27. Vibration Fatigue in Lead Wires and Solder Joints

27.1 Introduction

Electronic systems are often required to operate in severe vibration environments for commercial, industrial, and military applications for extended periods without failing. Some examples are in automobiles, airplanes, trucks, trains, ships, submarines, farm tractors, atomic and fossil fuel power plants, communication systems, petroleum refineries, oil drilling equipment, blenders, elevators, machine tools, foundries, light and heavy manufacturing, washing machines, garage door openers, missiles, rockets, and others. Electronic assemblies, such as television sets and radios, may not have to operate in vibration environments, but they have to survive vibration when they are being transported from the manufacturer to the consumer in various types of shipping crates.

There are two basic types of vibration: sinusoidal (or sine) and random excitation. Sine vibration, or simple harmonic motion, repeats itself, but random motion does not.

Vibration-induced failures are often caused by the relative motion that develops between the electrical lead wires and the PCB, when the PCB is excited at its resonant frequency, as shown in Figure 27.1. The resonant frequency of the PCB must be determined in order to obtain the approximate fatigue life relations.

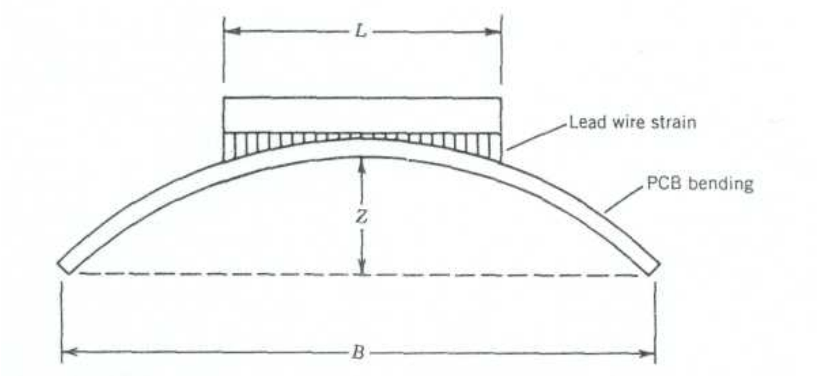

Figure 27.1 Relative motion in the lead wires of a large component due to the flexing of the PCB at its resonant frequency

26.4 PCB resonant Frequency

The resonant frequency of a plug-in type of PCB can be determined by considering it to be similar to a flat rectangular plate with four sides which can be clamped, or simply supported, or free, or any combination of these conditions. When a uniform load is distributed across the surface, and all four sides are assumed to be simply supported (or hinged), the resonant frequency can be obtained from Equation 27.1.

$$f_n = \frac{\pi}{2}\sqrt{\frac{D}{\rho}}\left(\frac{1}{a^2}+\frac{1}{b^2}\right) \quad \text{expected PCB resonant frequency} \qquad (27.1)$$

$$D = \frac{Eh^3}{12(1-\mu^2)} \quad \left(\frac{\text{flexural stiffness}}{\text{in}}\right) \qquad (27.2)$$

$$\rho = \frac{W}{gab} \quad \text{(mass per unit are)} \qquad (27.3)$$

Where:
E = modulus of elasticity, Ib/in^2
h = thickness of PCB, in
μ = Poisson's ratio, dimensionless
W = Weight of assembly, Ib
g = 386 in/sec^2, acceleration of gravity
a = PCB length, in
b = PCB width, in

Example: Determine the resonant frequency of a rectangular plug-in epoxy fiberglass PCB simply supported (or hinged) on all four sides, 0.080 in thick, with a total weight of 1.2 pounds, as shown in Figure 27.2.

