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Research Article

Experimental Investigations on Board Level Electronic Packages Subjected to Sinusoidal Vibration Loads

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Abstract

The lead wires and solder joints of surface mounted sensitive electronic components are more prone to failures due to vibration environments and leads to malfunctioning of electronic system. In this work a Plastic Small Outline Package (PSOP) and Printed Circuit Board (PCB) assembly is used as a test vehicle and subjected to sinusoidal vibrations by mounting the PCB assembly on conventional Nylon spacers. Then, the assembly is subjected to a constant input acceleration of 0.5G. Small input acceleration levels are amplified at resonant frequencies due to which high stresses are induced in lead wires and solder joints. Efforts are made to reduce the stress levels in critical elements of electronic packages, transmissibility ratio, PCB displacement and output acceleration levels by introducing damping using the resilient Neoprene rubber as a spacer material. By mounting the PCB assembly on Neoprene rubber spacers the displacement and output acceleration levels are minimized. The experimental results reveal that, the PCB mounted on Nylon spacers experienced a deflection of 0.1 mm (at PCB centre), output acceleration of 55G and a transmissibility ratio of 110 (at first resonant frequency and 0.5G input). When the PCB assembly was mounted on Neoprene rubber spacers and subjected to same input acceleration of 0.5G, the deflection and peak acceleration levels were reduced by 40% and 46% respectively. Also, the transmissibility ratio was reduced by 46%. Numerical simulation is also done to validate the experimental results. The experimental and numerical simulation results are in close agreement with each other. The methodology of the research work is explained in the following sections.

Keywords: *Printed Circuit Board, Lead wires, Solder joints, Rubber spacers, Vibration control, Fatigue life.*

1. Introduction

This Sinusoidal vibrations can induce very high acceleration (*G*) levels in lightly damped structures, when the natural frequency is excited. Transmissibility (*Q*) values can be greatly magnified, resulting in very high displacements, forces, accelerations, and stresses, which often result in electrical malfunctions and failures. High displacements often result in impacting between adjacent structural members such as circuit boards, resulting in cracked components, cracked solder joints, broken electrical lead wires and broken connector pins. High forces can produce high stresses in load carrying elements such as screws, rivets, and ribs, which may become loose or may fracture. High accelerations can cause relays to chatter, crystal oscillators to malfunction, and potentiometers to lose their calibration accuracy (Steinberg, 1973, 1988). High stresses typically result in very rapid fatigue failures in various electronic elements from aluminum housings to cables and harnesses.

In past, many researchers have worked on estimating the damage to electronic packages due to high input accelerations. The severities of vibration environment on component lead wires, solder joints, and PCB assembly have been dealt with by Steinberg (Steinberg, 1973, 1988, 2001). According to Steinberg, maximum deflection at PCB centre, will lead to failure of PCB components. He also proposed some methods, by which the dynamic response of the PCB assembly can be reduced and the life can be enhanced. One of the many methods proposed by (Eugene, 1970) for reducing the PCB resonant amplitudes used rubber pads and achieved substantial amount of reduction in resonance amplification.

It is known that the kinematic disturbance is transferred to the PCB through attaching points (fasteners) which are rigid. In a novel approach these rigid mounts were replaced by flexible mounts such as a tape of synthetic fabric to act as dry friction damper for vibration isolation (Silin *et al*, 2007). The problem of vibration protection of the critical components of electronic equipment, which operates in harsh environmental conditions, was addressed and the resilient mounts (Shock-Tech cable mounts) was proposed as the solution (Veprik *et al*, 2000, 2003). Many aspects of controlling the dynamic characteristics of PCBs were discussed in a paper by Eugene D.V (Eugene, 1970). The tuned dynamic absorber was effectively used to suppress the dynamic responses of PCBs operating in harsh environmental

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conditions under shock, wideband random and swept sine vibration (Ho C.V, *et al*, 2003).

U.S. Army Electronics Research and Development Command selected a viscoelastic polymer as a possible means of vibration damping for electronic PCB assemblies in a surface to air guided missiles application [Mark, 1979). An active mass damper (AMD) was developed by and used to protect PCBs and sensitive components mounted on it due to harsh vibrations in spacecraft, aircraft and missile systems (Esser, et al, 2004). In this paper a novel method of reducing vibration amplitudes at resonance is proposed, the methodology and results are discussed in the following sections.

