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Fatigue Prediction of Electronic Packages Subjected to Random Vibrations

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Abstract—**In modern automotive control modules, mechanical failures of surface-mounted electronic components such as microprocessors, crystals, capacitors, inductors, transformers, ball grid array packages (BGA), quad flat packages (QFP), and chip-scale packages (CSP) are major road blocks in the design cycle and reliability of the product. This paper presents a general approach for failure analysis and fatigue prediction of electronic component like QFPs under automotive vibration environments. The mechanical performance of this package was studied through a finite element modeling approach for a given vibration environment in an automotive application. The vibration simulation provides system characteristics such as modal shapes, modal frequencies, and dynamic responses, including displacements and stresses. By using the results of vibration simulation, fatigue life is predicted based on Miner's cumulative damage ratio and the three-band technique. Detailed (local) model of the lead wire joint is built to correlate the system level model to obtain solder stresses. On the test vehicle, a 160-pin gull-wing lead plastic QFP was chosen to illustrate this approach for failure analysis and fatigue life prediction. From the analysis, it was found that the life used up by the lead wires was 11.6% of the 4-h vibration test.**

Keywords—**Fatigue life, random vibrations, electronic components, plastic quad flat pack (PQFP)**

Introduction

Product reliability can be improved through understanding of the weakest link in the structure of the products. Improvements can be implemented in a timely manner only if the capability of the weakest link is known at the early design stage. Electronic-component stress failures are a primary concern in automotive control modules that often experience harsh environments, such as vibration and thermal fatigue. The most challenging issue in electronic packaging engineering is to predict the lifetime of the critical electronic components. Engineers also need to identify failure mechanism through physical failure analysis and simulated stress analysis. To predict fatigue failure life, one must have information regarding the structural responses and material behaviors.

The conventional design process is an iterative loop, i.e., design–prototype–test–fix. This process requires long times and high expenses related to physical prototyping and testing. When addressing the reliability of electronic components in recent literature, most of the research has focused on solder joints under thermal loads. Among the many references available, Frear et al. [1], Lau [2], and Hwang [3] are good collections of information on this subject. Thermal mismatch among various materials in the electronic packaging often causes large inelastic strain and creep strain in the solder joints [4]. The significant deformation in this case causes solder joints to be the weakest link in the system.

In addressing vibration fatigue, Hu [5] discussed the theory of life prediction and accelerated testing under various random loads. Similar formalism can also be found in Wirsching et al. [6] as well as in Henderson and Piersol [7]. Analyses of solder joint stresses associated with vibration are widely seen in the literature [2, 8-10]. Li [12] used experimental and numerical methods to predict the life of PQF (plastic quad flat) packages subjected to random vibrations. In dealing with high cycle fatigue of electronic components under random vibration loads, this paper focuses on the approach to damage analysis and its implementation through global/local finite element modeling. The methodology presented herein consists of utilizing simulation tools to gain understanding of structural responses and key area stresses under given vibration loads.

Methodology

The methodology adopted for solving the random vibration problem in this study is as shown in Fig. 1.

A. Finite Element Modeling of the Electronic Packaging System

In this work, a plastic quad flat package (PQFP) having 160 gull-wing lead wires was mounted at the center of the printed circuit board (PCB) and was considered for analysis. The body size of PQFP is 28 mm × 28 mm × 1.675 mm, the pin count is 160, and the lead pitch is 0.65 mm. The PCB is 240 mm × 210 mm × 1.6 mm in size and made of FR-4 fiberglass material. The lead wires of the PQFP are soldered to the PCB with a eutectic solder (63Sn/37Pb). PQFP assembly was meshed by using 10-node tetrahedron elements.

B. Analysis of PQFP Package Subjected to Random Vibrations

In general, the PQFP assembly consists of four constituents, namely, the PQFP body, the gull-wing lead, the FR-4 PCB, and the solder joint. For simplicity, instead of modeling all detailed structures inside the package, the PQFP body in the present model is considered as an effective material of all compositions.