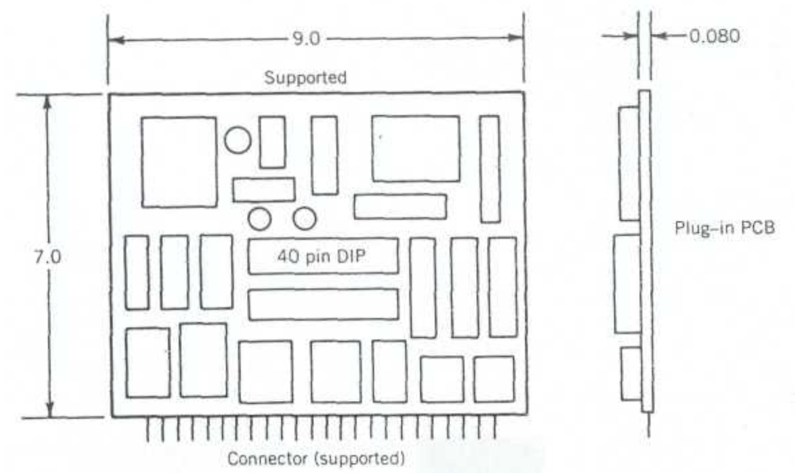

Figure 27.2 Plug-in PCB supported (hinged) on all four sides

Solution:
The following information is required for a solution:
E = 2 x 10^6 Ib/in^2 (epoxy fiberglass modulus of elasticity)
h = 0.080 in (PCB thickness)
μ = 0.12 (Poisson's ratio, dimensionless)
W = 1.2 Ib (weight)
a = 9.0 in (PCB length)
b = 7.0 in (PCB width)
g = 386 in/sec^2 (acceleration of gravity)

Substitute in Equations 27.2 and 27.3 yields to

$$D = \frac{(2 \text{ x } 10^6)(0.08)^3 h^3}{12(1-(0.12)^2)} = 86.6 \quad \text{Ib in} \quad \text{(stiffness)}$$

$$\rho = \frac{1.2}{(386)(9)(7)} = 0.493 \text{ x} 10^{-4} \quad \frac{\text{Ibsec}^2}{\text{in}^3}$$

Substitute in Equations 27.1 to get the resonant frequency of PCB.

$$f_n = \frac{\pi}{2}\sqrt{\frac{86.6}{0.493 \text{ x } 10^{-4}}}\left(\frac{1}{(9)^2}+\frac{1}{(7)^2}\right)$$
$$= 68.2 \text{ HZ}$$

27.2 Desired PCB Resonant Frequency for Sinusoidal Vibration

Extensive electronic vibration testing data and analysis techniques, using finite element methods (FEM), have shown that the fatigue life of many types of electronic components can be related to the dynamic displacements developed by the PCBs. These studies have shown that the component lead wires and solder joints will fail long before any failures occur in the printed circuit etched copper traces on the PCB. These studies also showed that the electronic components can achieve a fatigue life of about 10 million stress reversals in a sinusoidal vibration environment when the peak single-amplitude displacement of the PCB is limited to the value shown in Equation 27.4 for PCBs excited at their resonant condition, as shown in Figure 27.1, when the component is mounted at the center of the PCB.

$$Z = \frac{0.00022B}{Chr\sqrt{L}} \quad \text{(maximum desired PCB displacement)} \qquad (27.4)$$

Where:
B = length of PCB edge parallel to component, in
L = length of component body, in
h = height, or thickness of PCB, in
C = component type
= 1.0 (for standard DIP or a standard pin grid array)
= 1.26 (for a side-brazed DIP, hybrid, or pin grid array; two parallel rows of wires extending from the bottom surface of the component.)
= 2.25 (for a leadless ceramic chip carrier (LCCC))
r = relative position factor = 1.0 at center of PCB
= 0.5 at 1/4 point on X axis and 1/4 point on Y axis

The maximum single-amplitude displacement expected at the center of the PCB during the resonant condition can be obtained by assuming the PCB acts like a single-degree-of-freedom system, as shown in the following equation:

$$Z = \frac{9.8G}{f^2} = \frac{9.8G_{in}Q}{f_n^2} \qquad (27.5)$$

Where:
Q = transmissibility (Q) of the PCB
G = Peak input acceleration level of vibration
The transmissibility (Q) of the PCB at its resonance can be approximated by the following relation:

$$Q = \sqrt{f_n} \qquad (27.6)$$

The minimum desired PCB resonant frequency that will provide a component fatigue life of about 10 million stress cycles can be obtained by combining Equations. 27.4. through 27.6. Yields to:

$$f_d = \left[\frac{9.8G_{in}Chr\sqrt{L}}{0.00022B}\right]^{2/3} \quad \text{(mimimum desired PCB resonant frequency)} \qquad (27.7)$$

Example: A 40 pin DIP (Dual inline package, electronic equipment) with standard lead wires, 2.0 in length will be installed at the center of a 9.0 x 7.0 x 0.080 in plug-in PCB. The DIP will be mounted parallel to the 9 in edge. The assembly must be capable of passing a 5.0G peak sine vibration qualification test with resonant dwell conditions. Determine the minimum desired PCB resonant frequency for a 10 million cycle fatigue life, and the approximate fatigue life.