2. Methodology

2.1 Experimental procedure

The PSOP-PCB assembly (test vehicle) used for conducting the experiments is shown in Fig. 1. The experimental setup for conducting the sine-sweep test is as shown in Fig. 2. The experimental setup mainly consists of an electrodynamic shaker (DEV-001, 50 kg-f, 12 mm peak-to-peak displacement) for exciting the PCB assembly at constant input acceleration. An aluminum fixture (300 mm x 300 mm x 8 mm) is bolted onto the shaker head for mounting the Printed Circuit Board (PCB) made of glass-epoxy material (132 mm x 77 mm x 1.6 mm). Two accelerometers (B&K - 4517), one for controlling and monitoring the input acceleration level (G_{in}) in closed loop and the other for monitoring the output acceleration (G_{out}), are interfaced with a four channel signal conditioner. The first accelerometer is placed on the base plate (fixture) and the second accelerometer is placed near the component on PCB. The PCB assembly was mounted on the fixture using four fastening screws and plastic spacers placed at the corner of the PCB. The electronic package used for the test is a surface mounted 8 pin (4 pins x 2 rows) PSOP and is shown in Fig. 1. One package is mounted at the centre of PCB and four packages are mounted at four corners of the PCB. A failure detecting circuit for detecting the failure of component lead wires or solder joints during the test is shown in Fig. 3. In case, any of the lead wire or solder joint fails, the LED provided on the circuit will go off. Electrodynamic shaker is excited at constant input acceleration using sinusoidal vibration controller software.

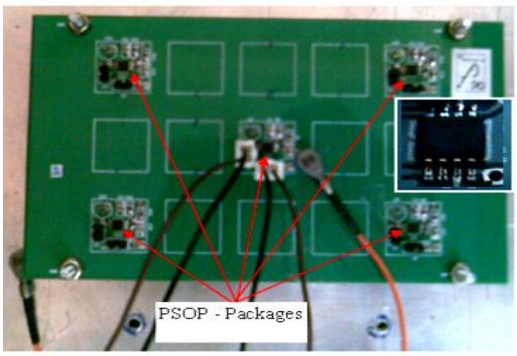

Fig. 1 PSOP-PCB assembly

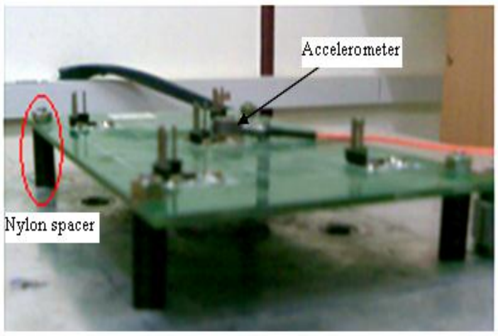

Fig. 2 PSOP-PCB assembly mounted on Nylon spacers.

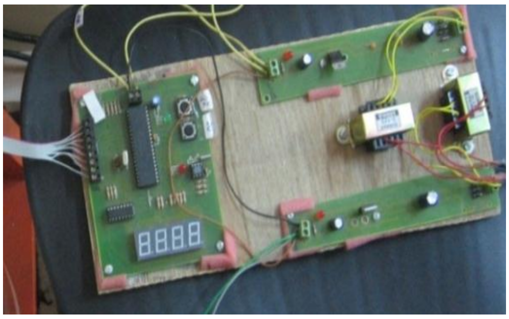

Fig. 3 Failure detecting circuit

2.1.1 Sine sweep test when the PCB assembly is mounted on plastic (Nylon) spacers.

The logarithmic sine-sweep at the rate of one octave per minute was programmed using sinusoidal vibration control software. Sine sweep tests were conducted on the PCB assembly by mounting it on four plastic spacers (encircled in Fig. 2) placed at the corner of the PCB, in the frequency range 100-800 Hz at a constant input acceleration of 0.5*G*. The displacement values at predominant natural frequencies were measured using a pen type digital vibrometer while holding the sweep (software facilitates this feature). The frequency response of the PCB assembly when mounted on plastic spacers is as shown in Fig. 4. The natural frequencies of the PCB assembly obtained from the logarithmic sine sweep test at 0.5G are: 110 Hz, 130 Hz, 180 Hz, 230 Hz, 370 Hz and 750 Hz.

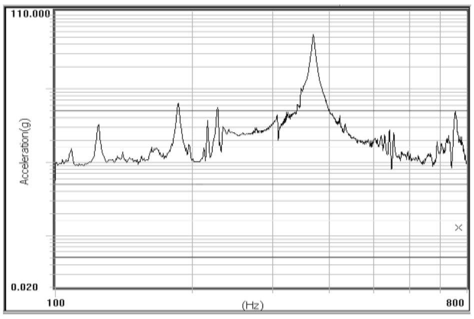

Fig. 4 Response of PCB assembly mounted on Nylon spacers

The peak response acceleration of 55*G* is observed at about 370 Hz and the deflection of PCB assembly at this resonant frequency is 0.1 mm and the transmissibility ratio (G_{out}/G_{in}) is 110. The transmissibility plot of the PCB assembly due to 0.5*G* input acceleration is as shown in Fig. 5. Using the half power bandwidth method (Andy Perkins *et al*, 2008), the damping ratio for this arrangement is calculated and it is found to be 0.011.

