGUE LIFE OF ELECTRONIC SYSTEMS REQUIRED TO OPERATE IN SEVERE VIBRATION AND SHOCK ENVIRONMENTS

One type of electronic system that works very well for severe vibration and shock is to bond snubbers to plug-in types of PCBs. These devices reduce the forces and dynamic displacements of the individual PCBs when they are properly used. This decreases the PCB stress, increases the PCB's fatigue life, and improves its reliability. Snubbers allow each PCB to vibrate at its own natural frequency. Every PCB will now have a different natural frequency. This prevents the individual PCBs from adding all their kinetic energy together and sharply increasing their failure rates. Snubbers usually use epoxy fiberglass dowel rods about 0.25 in. in diameter epoxy bonded at the center of each plug-in PCB on both faces of every PCB. The snubbers on adjacent PCBs facing each other must have a very small space between them, about 0.008 in., and be aligned so that they impact against each other during vibration, thereby reducing the displacement for improved fatigue life.

5 SAMPLE PROBLEM: CALCULATING FORCES, STRESSES, AND FATIGUE LIFE OF THE END ALUMINUM PLATES IN PREVIOUS HOUSING ENCLOSURE

High vibration acceleration "G forces" will often produce high stresses that can reduce the fatigue life of poorly designed structures (see [1], Fig. 14.29, p. 374). In this sample problem the dynamic forces F acting on the end plates are calculated first. The resulting stresses are calculated next. The expected fatigue life is calculated last:

$$\begin{aligned} F &= \text{mass} \times \text{acceleration} \\ &= \text{ma}, \end{aligned} \tag{1}$$

where Mass = weigh/gravity. So

$$m = \frac{w}{g} \quad \text{and} \quad G = \frac{\text{acceleration}}{\text{gravity}} = \frac{a}{g}. \tag{2}$$

Hence,

$$\text{Force} = ma = \left(\frac{w}{g}\right)(a) = (w)\left(\frac{a}{g}\right) = wG. \tag{3}$$

During resonant conditions the transmissibility Q amplification factor for the 20 internal PCBs must be included to obtain the total dynamic force F acting on the full structure. Test data showed that a good approximation for the PCB Q factor for the assembly with an input acceleration level of $5g$ sine could be approximated by the square root of the expected natural frequency. The natural frequency for the PCBs in this dip-brazed aluminum assembly was about 425 Hz:

$$\text{Approximate transmissibility } Q = \sqrt{425} = \text{about 20 (dimensionless)} \tag{4}$$

$$\begin{aligned} F &= wG_{IN}Q = (\text{weight})(G)(Q) = (20)(5)(20) \\ &= 2000 \text{ pounds on 2 ribs}, \end{aligned} \tag{5}$$

$$\text{Dynamic force acting on one rib} = 1000\,\text{lb},$$

$$\text{Chassis width} = 8\,\text{in.},$$

$$\text{Half of Chassis width} = 8/2 = 4.0\,\text{in.}$$

The approximate dynamic bending stress on the aluminum end plates of the housing can be obtained using the equation

$$S_b \frac{MC}{I}. \tag{6}$$

Here the Bending moment M for one reinforcing rib is given as

$$M = \frac{1000}{2}(4) = 2000\,\text{lb in.}, \tag{7}$$

$$C = \text{distance from end plate to neutral axis} = 0.50 \text{ in.},$$

$$I = \text{approximate moment of inertia, one rib} = 0.0316 \text{ in.}^4, \tag{8}$$

$$S_b = \left(\frac{(2000)(0.50)}{0.0316}\right) = 31,645 \text{ lb/in.}^2 \tag{9}$$

The approximate vibration fatigue life of the 6061 T-4 aluminum dip-brazed chassis can be obtained from [2], as shown below:

$$\frac{N_1}{N_2} = \left(\frac{S_2}{S_1}\right)^b$$

so

$$N_1 = N_2\left(\frac{S_2}{S_1}\right)^b = (1000)\left(\frac{36,000}{31,645}\right)^{6,4} = 2282 \text{ cycles to fail.} \tag{10}$$

The value b of the exponent was determined for the aluminum structure by using the typical physical properties of the aluminum alloy where the endurance stress is typically one-third of the ultimate tensile stress. A stress concentration factor of 2 was used to compensate for manufacturing tolerances and material properties, to ensure a good fatigue life in vibration and shock environments, without a large increase in the size, weight, and cost. The exponent ($b = 6.4$) represents the slope of the vibration fatigue curve on a log–log plot. The value of this function was derived in [1] (p. 168, Eq. 8.3). The estimated time to fail can be obtained from the chassis natural frequency of 425 Hz, as shown below:

$$\begin{aligned}\text{Time to fail} &= \left(\frac{2282 \text{ cycles to fail}}{(425 \text{ cycles/sec})(60 \text{ sec/min})}\right) = 0.089\,\text{min}\\ &= 5.4\,\text{sec.}\end{aligned} \tag{11}$$

The above time to fail is very close to the time of failure from the vibration test.