Solution:
B = 9.0 in (length of PCB parallel to component)
h =0.080 in (PCB thickness)
L = 2.0 in (length of a 40 pin DIP)
C =1.0 (constant for standard DIP geometry)
G = 5.0 (peak input acceleration level)
r = 1.0 (for component at the center of the PCB)

Substitute into Equation 27.7 for the desired PCB frequency

$$f_d = \left[\frac{(9.8)(5.0)(1.0)(0.08)(1.0)(\sqrt{2.0})}{(0.00022)(9.0)}\right]^{2/3} = 198.6 \text{ Hz}$$

The approximate fatigue life for 10 million cycles will be

$$\text{Life} = \frac{10\text{x}10^6 \text{ cycles to fail}}{(198.6 \text{ cycles/sec})(3600 \text{ sec/hr})} = 14 \text{ hr}$$

27.3 Random Vibration Fatigue Life

Random vibrations are nonperiodic in nature. Knowledge of the past history cannot be used to predict the precise magnitude of displacement or acceleration, but it is adequate to predict the probability of occurrences of these parameters.

Displacements and accelerations are typically expressed in terms of root mean square (rms) values, which follow the Gaussian or normal distribution patterns.

The method for designing PCBs for random vibration is very similar to the method used for sine vibration. The same equation can be used for the maximum allowable displacement Equation. 27.4. The expected displacement of the PCB is shown by Equation 27.5, and the approximate transmissibility Q is shown by Equation 27.6. One other equation is required, which is the response of the PCB to the random vibration input. This is shown below.

$$G_{rms} = \sqrt{\frac{\pi}{2} PfQ} \quad \text{(PCB response)} \tag{27.8}$$

Where:
P = power spectral density input = G^2/Hz at the PCB resonant frequency
f = resonant frequency of the PCB = Hz
Q = transmissibility of PCB at its resonance

Combining Equations 27.4, 27.5, 27.6, and 27.8 results in the minimum desirable PCB resonant frequency to achieve a 20 million cycle fatigue life for the components mounted on the PCB.

$$f_d = \left[\frac{29.4Chr\sqrt{(\pi/2)PL}}{0.00022B} \right]^{0.8} \quad \text{(mimimum desired PCB resonant frequency)} \tag{27.9}$$

Example: A 40 pin DIP with side-brazed lead wires with 2.0 in length is to be soldered to an 8.0 x 10.0 x 0.10 in plug-in PCB. The DIP will be mounted at the center of the PCB, parallel to the 8.0 in edge. The PSD (power spectral density) random vibration input is expected to be fiat at 0.075 G^2/Hz in the area of the PCB resonance. Find the minimum desired PCB resonant frequency for a 20 million cycle fatigue life. Also determine the expected fatigue life of the DIP lead wires.

Solution:
C = 1.26 (component type for side-brazed DIP)
h = 0.100 in (thickness of PCB)
r = 1.0 (for component at the center of the PCB)
L = 2.0 in (body length of a 40 pin DIP)
P = 0.075 G /Hz (power spectral density input)
B = 8.0 in (length of PCB edge parallel to DIP)

Substitute into Equation. 27.9 to determine the minimum desired PCB resonant frequency

$$f_d = \left[\frac{(29.4)(1.26)(0.10)(1.0)(\sqrt{(\pi/2)(0.075)(2)})}{(0.00022)(8.0)} \right]^{0.8} = 255.5 \text{ Hz}$$

The approximate fatigue life for 20 million cycles will be

$$\text{Life} = \frac{20\text{x}10^6 \text{ cycles to fail}}{(255.5 \text{ cycles/sec})(3600 \text{ sec/hr})} = 21.8 \quad \text{hr}$$

27.4 Miner's Cumulative Damage Fatigue Ratio

Every time a structural element experiences a stress cycle, a small part of the fatigue life is used up. When all of the life is used up, the structure can be expected to fail. This simple theory is widely used to determine the approximate fatigue life of structures operating in environments that produce stress reversals. The damage that is accumulated is assumed to be linear, so the damage developed in several different environments can simply be added together to obtain the total damage to determine if the part will fail. This is known as Miner's rule, or Miner's cumulative damage ratio R, which is defined below.

$$R = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + ... = 1 \qquad (27.10)$$

Where:
n = actual number of fatigue stress cycles accumulated at stress levels 1, 2, 3...
N = number of fatigue stress cycles required to produce a failure at stress levels 1, 2, 3…

Different fatigue cycle ratios are often used for different applications, depending upon how the electronic product will be used. For commercial electronic systems that have no involvement with the public safety, an R value of 1.0 is suggested. Where the public safety is involved, as in an airplane, train, or automobile, then an R value of 0.7 is suggested. Where a critical life system, such as a space shuttle, is involved, a higher safety factor is recommended, so an R value of 0.3 is suggested.