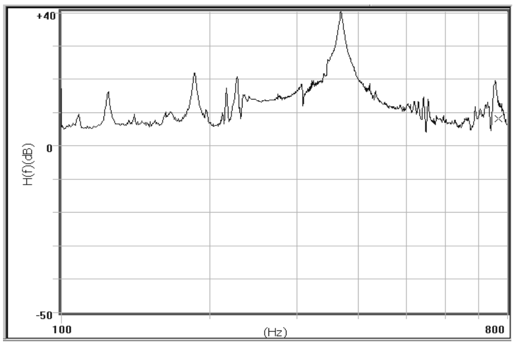

Fig. 5 Transmissibility plot of the PCB assembly

2.1.2 Sine sweep test when the PCB assembly is mounted on rubber spacers.

The transmissibility ratio of the PCB assembly mounted on plastic spacers was found to be 110 which lead to amplification of acceleration levels at resonant frequencies. In order to minimize the transmissibility ratio, the PSOP-PCB assembly was mounted on Neoprene rubber spacers instead of plastic spacers and the sine sweep tests were conducted as explained in the previous section. The properties of Neoprene rubber are given in Annexure 1.

The frequency response plot obtained from the sine-sweep test due to 0.5G input acceleration is as shown in Fig. 6. From Fig. 6 it is seen that, the peak acceleration level experienced by the PCB assembly is reduced to 30*G* (from 55*G*) and the deflection of PCB assembly at the first resonant frequency is found to be 0.06 mm. Thus, a reduction of 45% in peak acceleration and 40% reduction in displacement levels are obtained by using Neoprene rubber spacers.

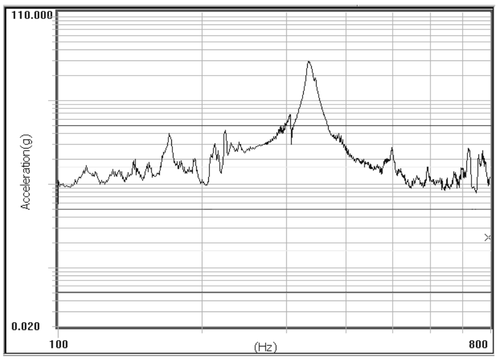

Fig. 6 Response of PCB assembly mounted on rubber spacers

The transmissibility plot of the PCB assembly due to 0.5*G* input acceleration is as shown in Fig. 7, from which the transmissibility ratio at first resonant frequency is about 60 i.e., a reduction of 46% is achieved by mounting the PCB assembly on rubber spacers. The damping ratio calculated for this type of PCB mounting is found to be 0.018 i.e., there is an increase of 39% in the system damping.

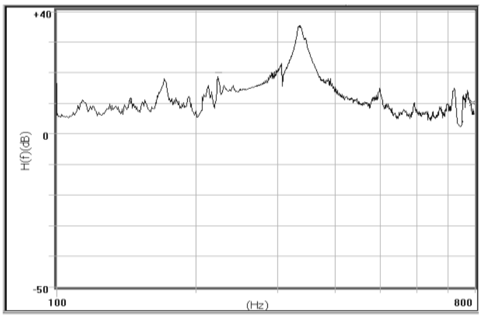

Fig. 7 Transmissibility plot of the PCB assembly

2.2 ANSYS simulation

2.2.1 PCB assembly mounted on Nylon spacers.

The computational model of PSOP-PCB assembly is created in ANSYS[www.ansys.com) to simulate the sinusoidal vibration tests conducted with Nylon spacers. The PCB made of FR-4 and the electronic package was meshed using Solid-92, 10 node elements. The material properties are given in Table 1. All the nodal degrees of freedom at the holes were constrained to simulate actual mounting conditions. A load of 0.5*G* is applied at the centre of the PCB assembly. The displacement plot obtained from simulation is as shown in Fig. 8. From this figure it is evident that the displacement at the PCB centre is 0.0993 mm which is close to the experimental results (0.1 mm). The maximum stress (von-mises) induced in the lead wires when the PCB assembly is mounted on plastic spacers is shown in Fig. 9 and from the figure it is observed that, the maximum stress of 29 MPa is induced in the outer pins of the centrally located package.