6 HOW DISPLACEMENTS ARE RELATED TO FREQUENCY AND ACCELERATION

A rotating vector is often used to describe the simple harmonic motion of a single spring–mass system. The projection of the rotating vector can be used to describe the vertical displacement Y of the mass at any time compared to the maximum displacement of the mass, Y_0, as the mass moves up and down, as shown in the following equation:

$$Y = Y_0 \sin \Omega t. \tag{12}$$

Here the rotation of the vector is $\Omega = 2\pi f$, where t is time and f is frequency. The velocity V is the first derivative as shown below:

$$V = \frac{dY}{dt} = \Omega . Y_0 \cos \Omega t. \tag{13}$$

The acceleration A is the second derivative:

$$A = \frac{d^2Y}{dt^2} = -\Omega^2 Y_0 \sin \Omega t. \tag{14}$$

The maximum acceleration will occur when $\sin \Omega t$ is 1:

$$A_{\text{MAX}} = \Omega^2 Y_0. \tag{15}$$

The negative sign indicates the acceleration acts opposite to the displacement direction. The acceleration can be obtained in terms of the gravity units (g) by dividing the maximum acceleration by the acceleration of gravity $g = 386$ in./sec^2 using inches for English units and the acceleration of gravity $g = 980$ cm/sec^2 using centimeters for metric units. The radians are changed into cycles per second as $\Omega = 2\pi f$ and substituted into Eq. (15):

$$G = \begin{cases} \dfrac{A_{\text{MAX}}}{g} = \dfrac{\Omega^2 Y_0}{g} = \dfrac{4\pi^2 f^2 Y_0}{386} = \dfrac{f^2 Y_0}{9.8} & \text{(English units, in.),} \quad (16)\\[2ex] \dfrac{A_{\text{MAX}}}{g} = \dfrac{\Omega^2 Y_0}{g} = \dfrac{4\pi^2 f^2 Y_0}{980} = \dfrac{f^2 Y_0}{24.9} & \text{(metric units, cm).} \quad (17)\end{cases}$$

It is convenient to change the displacement reference Y_0 to Z_{SA} for the single-amplitude displacement. Then, solving for the maximum single-angle displacement for the English and the metric units gives the values

$$Z_{\mathrm{SA}} = \begin{cases} \dfrac{9.8G}{f^2} & \text{(English units, in.),} \\ \dfrac{24.9G}{f^2} & \text{(metric units, cm).} \end{cases} \tag{18}$$

When the input G level is used, the above equations will give the input displacement Z. When the response (or output) G level is used, the above equations will give the output displacement Z usinsg the proper displacements in inches or in centimeters.

The amplification factor, which is called the transmissibility or the Q factor, can often magnify the input acceleration G level to the outer housing and also to any electronics that are mounted inside the housing. These Q factors can magnify the input acceleration G levels to the outer housing and the internal electronics by values as high as 10 or 20 or more; this can cause extensive damage and rapid structural failures. The transmissibility Q is defined as the ratio of the output divided by the input. This ratio can be in terms of the acceleration G levels, or displacements, or velocities, or forces. One of the most important equations in dynamics is

$$Z_{\mathrm{SA}} = \begin{cases} \dfrac{9.8G_{\mathrm{IN}}Q}{f_N^2} & \text{(English units),} \\ \dfrac{24.9G_{\mathrm{IN}}Q}{f_N^2} & \text{(metric units)} \end{cases} \tag{19}$$

where:

Z_{SA} = displacement, single amplitude, zero to peak, English units = inches, metric units = centimeters

G_{IN} = input acceleration G level, dimensionless

f_N = frequency or natural frequency, Hz

Q = transmissibility, dimensionless ratio of output/input

The above equations can be written in another way to demonstrate the effect of using a very low input G level for a vibration test in order to prevent damaging the hardware. In English units,

$$Q = \frac{f_N^2 Z_{\mathrm{SA}}}{9.8G_{\mathrm{IN}}}. \tag{20}$$

Equation (20) shows that if a very low input acceleration G is used for a sine vibration test (usually to prevent damage) on any nonrigid structure such as a PCB, the transmissibility Q can become very high. For example, test data show that, if an input acceleration level of $0.2g$ peak is used on a PCB with a natural frequency of 250 Hz, the response Q level of the PCB will be about 70, depending upon the damping available in the construction of the PCB. Transmissibility Q values of 70 will frighten many people who are not familiar with vibration. They will multiply the response Q of 70 × their $5G$ peak input required for the qualification test. This will give them a value of $350g$ peak. They are shocked because acceleration G levels this high will destroy the system very quickly. These people do not know that if an input acceleration level of $5g$ peak is used, test data shows the response Q level of the PCB will only be about 16, depending upon the damping. The higher $5g$ sine input acceleration level increases the force, stress, and displacement in the PCB. This will increase the PCB damping, which will reduce the transmissibility Q level. The new PCB response is now about $16 \times 5 = 80g$ peak. This is still a high acceleration level that may require the use of an isolation system or some structural reinforcement, or perhaps snubbers, to survive lengthy qualification tests. This also shows that the input acceleration G level, even for preliminary sine vibration tests, must be based upon the acceleration G levels expected in the qualification test program. This will assure the reliability of the electronic assembly so it will be able to pass the qualification test program without any failures. Equation (20) also shows that a higher frequency will always produce a higher transmissibility Q because the displacement Z and the acceleration G level are linear functions. However, the frequency is a square function so it increases at a more rapid rate.