Example: A communication system contains many throughhole mounted resistors similar to those shown in Figure 25.6, for the sample problem described in Section 25.4. Determine if the solder joints on these resistors are capable of reliable operation after exposure to the following temperature cycling conditions.

A) Five years of storage (nonoperating) where the average daily temperature change within the electronics system is expected to vary from a low of 10 °C to a high of 40 °C.

B) Four years of electrical operation where the system is turned on twice a day, once in the morning and once in the afternoon, for about 1 hr. The average temperature in the system is expected to vary from a low of 20 °C to a high of 80 °C.

Solution:
Miner's cumulative fatigue damage method will be used to obtain the fatigue cycle ratio R for the three conditions shown above. The method of solution is to assume the stresses in the solder joints follow linear laws, so the stresses determined in the sample problem of Section 25.4 can be modified by a direct ratio of the temperature variations.

The temperature changes that will be used to determine the stress levels in the solder joints are as follows:

Condition A $\Delta t = (40°C - 10°C)/2 = 15\ °C$
Condition C $\Delta t = (80°C - 20°C)/2 = 30\ °C$

The actual number of thermal cycles (n) accumulated at each stress level must be divided by the number of stress cycles that are required to produce a failure (N) at each stress level, to obtain Miner's cumulative fatigue damage ratio R shown in Equation 27.10.

Solution: Condition A

The solder joint stress can be determined by using a ratio of the temperature change for the solder joint stress level of 1063 psi and the 60 °C temperature rise shown in Equation 25.9. For the temperature rise of 15 °C for condition A, the solder join shear tear-out stress will be as follows:

$$S_{St} = \frac{15}{60}(1063) = 266\ \text{Ib/in}^2$$

The actual number of stress cycles that will be accumulated in the five years of storage is based upon one thermal cycle per day for five years.

$$n_A = (1\ \text{cycle/day})(365\ \text{days/year})(5\ \text{year}) = 1825\ \text{cycles}$$

The number of stress cycles required to produce a failure in the solder joint can be determined with the use of Equation 26.4 with b = 2.5 as follows:

$$N_A = (80000)\ (200/266)^{2.5} = 39216\ \text{cycles to fails}$$

Miner's cumulative fatigue damage ratio for condition A is:

$$R_A = n_A / N_A = 1825/39216 = 0.046$$

Solution: Condition B
The solder joint stress can be determined by using a ratio of the temperature change for the solder joint stress level of 1063 psi and the 60 °C temperature rise shown in Equation 25.9. For the temperature rise of 30 °C for condition B, the solder join shear tear-out stress will be as follows:

$$S_{St} = \frac{30}{60}(1063) = 531\ \text{Ib/in}^2$$

The actual number of stress cycles that will be accumulated in the four years of operation is based upon two thermal cycles per day for four years.

$$n_B = (2\ \text{cycle/day})(365\ \text{days/year})(4\ \text{year}) = 2920\ \text{cycles}$$

The number of stress cycles required to produce a failure in the solder joint can be determined with the use of Equation 26.4 with b = 2.5 as follows:

$$N_B = (80000)\ (200/531)^{2.5} = 6965\ \text{cycles to fails}$$

Miner's cumulative fatigue damage ratio for condition B is:

$$R_B = n_B / N_B = 2920 / 6965 = 0.419$$

Substitute into Equation 27.10 for Miner's system cumulative fatigue damage ratio. Yields to:

$$R = R_A + R_B = 0.046 + 0.419 = 0.465$$

Since Miner's ratio less than the maximum allowable value of 1.0 as defined in Equation 27.10, the design is acceptable.

27.5 Electronic Systems Operating in Combined Environments

Electronic assemblies are often required to operate in areas exposed to vibration and temperature cycling at the same time. Some typical industries include airplanes, automobiles, trucks, trains, missiles, atomic power plants, paper mills, steel mills, oil drilling, petroleum processing, washing machines, ships, submarines, communication systems, portable computers, and many others. Miner's cumulative damage indicates that anytime a structural element is subjected to a stress cycle, a small part of its life is used up. It does not matter if the stress is due to vibration or to thermal cycling, since they can both produce failures when the stress levels and the number of stress cycles reach a critical combination.

