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Estimating Fatigue Life of Space Electronic Package Subjected to Launch Loads

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Abstract

This paper deals with the design of mechanical housing and the PCB(Printed Circuit Board) for a newly developed Power distribution package, which houses relays, mosfets, etc, with an emphasis on fatigue life estimation for GP-250 relay soldered on to the PCB using the through hole mounting technique. In the first part classical methods are used to design the PCB and to calculate stress developed on the pins of GP-250 relays and further estimating its fatigue life using Palmgren-Miner cumulative fatigue damage theory. In the second part Finite Element analysis is carried out to determine natural frequency, displacements and forces due to random vibration loading and fatigue life estimation.

The work had been presented *at an* international conference ***Fatigue Durability India 2015****, 28-30th May 2015, JN TATA AUDITORIUM, Indian Institute of Science, Bangalore.*

Nomenclature

f_d = desired natural frequency
G_{in} = input G level
C = component mounting factor
h = PCB thickness
r = component position factor
L = length of component
B = length of PCB parallel to component
P = Power Spectral Density, in (g^2 /HZ)
R_n= Accummulative fatigue damage fator

Introduction

Electronic packages are extensively used in Space industry as control devices, data handling and power devices. They operate in severe environments like thermal cycling, vibratory and shock environments. Severe vibration levels particularly random vibrations produce high acceleration, displacement and stress levels, which can lead to the failures of lead wire, solder joints and Printed Circuit Board (PCB) cracks. Satellite electronic packages experience severe vibrations only for few minutes during rocket launch, Hence the design is mainly based on stiffness ie fundamental frequency, modes and the resulting maximum displacement and stresses.

Presently the space exploration has entered a new era in which deep space exploration and colonization of the Moon and 'earth like' planets are the main stay of research and development activities. In this regard reusable space transport systems and Lander crafts are envisaged to provide continuous and economically viable transport systems. Thus the electronic components and the mechanical enclosures for these missions must be designed to survive multiple launches and landings. Severe launch loads can produce high bending stresses and deflection of the component leads which are soldered on the PCB. Which in turn implies that the" high cycle fatigue" failure criterion has be applied for analyzing the failure modes of sensitive components and estimate the life of systems with high reliability. The following sections explain a case study on electronic package for which fatigue life of a typical relay component is determined using simple classical/empirical and FE methods.

Configuration and components of the Power Distribution package

The package consists of an aluminum module to hold the two PCBs. The module with a ' +' rib acts as a stiffened enclosure to the PCBs and provides the required protection to the components from vibration, thermal and radiation environment encountered during rocket launch and during its operating life in orbit. Fig. 1. shows the package and its main parts. The exploded view shows the module, two side covers and two PCBs, Clearance between the tallest components and the covers are given in Fig. 2. which reflects a minimum of 3 mm gap is available for the possible displacement of the PCB and the cover during vibration.

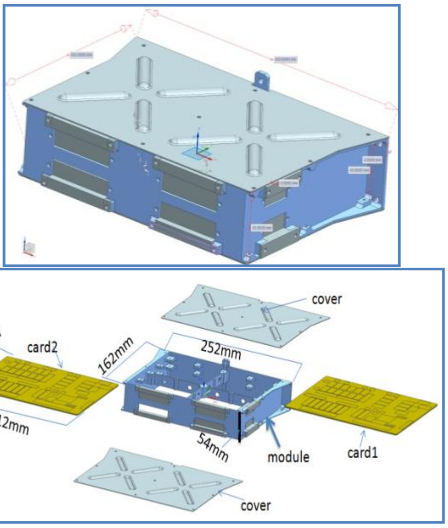

Figure 1: configuration and exploded view of the package

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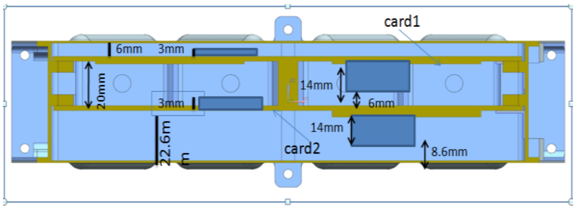