Table 1 Material properties

Component	Young's modulus (GPa)	Poisson's ratio	Density (kg/m^3)
PCB (FR-4)	24	0.284	2269
PSOP body	17	0.3	2200
Lead wires	121	0.34	8954

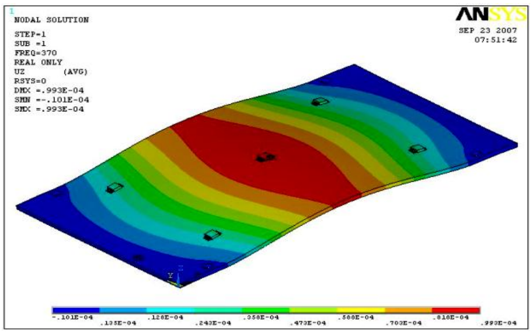

Fig. 8 Displacement plot of PCB mounted on Nylon spacers

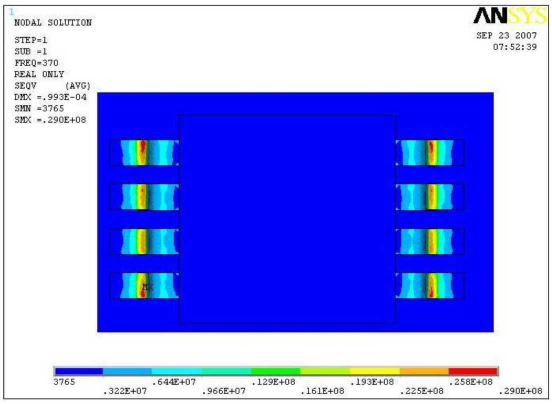

Fig. 9 Stress plot in PSOP at PCB centre

2.2.2 PCB assembly mounted on Rubber spacers

For simulating this condition a damping ratio of 0.018 is used. Fig. 10 below shows the displacement plot of the PSOP-PCB assembly mounted on rubber spacers. From this figure it is observed that, the displacement at the centre of the PCB is about 0.05 mm again which is close to the displacement value obtained from the experiment.

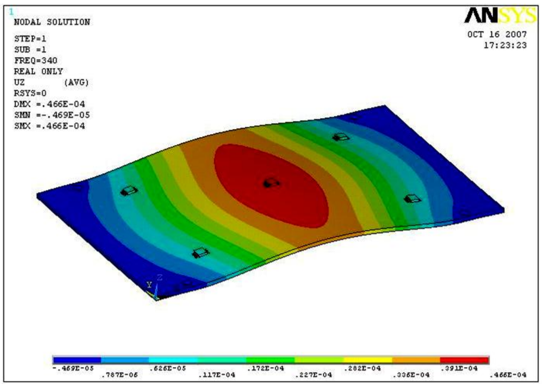

Fig. 10 Displacement plot of the PCB mounted on rubber spacers

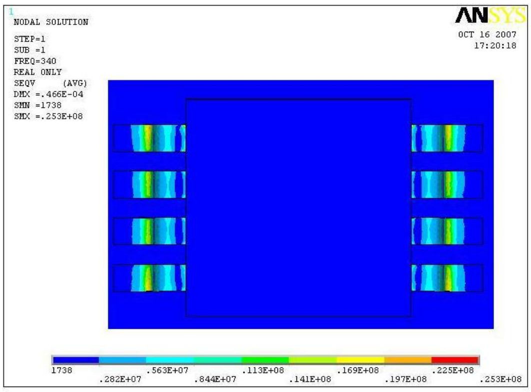

Fig. 11 Stress plot in PSOP at PCB centre

Similarly, the magnitude of stresses induced in the lead wires of centrally located PSOP when PCB assembly was mounted on rubber spacers is shown in Fig. 11 and the magnitude of stress levels experienced by the outer pins is found to be 25 MPa. Thus, by mounting the PSOP-PCB assembly on rubber spacers the stress magnitude is reduced by 14%. Due to reduction in the stress magnitude the lead wires will experience less fatigue damage ratio.

2.3 Comparison of Experimental and Simulation Results

The comparison of experimental and ANSYS simulation results of sinusoidal vibration tests conducted on PSOP-PCB assembly is shown in Table 2. From the table it is evident that, the experimental and the simulation results are in close agreement with each other.