Miner's cumulative fatigue damage ratio is convenient to use for combining the damage generated in vibration and in thermal cycling environments. The use of this ratio is demonstrated with a sample problem.

Example: An electronic controlled brake unit on an overhead rail car delivery system must provide a 15 year operational life. The car operates on a track system for 6 hours a day, 5 days per week, and 52 weeks per year. Test data on the track show sinusoidal vibration is present with a peak acceleration input level of 0.7 G over a frequency band from 10 to 500 Hz. The rail car is also required to enter a paint drying hot room for about one hour, three times a day, and 5 days a week for the same 15 year period. The hot room is maintained at a temperature that is 60 °C above the factory floor temperature.

An examination of the various components on the various PCBs shows that the most critical component is a poke-through hybrid at the center of several PCBs, as shown in Figure 27.3. Determine if the proposed design will meet the operating requirements.

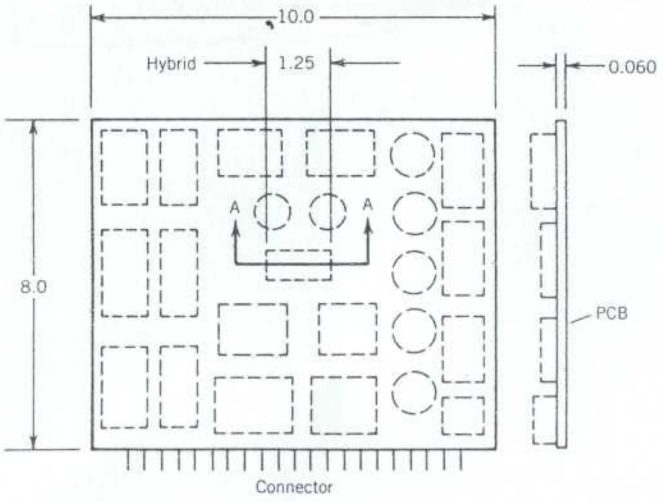

Figure 27.3 Throughhole mounted hybrid located at the center of the PCB

Solution:

Extensive testing of PCBs with throughhole mounted components shows that the electrical lead wires will fail more often than the solder joints during vibration. (For surface mounted components supported by electrical lead wires, vibration tests show that the numbers of wire failures are about the same as the number of solder joint failures.)

Thermal cycling test data for PCB expansions in the X-Y plane show that large throughhole mounted components will experience more solder joint failures than electrical lead wire failures.

In this sample problem the vibration fatigue life of the lead wires and solder joints were evaluated first. The thermal fatigue life of the wires and solder joints were determined next. Miner's cumulative damage index was then used to add up the total damage accumulated in the lead wires and solder joints. The worst-case conditions for the lead wires and the solder joints were combined to obtain a conservative estimate of the system fatigue life.

Solution: Track system vibration

The desired PCB resonant frequency necessary to achieve the approximate fatigue life of 10 million stress reversals in the sinusoidal vibration environment can be determined for the most critical hybrids by using Equation 27.7 when the hybrids are mounted at the center of the PCB.

Given:

C= 1.26 (component parameter for straight wires)
h = 0.060 in (PCB thickness)
r = 1.0 (relative position, component at center of PCB)
G = 0.7 G (peak sine vibration input acceleration)
L = 1.25 in (length of component)
B = 10 in (length of PCB parallel to component)

$$f_d = \left[\frac{(9.8)(0.7)(1.26)(0.06)(1.0)(\sqrt{1.25})}{(0.00022)(10)} \right]^{2/3} = 42 \text{ Hz}$$

The 42 Hz represents the desired resonant frequency the PCB must have to achieve an approximate fatigue life of 10 million fatigue cycles for the most critical electronic component. The minimum vibration life required for the electronic system can be determined from the duty cycle expected over the 15 year life span of the equipment on the rail car delivery system.

The minimum vibration life requirement for the electronic unit on the track system is as follows:

Life= (6 hr/day) (5 day/wk) (52 wk/year) (15 year) = 23400 hr

When the electronic unit has a resonant frequency of 42 Hz, and the most critical component has an approximate fatigue life of 10 million cycles, the lifetime is expected to be:

$$\text{Life} = \frac{10\text{x}10^6 \text{ cycles to fail}}{(42\text{cycles/sec})(3600 \text{ sec/hr})} = 66.1 \quad \text{hr}$$

Since the 42 Hz PCB resonant frequency will only provide a component lead wire fatigue life of about 66.1 hr, and since the desired fatigue life must be greater than 23,400 hr, the 42 Hz PCB resonant frequency is not adequate. The PCB resonant frequency must be much higher, since a higher resonant frequency results in smaller dynamic displacements, which will rapidly increase the fatigue life.