Figure 2: Package assembly section view

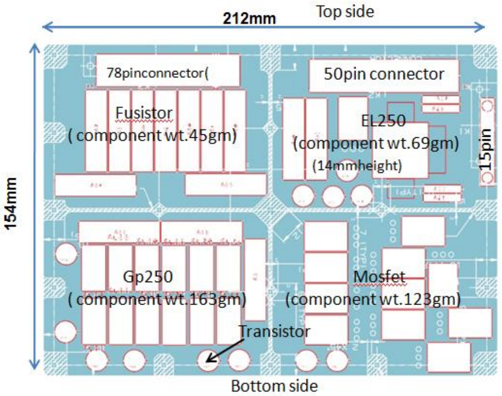


Figure 3: Component Layout on PCB

Figure 3 shows component layout on the PCB and mass distribution at the four quadrants, the details are given in Table 1.

Table 1: Mass distribution on the PCB

Component	Weight (gm)
Bare PC board	136
Components on each card	400
Edge connectors	75
Total(gms)	611

Estimating the fatigue life of the component

Determination of the fatigue life of a component is either displacement based or stress based. In this paper the life of GP250 relay is estimated using both the methods.

The following steps are followed for computing the fatigue life of a system subjected to vibration loads.

I. Displacement based estimation of life

i. Calculate the natural frequency of vibration for the PCB
ii. Compute the maximum displacement
iii. Determine the accumulative fatigue damage using Miner's equation

II. Stress based estimation of life

i. Calculate the natural frequency of vibration for the PCB
ii. Get a reliable data of the components viz material properties, cross sections of leads etc
iii. Create FBD for the component and Compute the loads and stresses at the leads
iv. Determine the accumulative fatigue damage using Miner's equation.

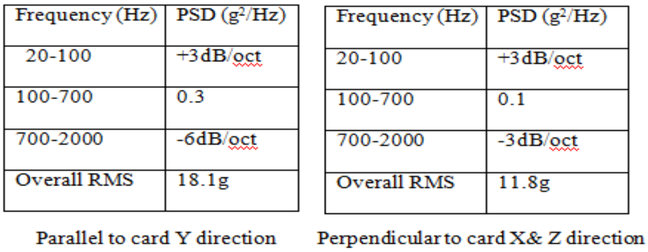
Computation of Natural frequency of the PCB

The first step in arriving at the expected life of a component is computing its natural frequency which gives displacement cycles per second. There are a few empirical equations (Steinberg [1] ,Arnold[2] etc) based on the test results of a typical PCB with different boundary conditions and on plate deflection equations with standard boundary conditions. The PCB for the package described in section 2 above is fastened to the module at 18 discrete locations and therefore it is not possible to get an exact equation for natural frequency with classical approach. However the equation (provided by Steinberg) which is closer to the actual boundary conditions are used here. FE analysis is also carried out for better accuracy and the same has been used for computing the life of components.

Displacement based Classical approach

Referring to Fig. 3. , the quadrant with highest mass of components is the one on which GP-250 relays are mounted. This paper will focus on to survival GP-250 relay as it is one of the critical components mounted on the PCB. Equation 1 gives the desired natural frequency of the PC board for an electronic component to survive typical random vibration environment. Expected Random vibration input to the package is given in Table 2.

Table 2: Random vibration input level



Frequency (Hz)	PSD (g^2/Hz)
20-100	+3dB/oct
100-700	0.3
700-2000	-6dB/oct
Overall RMS	18.1g

Parallel to card Y direction

Frequency (Hz)	PSD (g^2/Hz)
20-100	+3dB/oct
100-700	0.1
700-2000	-3dB/oct
Overall RMS	11.8g

Perpendicular to card X& Z direction

Desired natural frequency f_d for the PCB is given by [1]

$$f_d=\left(\frac{29.4Chr\sqrt{\Pi/2PL}}{0.00022\,B}\right)^{0.8} \qquad (1)$$

(*All linear dimensions are in inches*)

Where

C = 1.26 component mounting factor for DIP mounting
h = 2.1 mm (0.0827 inch) - Thickness of PCB
r = 1, position factor for the component mounted at centre of PCB
L = 21.6 mm (0.85 inch) Length of the component (GP250)
P = 0.1 Power Spectral Density, in (g2 /HZ)
B = 77 mm (3.03'') length of PCB parallel to component

Substituting the values in Equation (1), the desired natural frequency for the PCB, f_d *= 380 HZ for 20 million cycles.*

Natural frequency by comparing with test results of a standard PCB.