Equation (18) shows that the displacement, acceleration G, and frequency cannot be separated. They are locked together. Any two parameters determine the third parameter. Equation (18) also shows that increasing the natural frequency will result in a substantial reduction in the dynamic displacement because the frequency is a square function. Equation (18) shows that an increase in the acceleration G level will also increase the dynamic displacement if the frequency is held constant.

7 SAMPLE PROBLEM: FIND DYNAMIC DISPLACEMENT OF PCB EXPOSED TO SINE VIBRATION USING ENGLISH UNITS AND METRIC UNITS

A PCB supported on two opposite sides has a natural frequency of 225 Hz and a transmissibility Q of about 15. Find the single-amplitude displacement at its natural frequency using a sine wave with an input level of $5g$ peak using Eq. (18):

$$Z_{\mathrm{SA}} = \begin{cases} \dfrac{(9.8)(5)(15)}{(225)^2} : 0.0145\,\text{in.} \quad \text{(English units),} & (21) \\[2ex] \dfrac{(24.9)(5)(15)}{(225)^2} = 0.0368\,\text{cm} \quad \text{(metric units).} & (22) \end{cases}$$

8 OCTAVE RULE CAN AVOID VIBRATION FAILURES DUE TO RESONANCE COUPLING OF OUTER HOUSING ENCLOSURE WITH INTERNAL PCBs

Many electronic control systems are required to operate in severe vibration, shock, and humidity conditions, so sensitive PCBs are often mounted inside an enclosed housing for protection. Housings must be strong enough to withstand severe environments. Consider a relatively simple system where several plug-in types of PCBs are in an enclosure to provide protection from harsh outside environments. Vibration and shock tests are to be run so small accelerometers are mounted in several areas on the outside of the housing and on several PCBs inside the housing. These will record the acceleration levels observed at various points outside the housing and on the components inside the housing. The housing will have a fundamental (first) natural frequency which can be recorded and the various PCBs will typically have their individual fundamental natural frequencies. It is very important to avoid conditions where the housing natural frequency is very close to the natural frequency of any of the PCBs mounted inside the housing. This can cause a resonance coupling effect where the housing resonance multiplies the PCB resonance that can produce failures in some of the PCBs.

When the peak sine vibration input acceleration level is $5g$ and the housing Q value is about 4, the response of the housing at its natural frequency will be 5×4, or $20g$ peak. Acceleration levels this high may cause some failures in the housing structure and possible failures to some PCBs, depending upon the natural frequency of the PCBs. The same conditions must also be examined for the PCBs inside the outer housing when the assembly is exposed to a sine vibration input level of $5g$ peak. The internal PCBs have their own individual natural frequencies that can be excited during exposure to the sine vibration imposed on the outer housing because the PCBs are attached to the inside of the housing. The PCBs can amplify the housing acceleration G levels when the PCB natural frequencies are excited. Amplification Q factors for each of the PCBs will also depend upon the damping of the various PCBs. Vibration test data show that the PCBs inside the housing can further amplify the acceleration levels they receive from the outer housing. When the natural frequency of the housing is close to the natural frequency of the PCBs, their Q's can couple. This will increase the acceleration levels on the PCBs. Test data show the transmissibility Q values of the PCBs and the housings are multiplied. They are not added. For example, when the peak input sine level to the housing is $5g$, and the transmissibility Q for the housing at its natural frequency is 4, the transmissibility Q value for the housing at its natural frequency will be about 5×4, or 20. When the transmissibility Q of the typical PCB inside the housing is about 9, and the natural frequency of the PCBs are very close to the natural frequency of the housing, the resulting transmissibility Q of the housing will couple with the Q of the PCBs. The typical PCB Q will then be about $5 \times 4 \times 9 = 180g$ peak. The actual peak acceleration levels will be somewhat lower because the high-acceleration G levels will increase the dynamic displacements of the PCBs. This will increase the stress levels in the PCBs and convert more strain energy into heat, which increases the damping in the PCBs. This will slightly reduce the transmissibility Q acting on the PCBs, which will reduce the forces acting on the PCBs slightly. However, the reduced G forces in this general range can still do a lot of damage very quickly, even to rugged electronic systems.