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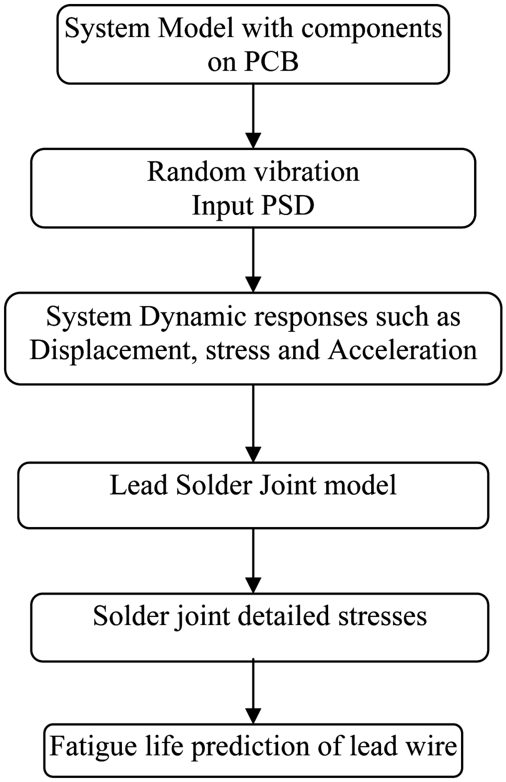

Fig. 1. Methodology for random vibration analysis.

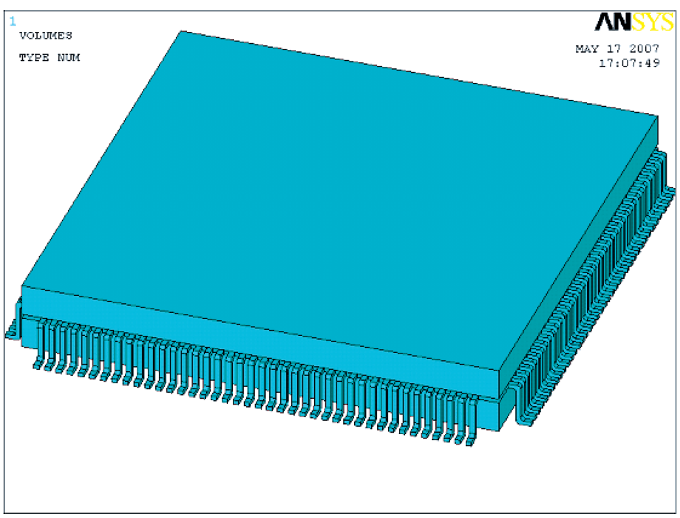

Fig. 2. Finite element model of the PQFP chip.

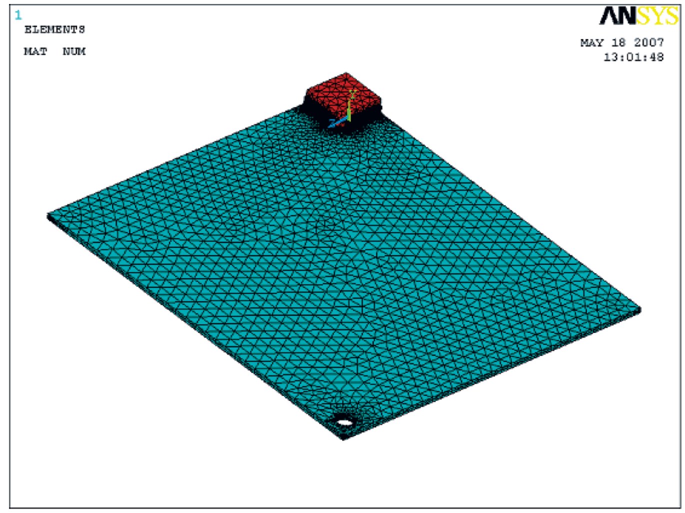

Fig. 3. Quarter model of PCB and PQFP.

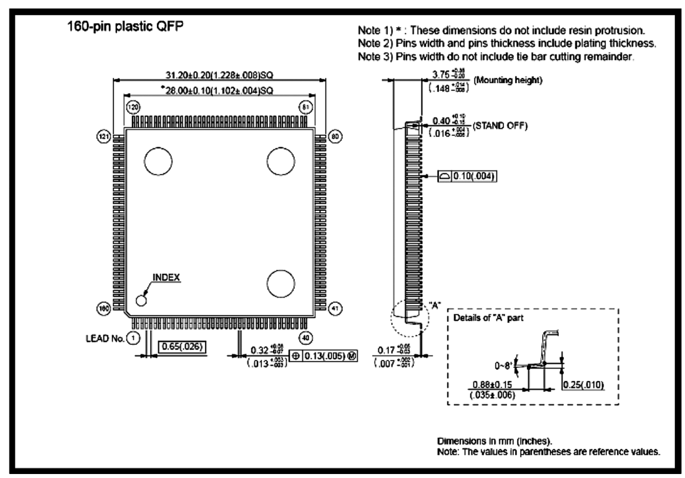

Fig. 4. Details of PQFP package.