The sinusoidal vibration acceleration response of the PCB for a 42 Hz resonant frequency is obtained using Equation 27.5.

Given:
G_{in} = 0.7 (peak acceleration input)
f_n = 42 Hz (PCB resonant frequency for 10 million cycle fatigue life)
Q = $\sqrt{42}$ = 6.5 (approximate PCB transmissibility)
$G_{out} = G_{in}Q$ = (0.70) (6.5) = 4.5 (peak acceleration response of PCB)

The peak single-amplitude response displacement of the PCB for the 10 million cycle life and the 42 Hz resonant frequency can now be determined for the sinusoidal vibration as follows:

Given:
Gout = 4.5 (peak acceleration response of PCB)
f_n = 42 Hz (PCB resonant frequency)

$$Z = \frac{9.8(4.5)}{(42)^2} = 0.025 \text{ in} \quad \text{(peak displacement)}$$

This provides a 10 million cycle life, which is equal to a life of 66.1 hr. This is not adequate. Therefore, a higher PCB resonant frequency is required to reduce the displacement.

Assumption of component fatigue life for a 95 HZ PCB resonant frequency

Since a 42 Hz PCB resonant frequency was shown to be too low, a higher value must be used. Assume a PCB resonant frequency of 95 Hz to start the revised analysis. If the results are not acceptable, another PCB resonant frequency can be assumed and the process repeated until an acceptable solution is obtained.

The peak acceleration response of the PCB can be determined for the sinusoidal vibration as follows:

$$G_{out} = G_{in}Q$$

Where:

$G_{in} = 0.7$ (peak acceleration input)

$f_n = 95$ Hz (PCB resonant frequency, assumed to start)

$Q = \sqrt{95} = 9.7$ (approximate PCB transmissibility)

$G_{out} = (0.7)\,(9.7) = 6.8$ (peak acceleration response)

The peak displacement of the PCB with the 95 Hz resonant frequency can be obtained from Equation 27.5 for the sine vibration.

Given:

$G_{out} = 6.8$ (peak acceleration response of PCB)

$f = 95$ Hz (PCB resonant frequency assumed to start)

$$Z = \frac{9.8(6.8)}{(95)^2} = 0.0074 \text{ in} \quad \text{(peak)}$$

The fatigue life of the component lead wire in the vibration environment can be determined with Equation 26.4. Assuming a linear system, the stress value S can be replaced with the displacement value Z. The b exponent includes a stress concentration of 2.0.

$$N_1 Z_1^b = N_2 Z_2^b$$

Where:

$N_2 = 10 \times 10^6$ (cycles for lead wire to fail when PCB resonant frequency is 42 Hz)

$Z_1 = 0.0074$ in (peak PCB displacement, for 95 Hz frequency)

$Z_2 = 0.025$ in (peak PCB displacement, for 42 Hz frequency)

$b = 6.4$ (fatigue exponent for electrical lead wires, which includes a stress concentration of 2.0)

$$N_1 = 10 \times 10^6 \, (0.025/0.0074)^{6.4} = 2.42 \times 10^{10} \text{ cycles to fails}$$

The actual number of fatigue cycles that will be accumulated by the 95 Hz PCB resonant frequency during operation in the sine vibration environment for 23,400 hr, can be determined as follows:

$$n = (95 \text{ cycles/sec})\,(3600 \text{ sec/hr})\,(23400 \text{ hr})$$

$= 8 \times 10^9$ Actual cycles accumulated

The Miner's damage index for the sinusoidal vibration due to the rail car operation on the track system is:

$$R = n / N = (8 \times 10^9) / (2.42 \times 10^{10}) = 0.331 \text{ (vibration ratio)}$$

This vibration fatigue cycle ratio looks good at this time. Some parameters may have to be changed later, depending upon the value obtained from the thermal cycle fatigue environment.

Solution: Thermal cycle fatigue environments
Figure 27.3 shows a hybrid component in a kovar case, flow-soldered to a through-hole epoxy fiberglass PCB. Differences in the thermal coefficients of expansion (TCE) between the kovar and the PCB will produce expansion differences that will force the electrical lead wires in the component to bend as shown in Figure 27.4, at the high-temperature end of the cycle. This will induce bending stresses in the wires and shear tear-out stresses in the solder joints.