Steinberg [1] has given Equation 2 to find out natural frequency of any PCB by comparing ratio of mass and dimensions of the PCB with a standard PCB for which natural frequency is obtained by vibration testing. The material properties are given in Table 3. A boundary condition, with all four sides fixed gives a natural frequency of 662Hz.Whereas with changed boundary condition from edges fixed to 'eight discrete points clamped' (for the GP250 relay quadrant) gives a natural frequency of 405 Hz.

$$f_2 = f_1\left(\frac{a_1 b_1}{a_2 b_2}\right)\sqrt{\frac{E_2 h_2^2 p_1 (1-\mu_1^2)}{E_1 h_1^2 p_2 (1-\mu_2^2)}} \qquad (2)$$

Test Data from standard PCB [1]

f_1=450Hz
(Length) a_1=6''
(Width) b_1=4''

Young's modulus E_1*=2x106 lb/in2*
$(Poisson\,ratio)\mu_1 = 0.12$
Thickness h_1*=0.1''*
(density)ρ_1*=0.208 lb/in3 (density)*

PC board Parameters

$f_2=?$
$a_2=106mm = 4.17''$
$b_2=77mm = 3.03''$
$E_2=22.5GPa=3.26x10^6 lb/in^2$
$h_2=2.1mm\ (0.0827'')$
$\rho_2=10910Kg/m^3 = 0.3933\ lb/in^3$
$\mu_2 = 0.18$

Table 3: Material Properties

Property	Cover (AL-6061-T6)	PCB (FR-4)	Base module (Mg alloy Az31b)
Young modulus(GPa)	70	22	45
Poisson's ratio	0.33	0.18	0.29
Density (kg/m³)	2711	2000	1740
Allowable strength (MPa)	248	310	190
Weight(gm)	207	272	228

Finite Element model

UGNX7.5/NASTRAN software is used to develop a detailed FE model shown in Fig.4. Component mass is distributed in accordance with their actual location on the PCB. Literature shows that the components mounted on the PCB increase the local stiffness and hence Young's Modulus at local zones are increased by about 70%. FE Model details are tabulated in Table 4.

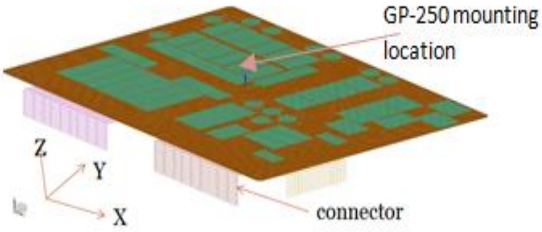


Figure 4: FE model of PC board

Table 4: FEM Details

Property	PCB	Module	Cover
Type of element	quad4	quad4	quad4
Element property	Pshell	P shell	Pshell
Material used	Fr-400	Mg alloy	AL-6061-T6
Total number of elements	404640	156724	54687

The FE analysis gives the first natural frequency of PC board at 481 Hz for GP-250 mounting location perpendicular to plane of PCB, as shown in Fig .5.

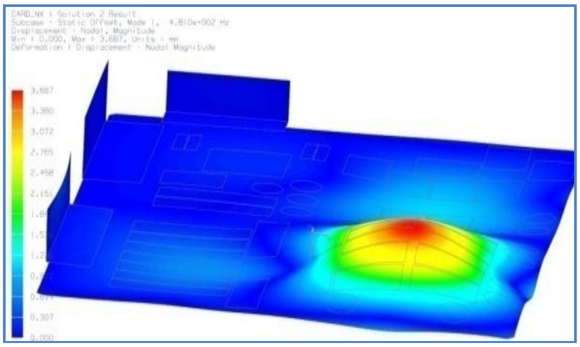


Figure 5: 1st mode of vibration of PCB

FE analysis of assembly of the two PCBs and the housing gives a first global natural frequency at 199Hz.The response near GP250 relay at its own natural frequency of 481 Hz is shown in Fig .6.