Sine vibration-induced failures in electronic systems can be reduced by using the "octave rule." "Octave" means to double. In this case it means that the natural frequency of the outer housing structure must be an octave (factor-of-2) away from the natural frequency of the PCBs mounted inside the housing. Test data show that when the natural frequencies of the outer housing and the internal PCBs are separated by a factor of at least 2, the magnitude of the coupling forces between the housing and the PCBs are sharply reduced. This substantially increases the fatigue life of the electronic system by reducing the internal forces and stresses. The outer housing and the internal PCBs will have several different natural frequencies. The first natural frequency usually has the highest Q value. Vibration tests on prototype models have to be made to ensure the most critical combinations of housing frequencies and PCB frequencies are used to follow the octave rule for the minimum forces acting on the internal PCBs.

The dynamic force path through the structural assembly should be examined closely to make sure that the octave rule is being followed properly. For example, when the fully assembled electronic system is being vibrated, the exciting force first acts on the outer housing. The outer housing then becomes the first degree of freedom. The force path then goes from the outer housing to the internal PCBs that are attached to the housing. The internal PCBs then become the second degree of freedom. The natural frequency of the first-degree-of-freedom structure (the housing) must be at least one octave (a-factor-of-2) or more away from the natural frequency of the second degree of freedom (the PCBs). This will avoid severe coupling that can generate high forces and stresses that can reduce the fatigue life of the housing and the PCBs.

This means that if the lowest natural frequency of the typical internal PCB is about 200 Hz, the lowest natural frequency of the external housing should be about 100 Hz (which is half of 200 Hz on the PCB), or the natural frequency of the housing should be about 400 Hz (which is 2 times the 200 Hz on the PCB) to follow the octave rule. In the case just described, the housing natural frequency should be either slightly below 100 Hz or slightly higher than 400 Hz to follow the octave rule. Housing natural frequencies between 100 and 400 Hz for this specific condition should be avoided, if possible, to ensure a good fatigue life for the PCBs mounted inside the housing. This means that the internal PCB natural frequency design must be carefully separated from the housing natural frequency. This will avoid close resonances between the PCBs and the housing that can produce rapid failures in the PCBs during vibration conditions. It should be noted that the natural frequency of the PCBs and the natural frequency of the outer housing refers to their first resonant mode, which is usually the lowest natural frequency of the PCBs and the lowest natural frequency of the housing. Shock is not as important in this application because the shock environment very seldom experiences as many stress reversal cycles as vibration in most applications. Shocks usually produce much higher acceleration *G* levels than sine vibration, which can also produce rapid structural failures in the outer housing and the internal PCBs.

9 ANOTHER APPLICATION WHERE SNUBBERS CAN BE USED TO IMPROVE FATIGUE LIFE OF PCBs IN SEVERE VIBRATION AND SHOCK ENVIRONMENTS

The octave rule is often difficult to implement because of possible size and weight limitations and lack of information relating to the transmissibility *Q* values of the structural elements or the natural frequencies and these structural members. Under these conditions the use of snubbers is highly recommended. The best snubbers are made from epoxy fiberglass dowel rods about 0.25 in. in diameter. They should be epoxy bonded near the center of every circuit board on both opposite faces of the circuit board. These snubbers must be positioned on each circuit board and aligned so the snubbers on adjacent PCBs impact against each other, which will reduce their dynamic displacements. The spacing between the snubbers on adjacent PCBs must be small, typically less than about 0.010 in., so that they will impact against each other at each PCB resonant frequency. This also reduces the PCB dynamic stresses in the electronic components and their electrical lead wires and solder joints, which improves the reliability of the electronic system. Some sine vibration testing may have to be done with the snubbers to make sure the spacing forces snubbers to impact against each other.

Another method for reducing large dynamic displacements and stresses in the PCBs is to just fill all the empty spaces in the enclosure, between all of the PCBs, after their final assembly using small, lightweight spheres. These look like small hollow ping pong balls that add very little weight to the electronic assembly. These small spheres can be added at the final assembly while it is being vibrated at a very low frequency to allow the spheres to settle in place.

10 VIBRATION FAILURES DUE TO CONNECTOR FRETTING CORROSION IN RANDOM VIBRATION

A wide variety of electrical connectors are being used in a very large number of different applications, in many different types of industries, and in many countries all over the world. These applications vary from the very simple devices to the very complex devices. Some applications monitor sensitive stationary conditions and some monitor rapidly changing conditions. Most connector applications involve the transfer of some type of analog or digital data from one point to another point. Sometimes the data being transferred can be very critical and sometimes not really important. When the data being carried are very important, then it is necessary to understand the characteristics of the connector that will be used to transfer the critical data, and the operating environment, in order to be sure the data will be accurate.