Table 2 Comparison of experimental and simulation results

Parameters	Experimental		ANSYS	
	Plastic spacers	Rubber spacers	Plastic spacers	Rubber spacers
Displacement (mm)	0.1	0.06	0.099	0.05
Stress (MPa)	--	--	29	25

2.4 Fatigue Life Estimation

The lead wires and solder joints of electronic components are usually the most critical elements of an electronic package. The stress magnitudes induced in the lead wires of the electronic package are obtained from finite element simulation. The fatigue damage ratio (R_n) of the lead wires of the PSOP subjected to 0.5*G* input acceleration load was estimated when the PCB-PSOP assembly was mounted on plastic spacers and rubber spacers. The stresses induced in the lead wires are obtained from the finite element analysis results (Fig. 10, Fig. 11). The maximum stress induced in the lead wires when the PCB assembly is mounted on plastic spacers is 29 MPa and is induced in the outer pins of the centrally located package. Hence, the outer pins of PSOP will be treated as critical elements in the assembly and fatigue damage ratio will be estimated for these elements.

The fatigue damage ratio is estimated by equation (1)

$$R_n = \frac{n}{N} \tag{1}$$

where,
n = The number of cycles accumulated during a specified test duration.
N = The number of cycles necessary for the failure.

The time taken for one resonance sweep (logarithmic) between ± 5% of first resonant frequency is calculated using the following equation.

$$t = \frac{\log_e\left(\frac{f_2}{f_1}\right)}{R\log_e 2} \tag{2}$$

Where, f_2 = upper frequency, Hz.
f_1 = lower frequency, Hz
R = sweep rate in octave per minute

The time taken for one sweep between the limits ±5% of first resonant frequency (110 Hz) and at a sweep rate of one octave per minute is found to be 0.145 minute. Hence, the number of cycles accumulated in lead wires during 2500 sweeps or 6.04 hour test duration will be: 110 Hz *(3600 sec)*(6.04) = 2391840 cycles

The number of cycles (N) required for the failure of lead wires at a specified stress level is calculated by using equation (3).

$$N_1 = N_2 \left(\frac{S_2}{S_1} \right)^b \tag{3}$$

where,
N_1 = expected number of cycles for lead wire to fail at stress level S_1
N_2 = 1000 cycles (number of cycles to fail at reference stress S2, Fig. 12)
S_1 = 29 MPa (stress magnitude in the outer lead wire, from Fig. 9)
S_2 = 310.26 MPa (stress magnitude at N_2 cycles, from Fig. 12)
b = 6.4 (slope of S-N curve, Fig. 12)

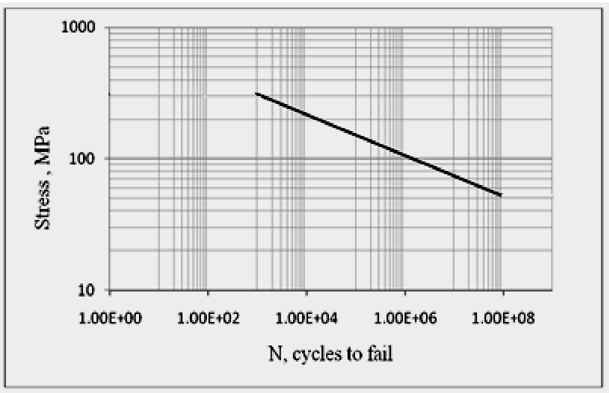

Fig. 12 S-N Curve for the lead wire material

The fatigue damage ratio is estimated for the cases when the PCB assembly is mounted on plastic spacers and rubber spacers and tabulated in the following table.

Table 3 Fatigue damage ratio calculations

PCB assembly mounted on	N (cycles)	n (cycles)	Fatigue damage ratio $R_n=n/N$
Plastic spacers	3870×10^6	2.4×10^6	0.0006
Rubber spacers	10005×10^6	2.6×10^6	0.00026

From Table 3 it is evident that the fatigue damage ratio is reduced by about 57% when the PCB assembly is mounted on rubber spacers.

3. Conclusions

From the sinusoidal vibration tests conducted on the PSOP-PCB assembly the following conclusions are drawn.

1. When Neoprene rubber spacers are used to mount the PCB assembly the displacement and acceleration levels are respectively reduced by 40% and 45% when compared to the responses of the PCB assembly mounted on Nylon (plastic) spacers.
2. The damping ratio of the PCB assembly was improved by about 39% when it was mounted on resilient rubber spacers.
3. The stresses induced in package lead wires was reduce by about 14% when the PCB assembly was mounted on rubber spacers.
4. The fatigue damage ratio (of lead wires) is reduced by about 57% when the PCB assembly was mounted on rubber spacers.

From above facts it is evident that, by using Neoprene rubber as spacer material, the life of the critical elements of electronic packages is improved.

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Annexure 1: Properties of Neoprene rubber

Youngs Modulus: 1.05MPa	Density: 1020 kg/m^3	Hardness: 60 grades (shore A)