Table I
Material Properties

Serial number	Component	Material	*E* (GPa)	*ν*
1	PCB	Fiberglass FR4	24.1	0.39
2	PQFP body	Plastic	14	0.23
3	Lead	Copper alloy	121	0.35
4	Solder	Lead/tin alloy	10	0.4
6	Copper pad	Copper/phosphorous alloy	110	0.33

The 3-D model of the PQFP chip along with lead wires is as shown in Fig. 2. Owing to symmetry in geometry, only a quarter model of the assembly is simulated (Fig. 3). Actual configuration and details of the PQFP package are shown in Fig. 4. Material properties used in the finite element analysis are listed in Table I.

The random vibration excitation profile to which the electronic assembly was subjected (normally found in automotive applications) is shown in Fig. 5. The power spectral-density curve lies in the frequency range of 50-2000 Hz. A uniform damping ratio of 1.25% was used for the analysis. The system-level model was given random excitation in nodes where the PCB was supported.

C. Results of PQFP Subjected to Random Vibrations

First of all, the modal analysis of PQFP assembly was carried out. The first five modes were extracted and are listed in Table II.

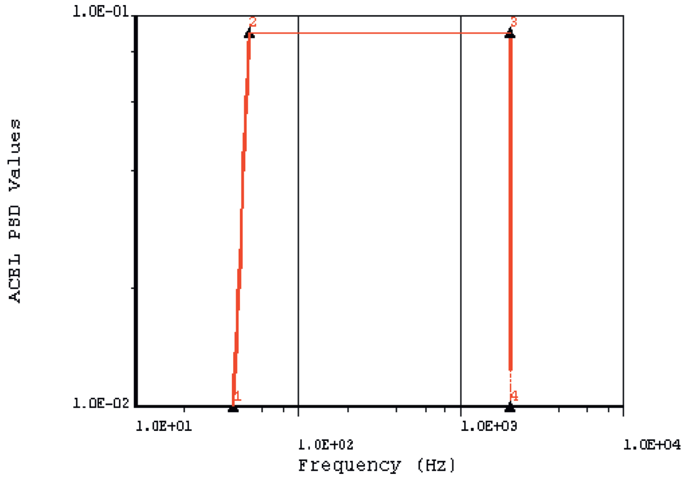

Fig. 5. Random vibration excitation profile used in FEA simulation.

Table II
Results of Modal Analysis of PCB with PQFP

	Mode no.				
	1	2	3	4	5
Frequency (Hz)	68.9	159.17	275.88	579.04	757.27

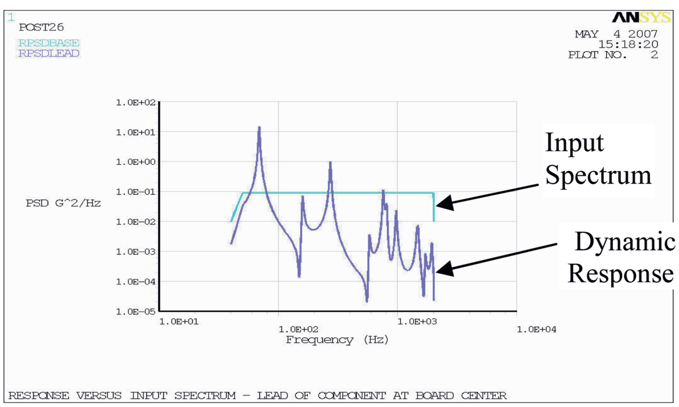

Fig. 6. Dynamic response of the PQFP assembly.

The input random vibration spectrum is given to nodes where the PCB is supported, i.e., at the screw holes. The response obtained from finite element simulation is shown in Fig. 6. From Fig. 6, it can be seen that the response is maximum at the first fundamental frequency of 68.9 Hz. From Fig. 7, the maximum displacement at the center of the PCB is found to be 0.324 mm. The bending stresses of the leads from the system-level model are further verified through a detailed solder/lead joint model (Fig. 8). In this particular case, the gull-wing lead wire at the corner of the PQFP is subjected to the maximum displacement and is the weakest link; therefore, the system reliability is dominated by the lifetime of the gull-wing leads.