The temperature in the electronics section is not expected to stabilize for a long enough period to allow the solder joint stresses to completely relax to a strain-free condition. Under these circumstances, the neutral point to the high or low temperature will be half the peak-to-peak temperature.

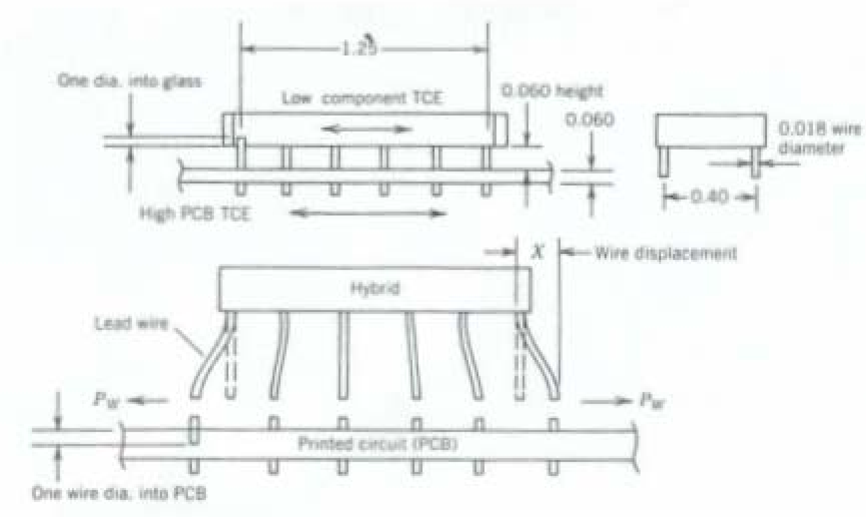

Figure 27.4 Cross section A-A of the hybrid shown in Figure 27.3, where the end lead wires are forced to bend due to differences in the expansions of the hybrid and the PCB

The difference in the thermal expansion between the hybrid and the PCB in the X-Y plane can be determined from Equation 25.1. The subscripts H and P now refer to the hybrid and the PCB.

$$X = (a_p — a_H)d_H \, \Delta t = \text{in} \quad \text{(expansion difference)}$$

Where:
a_P = TCE of epoxy fiberglass PCB in X-Y plane
= 15 x 10^{-6} in/in/°C
a_H = 6 x 10^{-6} in/in/°C (TCE of hybrid kovar case)
$d_H = \sqrt{\frac{(1.25)^2 + (0.4)^2}{2}}$ = 0.65 in (effective diagonal length of hybrid body)
Δt = 60°C (temperature of hot room above factory floor)

Δt =60 /2 = 30°C (neutral point to high and low value for a rapid temperature cycle)

$$X = (15\text{-}6) \times 10^{-6}\ (0.65)\ (30) = 0.000175 \text{ in}$$

The horizontal force developed in the electrical lead wires as they are forced to bend through this deflection can be determined from the wire geometry as shown in following equation.

$$P_W = \frac{12 E_W I_W X}{L_W^3} \quad \text{Ib} \tag{27.11}$$

Where:
Ew = 20 x 10^6 Ib/in^2 (modulus of elasticity, kovar wire)
d = 0.018 in (wire diameter)
$I_W = \frac{\pi (0.018)^4}{64} = 5.15 \times 10^{-9}$ in^4 (moment of inertia of lead wire)
L_W = 0.060 in (plus one diameter into PCB and hybrid)
Lw = 0.060 + 0.018 + 0.018 = 0.096 in (wire length)
X = 0.000175 in (wire deflection)

$$P_W = \frac{12(20 \times 10^6)(5.15 \times 10^{-9})(0.000175)}{(0.096)^3} = 0.244 \text{ Ib}$$

The bending moment in the wire and solder joint can be determined by taking the moments about either end of the wire.

$$M = P_W L_W / 2 \text{ (bending moment, Ib in)}$$

Where:
Pw = 0.244 lb
Lw = 0.096 in

$$M = (0.244)\ (0.096)/2 = 0.0117 \text{ Ib in}$$

Substitute into Equation 25.4 to obtain the lead wire bending stress. A stress concentration of 1.0 is used to start, since the number of thermal stress cycles accumulated is usually not enough to produce a fatigue failure unless there are sharp cuts in the wire at the high stress areas. A stress concentration of 2 will be used later for a conservative evaluation of the fatigue life.