Extensive test data on many different types of connectors operating in different types of vibration and shock conditions have shown some strange results. A series of tests were run with PCBs that had multiple plug-in pin types of NAFI flat-blade and tuning fork connectors. Each connector blade had two electrical contacts, one on each face of the blade. All the electrical brass contact faces were protected with 30 millionths of gold over 150 millionths of nickel over the brass connectors. The tests were run using a $5g$ root-mean-square (rms) random vibration input with a PCB resonant frequency of about 150 Hz. This showed what appeared to be open circuits (called “glitches”). Each glitch lasted about 1 μsec. The first glitch was observed after 15 or 20 min of testing. No one was worried. All went well for the next 10 min, then another glitch was observed. Now the engineers began to worry. In a high-speed digital system a lot of information can be lost if there is an open circuit. Again all went well for another 5 min, then another glitch was observed. As the tests continued, the glitches were observed to occur more often at closer intervals. The tests were stopped and the housing was opened so the PCB solder joints, the connectors, and the cables could be inspected for problem areas. Everything looked normal so the housing was assembled and the vibration started again. The system looked normal for a few minutes, then the glitching started again. Every time the electrical system was tested without the imposed vibration, the system worked perfectly normal. Every time the tests were run with the imposed random vibration, the glitching occurred. A mechanical engineer from another group walked up to the test engineers and asked them if they checked the plug-in connectors on the PCBs to see if the protective layers of gold over nickel over brass were worn away. The test engineers were very upset by this outside engineer asking questions and they wanted him to leave. The test engineers said they checked the gold coatings and they looked good. The outside engineer walked over to the housing and wiped his finger across the inside surface and showed a finger with a fine black powder to the test engineers. He said his black finger was from the black copper oxide generated by the heat of a very rapid weld shear action because the nickel and the gold protection on the contact pins was worn away. They did not believe him when he said polished brass looks like gold. He reached into a box and removed a small bottle that contained a 5% solution of sodium sulfide. He brushed this solution on every connector on every PCB. A small black spot appeared on every connector contact in about 7 sec. This showed there was copper present and that the gold-over-nickel protection on the contacts had been worn away by the rapid 150-Hz oscillations generated by the vibration. Some care must be used when purchases are made of the sodium sulfide solution for testing the presence of any copper alloys. Many companies sell a 3% solution of sodium sulfide. This solution is not strong enough to detect the presence of any copper-based alloy. The minimum solution strength of 5% sodium sulfide must be used to detect the presence of a copper-based alloy. The test engineers did not understand why the glitches were occurring. It was pointed out that each connector pin had two points of contact for improved reliability. When one contact point on the pin failed, there was always a second contact point that could pick up and transmit the same signal to ensure the reliability of the signal and the system. The fine black powder is an electrical insulator. During vibration, the fine black powder can be deposited on both faces of one flat connector pin. The black powder can creep in between some of the pins and the sockets on the plug-in PCBs, producing an open circuit for a 1-μs glitch. Long vibration periods can accumulate such a large amount of black powder that it coats the entire inside surface of the housing. This problem can be solved by using connectors with pins that have more than two points of contact. Tests with connectors that had four or more contact points on each pin for the electrical contacts did not show any glitching when the vibration was imposed. The normal fretting corrosion still occurred and the fine black powder was still there. However, the probability of all four points on a pin having the black powder get under all four points at the same time and causing an open circuit was shown by the tests to be almost impossible. No open-circuit glitches were observed after several hours of random vibration using an input level of 5*g* rms.

Many of the latest Air Force airplanes have had similar glitching problems with old-type connectors on new electronic equipment. Changes were made using the new Bendix Bristle Brush (B cube) connectors with redundant pins that have about 12 points of electrical contact to solve the problem. The Smith Hypertronix connector is also popular for solving the glitching problem. This connector has about eight points of electrical contact for each pin. The fine black powder will still be created with these connectors, but it will not cause any glitching with open circuits with the use of random vibration, since these connectors have more than four points of electrical contacts on each pin. They have been used to avoid the glitching open-circuit problems during vibration when the resonant frequency is excited. This can impose millions of stress cycles that can wear through the gold-over-nickel protection for the copper-based alloy connectors, but this will not affect the reliability of these connectors, even in harsh environments.

The fretting corrosion and open circuits only appear to occur with random vibration during extensive exposure to long periods of high-vibration *G* rms levels. This can produce many million stress cycles that can cause extensive wear on the gold and nickel protective coatings over the connector pins. Test data using sine vibration with a greater equivalent energy input acceleration peak level did not cause any problems with glitching or open circuits or the fine black powder being developed. The rapidly changing random vibration frequency and amplitude, over the very wide bandwidth, sharply increases the number of critical stress cycles imposed at different frequencies. This increases the wear through the gold and nickel connector protective coating and decreases the fatigue life of the electronic assembly.

11 WHY SOME FAILURES MAY BE DIFFICULT TO SOLVE OR MAY NEVER BE SOLVED

When groups of people work together on the same project, there is usually a feeling of friendship among the workers. There are times when failures will occur during the testing of an important new prototype electronic assembly. People with the most knowledge and experience will usually be assigned to examine the assembly to try to find the source of the failure and to make recommendations for some corrective action. Everyone in the group appears to be willing to help solve the problem as quickly as possible. Time is money, so that a quick solution to the problem is desired. Under these conditions no one at this time would believe that the failure could have been caused by one of their own friends. An investigation of the failure might show something out of the ordinary, like a bent pin on a connector, or a loose wire, or a cracked solder joint in a strange place. These do not look like natural failures. However, after repairs have been made and tests are resumed, more failures in different areas appear. Some people may begin to wonder if the failures are natural or man made. It can be very difficult to separate real failures from deliberate man-made failures, depending upon the experience and skills of the people involved.