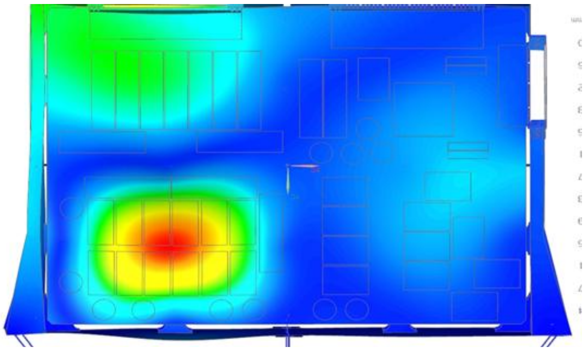


Figure 6: Response near GP250 in assembly at 481Hz

Response calculation

An electronic assembly experiencing random vibration load as in Table 2 can produce high level of response in all three directions X,Y and Z, which in turn results in tensile and bending stresses on relay pins. To design a more reliable package it is necessary to find out the response output near the relay mounting location. FE analysis shows that maximum response is at the centre of GP-250 mounting quadrant (Refer Fig. 6). Grms values obtained in all three direction are tabulated in Table 5.

Table 5: PCB Responses along the 3 directions

Direction	Grms
X	28
Y	18
Z	32

Accumulated fatigue damage calculation based on displacement

Steinberg has given a empirical formulation for calculating maximum displacement allowed in PC board for 20 million cycle as [1]

$$Z\infty = \frac{0.00022\,B}{Chr\sqrt{L}} \tag{3}$$

$Z\infty$- Maximum allowed deflection for 20 million cycles; Which gives a value of $Z\infty$ =0.176mm. And maximum displacement due to random vibration for PC board is

$$Z_{rms} = 0.0835mm\ (from\ FE\ analysis)$$

Therefore the peak value is 3*Z_{rms} that is 0.25mm.

It may be noted that this value exceeds the safe displacement value and the life of the component will be less than 20 million cycles. In this case study the time duration for cyclic loading due to 15 flights of 500 sec and 15 ground vibration tests of 60 sec each [3] is about 2.4 hrs. The time duration for failure of the pins due to accumulative fatigue damage can be calculated using Palmgren-Miner accumulative fatigue damage theory.

$$R_n = f_n T(0.683/N_{1\sigma} + 0.271/ N_{2\sigma} + 0.043/ N_{3\sigma}) \qquad (4)$$

Where

$R_n = 1$ *Accumulated damage factor (<1 for survival of component)*

$T =$ *Limiting Duration of cyclic load for failure of component*

$N_{1\sigma} = (Z_\infty / Z_{1\sigma})^b x10^7$ *cycles[4]*

$Z_\infty = 0.176mm$

$Z_{1\sigma} = 1^* Z_{rms} = 0.0835mm \quad N_{1\sigma} = 1.2x10^9$ *cycle*

$Z_{2\sigma} = 2^* Z_{rms} = 0.167mm \quad N_{2\sigma} = 1.4x10^7$ *cycle*

$Z_{3\sigma} = 3^* Z_{rms} = 0.25mm \quad N_{3\sigma} = 10^6$ *cycle*

$b=6.4$ *(for kovar which is the pin material)*

This gives T=9.32 hrs for component to fail or 15.7million cycles life,wheres a typical requirement is to survive the component maximmu for 2.4 hrs in the cumulative rocket launch /landing environment in which 27% of component life gets damage due to relative displacement between card and component of card . Hence a good margin exists for the life of GP250 relays.