Given:
M = 0.0117 lb in (bending moment in wire)
C = 0.018/2 = 0.009 in (wire radius)
I_w = 5.15 x 10^{-9} in4 (wire moment of inertia)

$$S_b = \frac{(1.0)(0.0117)(0.009)}{5.15 \times 10^{-9}} = 20447 \ \text{Ib/in}^2$$

The number of stress cycles required to produce a failure in the electrical lead wire can be determined from the fatigue curve for kovar wire as shown in Figure 27.5. Considering a worst-case condition, where a stress concentration value of 2 exists at the highest stress point on the wire, the stress in the wire will be about 40,900 psi. The number of cycles (N) required producing a failure in the kovar lead wires will be as follows:

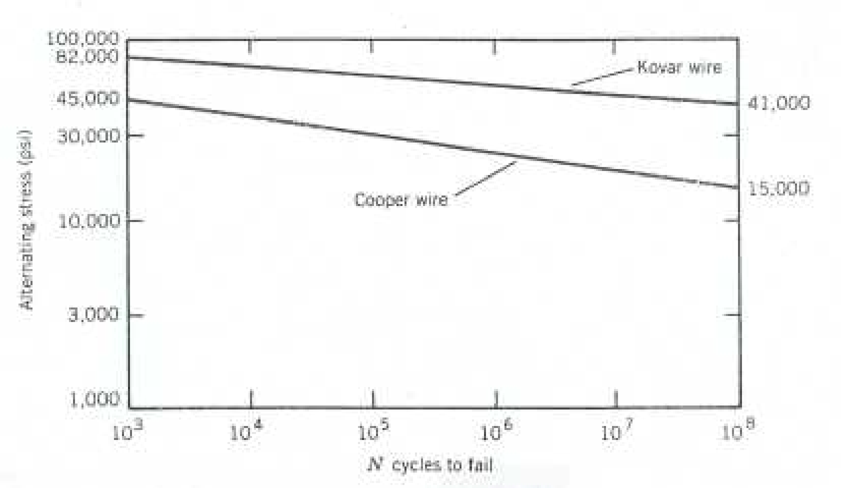

Figure 27.5 Alternating stress fatigue curves for kovar and copper wires with no stress concentrations

$$N = 100 \times 10^6 \text{ cycles for wire to fail}$$

The actual number of thermal cycles (n) expected over the 15 year life can be determined as follows:

$$n = (3 \text{ cycle/day}) (5 \text{ day/wk}) (52 \text{ wk/year}) (15 \text{ year})$$
$$= 11700 \text{ actual thermal cycles expected}$$

Miner's rule can be used to find the fatigue cycle ratio for the lead wire for the thermal cycling condition.

$$R_2 = n / N = 11700 / 100 \times 10^6 = 0.00017 \text{ (wire thermal cycle ration)}$$

This damage accumulation in the lead wires due to thermal cycling is very small compared with the damage obtained from the vibration environment, so it is ignored.

The solder joint shear tear-out stress value can be obtained from Equation 25.9. The solder joint height is based upon the PCB thickness only, assuming there are no solder joint fillets at the top or bottom surfaces of the PCB. The shear tear-out area in the solder joint is based upon the average diameter of the solder joint. This is the average of the 0.018 in wire diameter and a PTH diameter of 0.038 in, resulting in a 0.028 in average diameter.

Given:
M = 0.0117 Ib in (overturning moment)
h = 0.06 in (PCB thickness, ignoring solder fillets)
$A_S = \frac{\pi(0.028)^2}{4} = 0.000616 \text{ in}^2$ (solder area)
Substitute into Equation 25.9 for the solder shear tear-out stress level.

$$S_{ST} = \frac{0.0117}{(0.06)(0.000616)} = 316 \frac{\text{Ib}}{\text{in}^2}$$

The approximate number of stress cycles required to produce a failure in the solder joint can be determined from Equations 26.4 and Figure 27.2.

Given:
N_2 = 250 cycles to fail (solder reference point)
S_2 = 2100 Ib/in^2 (solder stress reference point)
S_1 = 316 Ib/in^2 (solder stress)

$$N_1 = 250(2100/316)^{2.5} = 28462 \text{ cycles to fail}$$

Miner's rule can be used to find the fatigue cycle ratio for the solder is:

$$R_3 = n / N = 11700 / 28462 = 0.411 \text{ (solder thermal cycle ratio)}$$

The total damage ratio accumulated during the vibration and thermal cycling is:

$$R = 0.331 + 0.411 = 0.742$$

Although this value is slightly over the maximum acceptable level of 0.7, where public safety is involved the design can be considered safe because the combined damage ratio was very conservative.