Several years ago an engineer was working on a program where the vibration levels were quite high, with a requirement for a lightweight system. A qualification test was set up using several prototype models to evaluate proposed designs. Natural frequencies with calculations of the forces, stresses, and expected fatigue life of critical structures were made before the vibration test program to ensure a reliable design. The vibration tests on some of the models were very good. Some models showed a rapid fatigue failure in one of the structural elements that was used on all of the prototype models. This was very strange because the calculations showed this structural element was expected to be very reliable. The structural element involved was a steel shaft about an inch long with a diameter of 0.50 in. One end was machined down to a diameter of about 0.25 in. over a length of about 0.50 in. to fit a bearing. Several failures occurred at the step in the shaft where the shaft diameter changed from 0.50 to 0.25 in. High stresses were expected at the step because of high stress concentrations, so that a generous fillet was used at the step to reduce these stresses. One of the engineers suspected there might be a problem with cutting the step in the shaft using a single cutter on a lathe instead of three cutters at 120° apart. A single cutter would apply a high concentrated force at the end of the shaft which could produce cracks at the step and generate more rapid failures. He went to the machine shop and spoke to the manager of the department about a single cutter. The manager became very angry at the idea and insisted that he personally directed every machinist to use three cutters on the shafts. The manager then insisted that the engineer leave his shop immediately, because the failures were due to the engineer's poor design. The engineer went back to his calculations that showed the shafts should not fail. He went to the machine shop again and waited until the manager left the area. The engineer then took a walk through the small machine shop to see for himself how the shafts were being cut. He saw one of the shafts being cut with a single cutter. The manager saw the engineer and demanded that he leave the machine shop immediately. The engineer did not move. Instead he pointed to the operation that was using a single cutter. The manager looked at the single-cutter operation and his face turned white. He yelled at the machinist, asking him why he was using a single cutter when he was told to use three cutters. The answer came back that he could not make his quota using three cutters because it took much more time to make the adjustments. The single cutter was much faster and the results were just as good. The engineer was lucky because the machine shop was operating two shifts. With a little bad luck he would have completely missed seeing the operations using one cutter so he would never know the real reason for the failures. He would have less confidence in the accuracy of his calculations. This also points out the poor practice of some managers. They give instructions to people but never explain why the instructions are important and they never take the time to follow up to see that these people are really following his instructions.

12 COMPANIES WITH FINANCIAL PROBLEMS MAY REDUCE QUALITY TO SAVE MONEY

Companies often try to find ways to improve their profit margins when their business slows down. An example of this involved the temper of aluminum wedge clamps that were specified as 6061-T6 for plug-in PCBs to operate in severe environments. These conditions involved vibration, shock, and thermal cycling. Many electronic systems had early failures due to loose wedge clamps that were blamed on the manufacturing group. The manufacturing group said they always inserted the PCBs in the guides at the sides of the housing; then they tightened the screws using the proper torque until the PCBs were locked in position. There must be another reason for the failures. The engineering group looked and looked for other possible reasons for the failures, but they could not find any. They were about to go back to the manufacturing group again when one engineer took another look at the three-piece wedge clamps on both sides of the PCB. These centerpieces were very long and they were attached to the sides of the PCB. The centerpiece had a 45° wedge at each end. The top and bottom end pieces were very short. They each had one 45° wedge on one face. The 45° wedges on the two short pieces interfaced with the 45° wedges on the long centerpiece. The small bottom wedges had threads for a long screw. The center wedge and the top wedge had clearance holes for the long screw. When the screw is tightened at the top wedge, the bottom wedge rides up the 45° angle on the centerpiece and the top wedge rides down the 45° angle on the centerpiece. This forces the top and bottom wedges to expand and lock the PCB in position against the side guides on the PCB. The engineer noticed a small notch near the bottom of the center wedge and a similar small notch near the top of the bottom wedge. These two notches appeared to be very close to each other. The engineer turned the screw at the top of the wedge and watched the bottom wedge rotate and start to ride up the centerpiece. He continued to turn the screw to the required torque and noticed that the bottom wedge did not fully rotate and did not properly ride up the centerpiece. The small notch on the half-rotated 45° wedge on the bottom part was now locked on the small notch on the centerpiece. The proper torque had been applied to the screw for locking the PCB to the housing, but the PCB was still loose. During normal operation the heat from the PCB must be carried away to prevent the PCB from overheating and failing. The heat must be conducted across the interface from the wedge clamps on the PCB to the housing metal side walls. This carries the heat from the PCB to the local ambient outside the housing so the PCB stays cool. If the PCB wedge clamps are loose, there will be air gaps between the PCB and the housing. Air does not conduct heat very well so the PCB temperature rises and the PCB fails. Wedge clamps have been used for many years without any failures. Small notches in the wedge clamps mean the aluminum metal must be softer than 6061-T6. The engineer calls the wedge clamp company to verify if the wedges are using the proper heat-treated aluminum. The company insists his wedge clamps have the proper hardness. The wedge clamps are then sent to three outside testing groups to verify the temper of the aluminum. The reports show a temper of only T-4, which shows the aluminum is too soft and is causing the failures. The engineer calls the wedge clamp company and reports the outside tests show a temper of only T-4 which is causing the failures. The company again insists his temper is T-6 and the other outside testing groups do not know how to run proper tests. The engineer goes to his purchasing department and tries to cancel the contract and go to a different company to purchase the wedge clamps with the proper T-6 hardness. He is told the contract cannot be canceled because this owner of the wedge clamp company is a relative of the president of the engineer's company. The engineer must find a way to use the T-4 temper aluminum wedge clamp so they do not fail in harsh environments. Every idea he has is not practical because it requires a redesign and a large increase in the cost with a long time delay in the delivery of the hardware. He finally remembers that aluminum can be anodized with a thin coating that is very hard because it is a ceramic, with a modulus of elasticity that is three times higher than the aluminum. He also finds the process will only cost about one dollar for each wedge clamp. This solves the problem with no more loose PCBs and no more failures.