D. Fatigue Life Prediction of Gull-Wing Lead Wires of PQFP

In this work, the Three-band technique and Miner's cumulative damage ratio [11] was used to find random vibration fatigue

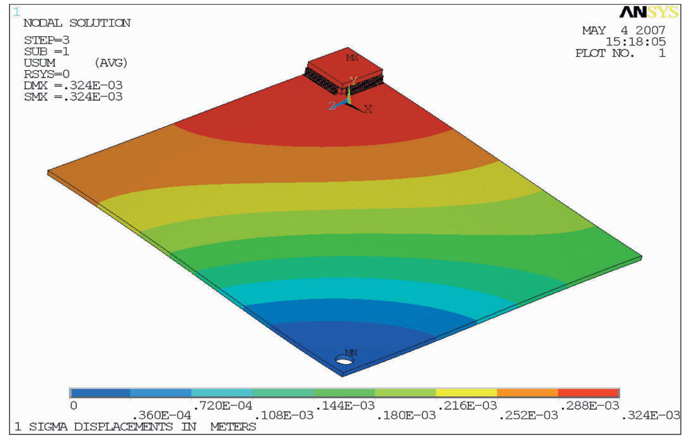

Fig. 7. Displacement of PCB with PQFP.

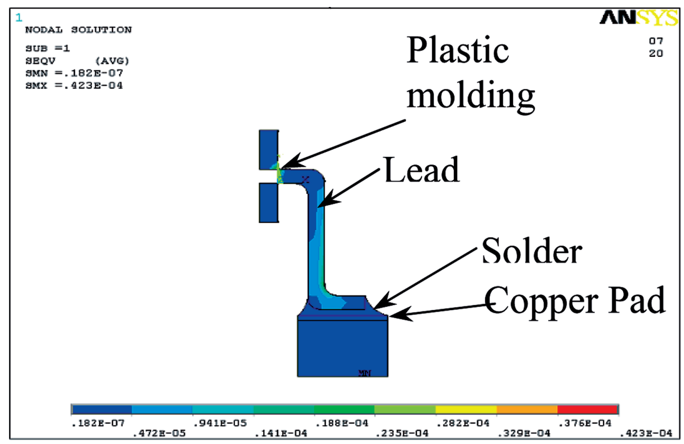

Fig. 8. Stresses in the local model of the lead wire.

life of the lead wires. The basis for the three-band technique is the Gaussian distribution. The instantaneous accelerations between $+1\sigma$ and -1σ are assumed to act at the 1σ level 68.3% of the time. The instantaneous accelerations between $+2\sigma$ and -2σ are assumed to act at the 2σ level 27.1% of the time. Instantaneous accelerations between $+3\sigma$ and -3σ are assumed to act at the 3σ level 4.6% of the time. Miner's cumulative fatigue damage ratio is based on the idea that every stress cycle is due to sinusoidal vibration, random vibration, thermal cycling, shock, or acoustic noise. In the present case, only random vibration is present. A fatigue ratio of n/N is used to show the percentage of life used up. The actual number of stress cycles generated in a specific environment is shown as n. The number of stress cycles required to produce a fatigue failure in a specific environment is shown as N. When the ratios are all added together, a sum of 1.0 or greater means that all of the life has been used up so the structure should fail. The cumulative damage ratio can be found from eq. 1,

$$R_n = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots \frac{n_n}{N_n} = 1.0 \tag{1}$$

where R_n is the cumulative damage ratio, n is the actual number of stress cycles generated in a specific environment, and N is the number of cycles required to produce fatigue failure in a specific environment.

The approximate number of stress cycles N required to produce a fatigue failure in the structure for 1σ, 2σ, and 3σ stress levels can be obtained from eqs. (2)-(4):

$$1\sigma N_1 = N_2\left(\frac{S_2}{S_1}\right)^b \quad (2)$$

$$2\sigma N_2 = N_2\left(\frac{S_2}{2\times S_1}\right)^b \quad (3)$$

$$3\sigma N_3 = N_2\left(\frac{S_2}{3\times S_1}\right)^b \quad (4)$$

where $1\sigma N_1$ is the number of cycles required to produce fatigue failure for 1σ stress, $2\sigma N_2$ is the number of cycles required to produce fatigue failure for 2σ stress, $3\sigma N_3$ is the number of cycles required to produce fatigue failure for 3σ stress, N_2 is the cycle to fail at the reference point, S_2 is the stress to fail at the reference point, S_1 is the 1σ root mean square (RMS) stress, and b is the slope of the fatigue line.