Accumulated fatigue damage calculation based on stress developed on pins

A three axis load develops inertia force on the GP-250 having mass of 11gm in all three directions, resulting in bending and tensile stress on the pins. As the maximum force is experienced by outer corner pins, only 4 pins (2mm pin length) at the corners are considered for calculating the stress on pins. A schematic drawing of force acting on centre of gravity of GP-250 is shown in Fig.7.

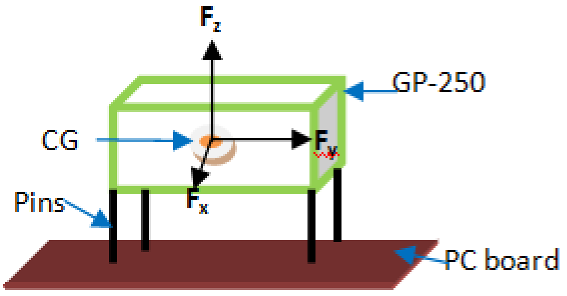


Figure 7: GP 250 relay schematic

The force developed in all three direction X,Y &Z due to random vibration will be calculated in terms of rms value on each pin having length of 2mm and diameter 0.76mm. as

$$F_{xrms} = (m^* G_{rms} {}^*9.8)/4$$

Where,

$F_{xrms} =$ *rms value of force in x direction*

$m =$ *Mass of the component (11gm)*

$F_{xrms} = (0.011^*28^*9.8)/4=0.76N$

$F_{yrms} = (0.011^*18^*9.8)/4= 0.5N$

$F_{Zrms} = (0.011^*35.8^*9.8)/4 = 1N$

Bending moment on each pin due to F_{xrms} & F_{yrms}

$$M_{xrms} = F_{xrms} {}^* 2 =1.52N\text{-}mm$$

$$M_{yrms} = F_{yrms} {}^* 2 =1N\text{-}mm$$

Stress developed on each pin in three directions can be calculated as

$$\sigma_{xrms} = M_{xrms} {}^*r/I$$

where,

$I =$ *moment of inertia of the pin* $(\pi d^4/64 = 0.012mm^4)$

$\sigma_{xrms} = 1.52^*0.35/.012=44.3MPa$

$\sigma_{yrms} = M_y {}^*r/I= 1^*0.35/.012=29.2MPa$

$\sigma_{zrms} = F_Z/(\pi d_w^2/4) =2.6 MPa$

As all the three stresses are mutually perpendicular their resultant will be

$$\sigma_{rms} = \sqrt{\sigma xrms^2 + \sigma yrms^2 + \sigma zrms^2} = 53.12MPa$$

$\sigma_1 = 1^* \sigma_{rms}=53.12MPa$

$\sigma_2= 2^*\sigma_{rms}= 106.24MPa$

$\sigma_3= 3^* \sigma_{rms} = 159.36MPa$

σ_e *(for kovar for 10^8 cycle) 95 MPa [1]*

Accumulated fatigue damage can be calculated using Palmgren-Miner cumulative fatigue damage theory given Equation 4.

$$N_{1\sigma} = 10^{\wedge 8}(95/53.12)^{6.4}=41.3x10^8$$

$$N_{2\sigma}= 10^{\wedge 8}(95/2^*53.12)^{6.4}=0.5x10^8$$

$$N_{3\sigma}= 10^{\wedge 8}(95/3^*53.12)^{6.4}=0.037x10^8$$

Equation 4 gives a time duration of 33hrs for the component to fail against typical 2.4 hrs requirement which amounts to 7% of life.

Conclusions

Electronic components and the mechanical enclosures for reusable space missions must be designed to survive multiple launches and landings. In this case study life assessment for a typical electronic card with focus on fatigue life for GP250 relay is explored based on i) maximum displacement and ii) on stresses induced at the pins due to vibration environment of rocket launch The first approach (displacement based) gives a life of 15.7 million cycles where as the second method based on induced stresses give a much higher life. However the life estimated meets the requirement for a typical reusable space mission. The temperature induced stresses are neglected basically because the temperature of the component shall be maintained by the thermal design to have very less temperature gradients and the nominal temperature does not exceed 40°C.

Further studies are planned using FE fatigue analysis module with combined thermal and structural stresses induced at the pins.

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