13 WHY SOME PEOPLE WILL SHIP ELECTRONIC EQUIPMENT THEY KNOW WILL FAIL JUST TO GET THEIR SHIPPING BONUS

Many companies often reward their employees with extra bonus money if they ship some equipment ahead of schedule. These companies always assume their employees are very honest so they would never ship any equipment they know is bad and will fail quickly. In this particular investigation, a large well-known Midwest company always performed an environmental stress screening (ESS) on its electronic equipment before shipping to ensure a reliable product. The purpose of the ESS is to stimulate the electronic equipment for a short period of time in some way that will force the most critical hidden flaws into hard failures. The equipment can then be repaired before it is shipped so the customer will receive a very reliable product with a long fatigue life. The stimulus is often called a bake-and-shake test. This covers about a dozen thermal cycles over a broad temperature range and several minutes of a broadband random vibration test, each performed separately while the equipment is electrically operating. The problem in this case was that a 50-pin ceramic microprocessor about 2 in. long kept failing after only a few minutes. The solder joints were failing in the thermal cycling tests and the lead wires were failing in the random vibration tests. Surface-mounted lead wires were tried and through-hole lead wires were tried with the microprocessor with no success. An engineer made an analysis of the solder joint and lead wire forces and stresses that showed the failures would not occur if the wires were made more flexible and more compliant. This could be done by forming an S shape in the lead wires with a special forming die. The production people said that could not be done. Instead they wanted to epoxy bond a nickel steel shim under the component to stiffen the PCB near the area of the lead wires. This might work if the shim could be attached very rigidly to the PCB. The production people wanted to simply apply the epoxy adhesive to the shim and place it on the PCB under the component. The engineer said that will not work because the nickel steel shim is very smooth so the epoxy bond will not hold. The engineer wanted to drill about 10 small holes through the shim so the epoxy adhesive will flow through the holes and act like rivets. This arrangement can carry very high shear forces without failing. This idea fell on deaf ears as the production people went ahead with their method. The epoxy bond failed very rapidly. The production people decided to solve the problem another way, by simply leaving the microprocessor off of the PCB and sealing the assembly. They then simply ran reduced ESS thermal and vibration tests without the microprocessor. The seals were then broken and the microprocessor was hand soldered back on the PCB. The new systems were then shipped. The upper management people were never aware of what was being done in the production area. The engineer overheard some production people talking and laughing about the new production shipments. The engineer ran to the people in the production area demanding to know why they shipped defective hardware. They said, “If we do not ship, we do not get our bonus.” The engineer was shocked. He did not know how many different organizations were buying this defective equipment. He was going to blow the whistle and inform upper management what was going on without their knowledge. He spoke to a lawyer who advised him to keep his mouth closed. The lawyer said that whistle blowers always lose. You are only one against a dozen other people who will claim you are trying to get even with them because they did not listen to your advice. You will probably be the one that gets fired. Do not say anything to anyone. Do not write anything about this. The engineer kept quiet. The sad part of this situation was that some of this electronic equipment was for military use, which could affect the lives of soldiers. The good part of this situation was when the company decided to outsource the production of this piece of electronics to a job shop. A short time later all of the production people that were involved with the shipping of the defective electronics were laid off.

14 CAN VIBRATION ALONE PRODUCE A V-SHAPED DEEP HOLE IN A 65-POUND ALUMINUM CASTING 12 INCHES IN DIAMETER THAT IS 0.25 INCH THICK?