The actual number of fatigue cycles n accumulated during 4 h of vibration testing can be obtained from the percent of time exposure for the 1σ, 2σ, and 3σ values in the three-band method of analysis as follows:

$$\begin{aligned}1\sigma n_1 &= f_n \times 3600 \times 4.0 \times 0.683\\ &= 68.9 \times 3600 \times 4.0 \times 0.683\\ &= 677{,}645.28 \text{ Cycles} \quad (5)\end{aligned}$$

$$\begin{aligned}2\sigma n_2 &= f_n \times 3600 \times 4.0 \times 0.271\\ &= 68.9 \times 3600 \times 4.0 \times 0.271\\ &= 268{,}875.36 \text{ Cycles} \quad (6)\end{aligned}$$

$$\begin{aligned}3\sigma n_3 &= f_n \times 3600 \times 4.0 \times 0.0433\\ &= 68.9 \times 3600 \times 4.0 \times 0.0433\\ &= 42{,}960.53 \text{ Cycles} \quad (7)\end{aligned}$$

1) Calculation of Number of Stress Cycles Needed to Produce a Fatigue Failure for 1σ, 2σ, and 3σ Stresses:

Here N_2 = 1000 cycles, S_2 = 310.261 MPa (from S–N curve, Fig. 9), S_1 = 4.71 MPa (result from FEA simulation, Fig. 8), and b = 2.4 (from Fig. 9):

$$1\sigma N_1 = 1000\left(\frac{310.261\times 10^6}{4.71\times 10^6}\right)^{2.4} = 23{,}168{,}169.11 \text{ Cycles}$$

$$2\sigma N_2 = 1000\left(\frac{310.261\times 10^6}{2\times 4.71\times 10^6}\right)^{2.4} = 4{,}389{,}547.22 \text{ Cycles}$$

$$3\sigma N_3 = 1000\left(\frac{310.261\times 10^6}{3\times 4.71\times 10^6}\right)^{2.4} = 1{,}658{,}825.50 \text{ Cycles}$$

2) Calculation of Cumulative Damage Ratio using eq. (1):

$$\begin{aligned}R_n &= \frac{677{,}645.28}{23{,}168{,}169.11} + \frac{268{,}875.36}{4{,}389{,}547.22} + \frac{42{,}960.53}{1{,}658{,}825.50}\\ &= 0.02925 + 0.06127 + 0.0259\\ &= 0.116\end{aligned}$$

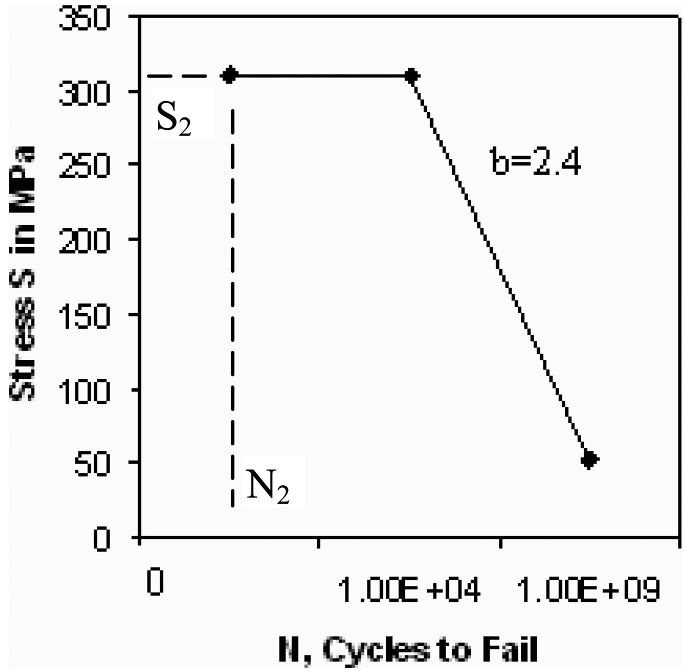

Fig. 9. S–N curve for lead wire material.

Examination of above cumulative damage ratio shows that the 3σ RMS level does little damage. Most of the damage is generated by the 2σ level, which acts only about 27.1% of the time. The 2σ level generates more damage than the damage at the 3σ and 1σ levels. The above cumulative damage ratio shows that about 11.6% of the life is used up by the 4-h vibration test. This means that 88.4% of life is left. The expected life of the component can be obtained as shown below:

$$\begin{aligned}\text{Expected life of lead wires} &= 4.0 + (4.0)(1.0 - 0.116)\\ &= 7.5636 \text{ h}\end{aligned}$$

Conclusions

The PQFP package mounted at the center of the PCB was subjected to a known pattern of random vibration excitation. A one-quarter model of the PCB-PQFP assembly was analyzed for stresses induced in the gull-wing lead wires of the package. The weakest link in the package is the corner lead wire (as it is subjected to maximum stress of 4.71 MPa). The life consumed by the lead wires was estimated using the three-band technique and Miner's cumulative damage ratio. From the analysis, it was found that the life used up by the lead wires was 11.6% in the 4-h vibration test. Finite element simulation can be conveniently used to predict the fatigue life of lead wires of PQFP subjected to random vibrations.

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