Three graduate engineers wheeled a cart to the office of an engineering manager who had extensive testing experience. The cart contained a 65-lb cast aluminum sphere about 12 in. in diameter with a wall thickness of 0.25 in. and full of electronics. The three visiting engineers wanted to know how vibration produced a deep V-shaped hole in the aluminum casting 0.25 in. thick. The manager took one look at the hole in the casting and said the hole was not caused by vibration. It was produced by a high impact, probably caused by dripping it on the floor, in an area like a machine shop where there are often some loose bolts and nuts lying on the floor. The visiting engineers said they had proof that the hole in the aluminum sphere was caused by vibration and not by being dropped. When they were asked for the proof, they said they questioned the test people who maintained there was no hole in the casting before the vibration test started. The hole in the casting was noticed after the vibration test was completed. Therefore, the hole in the casting has to somehow be related to the vibration. The manager laughed and said that the only other way the hole could have been caused was by someone hitting the casting with a great deal of force using a ball peen hammer. Anyone with a little testing experience associated with vibration would come to the same conclusion. It was obvious that the testing people were lying about the hole in the casting to protect their friends who dropped the casting. There was the fear that they might have to pay for the damage to the casting assembly, which cost about $150,000. The most disturbing part of this investigation was that three graduate engineers, each with several years of experience, could not tell the difference between a vibration-induced crack in a casting and a hole in the thick wall of the casting that could only be caused by a single heavy impact.

15 FAILURE MODES IN OPTO-ELECTRONIC FIBER-OPTIC SYSTEMS RELATED TO STRUCTURAL DYNAMICS

Optical fibers are being used in fiber-optic communication systems because they are very efficient for transmitting data over long distances. They permit higher data rates than the wired or wireless forms of communication with cables. Two common types of systems are the multimode fiber optics and the single-mode fiber optics, often called the monomode fiber. The glass optical fibers are usually made from silica. Plastic optical fibers (pof) are also used, but they have a much higher attenuation than the glass fibers so they are not used for long-distance communications. Protective plastic jacket layers of a tough resin are applied to the outer glass fibers. This adds strength to the brittle glass fiber cable which allows it to have a long fatigue life so it can be used in severe environments such as vibration and shock. These reinforced cables are also used extensively in areas where extra protection is needed from animals that chew through the cables. Underwater applications also work very well for protection against sharks. Some heavy-duty cables can have as many as 1000 fibers assembled in a single cable. These optical fibers are often connected to networks by splicing or fusion. Here the fiber ends are melted and welded together with an electric arc. The ends must be very closely aligned to get good performance. Opto-electronic systems make extensive use of optical fibers that are made of very thin glass, which is brittle. When these materials are used in dynamic environments, their displacements must be kept very small to avoid cracking the glass. The most critical areas are at the termination points at the beginning and at the end of the fiber-optic cable. These areas must be reinforced so they are stiff enough to reduce the bending and the failures in the glass fibers where the glass fibers are joined to the operating system using plastic jackets or fusion methods. These connecting joints must be supported to prevent relative motion in the thin glass fibers. The individual glass fibers can be fastened to an epoxy fiberglass pad about 0.12 in. thick that is wide enough and long enough to support all of the glass fibers. The fibers can be bonded to the epoxy pad using a semirigid room temperature vulcanized (RTV) material for support, so repairs can be made if necessary. The epoxy fiberglass pad itself may have to be bonded to a rigid support to prevent excessive motion if the fiber optics will be exposed to severe environments that can produce these effects. The safe displacement levels can be established by testing the cables in environments similar to the expected operating conditions to ensure the reliability of the cables.

16 HOW ELECTRONICS ARE BEING USED TO CONTROL STRUCTURAL DYNAMICS AND DYNAMIC STABILITY OF SYSTEMS FOR IMPROVED RELIABILITY AND SAFETY

New electronic components are rapidly shrinking in size while they are expanding their functional capabilities at the same time. This has resulted in the development of many new applications for control systems that were not available before. This new technology has been given many different names. One of the most popular names is electronic stability control (ESC). This new technology is being applied to many different industries for use in industrial, commercial, and military applications such as homes, hospitals, construction, manufacturing, and many other areas. Improvements associated with this new technology are reduced costs, improved safety, performance, reliability, stability, and control of many different types of mechanical devices. This includes automobiles, airplanes, helicopters, trains, trucks, and missiles, just to name a few. The automobile area is very interesting in the use of special sensors that can prevent accidents and injuries by controlling skids, yaw, steering, poor tires, improper air pressure in a tire, direct fuel to different engine cylinders, traction, rollover, automatic reduction in speed in unsafe conditions, and many other safety functions. Airplanes are also interesting. The B2 flying wing cannot be flown manually because there is no tail to control stability, which is controlled by sensors. The latest fighter aircraft, such as the Lockheed F-22 and F-35, are designed to be unstable and cannot be flown by hand. The sensors control all the flight functions so the airplane can instantly change its flight maneuvers for a snap roll or dive or a quick turn. A stable airplane will lose a couple of seconds, which can mean the difference between life and death in combat.

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