Applicability Study of Steinberg Vibration Fatigue Model in Electronic Products

Ying Chen Liu Yang Bingdong Liu
School of Reliability and Systems Engineering, BeiHang University
Beijing, China
e-mail:yangliu92616@163.com

Dan Xue
AVIC Aviation Motor Control System Institute
Wuxi, Jiangsu, China

***Abstract*—In the vibration environment, electronic products may have fatigue failure, which affects its reliability level seriously. Therefore, it is important to estimate the vibration fatigue life of electronic products. The common used vibration fatigue model is Steinberg model which is necessary to be studied. This paper analyzes the derivation of Steinberg vibration fatigue model. Assumptions and simplifications of the model and the influence of parameters on the vibration fatigue life are studied. Finally, the applicability of the model and vibration design guidelines of electronic products are summarized. It provides a basis for the improvement of vibration design.**

Key words-Steinberg vibration fatigue model； applicability； design guidelines for vibration

I. INTRODUCTION

In the vibration environment, due to the fatigue effect of vibration, there will appear some phenomena of performance degradation, component failure, fatigue damage, or even destruction in electronic products[1]. These phenomena reduce reliability seriously. So it is necessary to estimate the vibration fatigue life[2]. The common used vibration fatigue model is Steinberg model. In the 1970s, Steinberg model is proposed[3]. According to many years of practical experience, Dave S. Steinberg systematically described the model and its application under random vibration, shock and other conditions in his book. It combines the dynamic response characteristics of single degree of freedom system response, vibration fatigue characteristic curve and empirical formula of test analysis. Based on some assumptions and simplifications, Steinberg put forward an empirical formula for estimating PCB's vibration fatigue life, which quantitatively reflects the relation between the material, structure, vibration stress and vibration fatigue life.

At present, Steinberg vibration fatigue model is used in the reliability simulation software tool CalcePWA which is developed by CALCE of Maryland University. However, when the vibration fatigue life calculated by the model is unreasonable, we have no idea how to deal with it. More seriously, we cannot get the true estimation of vibration fatigue life.

Dehbi.A [4] studied the application of Steinberg model in tantalum capacitor. Through the practical experiment, they provided the S-N curve in different sine sweeping-frequency vibration conditions. Chin and Wong[5] put forward the method to predict the solder ball life with E-N curve instead of S-N curve in the application of Steinberg model. Liu [6] studied the dynamic response and reliability of BGA lead-free solder ball at the basis of Steinberg model. Urgueira[7] used a variety of life prediction models including the Steinberg model and evaluated the life at the position with maximum stress. Wu[8] gave a suggestion that the Steinberg model in CalcePWA software required correction work for PCB with new structure and materials.

Although Steinberg model is widely used in specific product's life prediction, but there is little research on applicability of Steinberg vibration fatigue model. Therefore, in order to use the model to evaluate the vibration fatigue life of electronic products in the engineering application, it is necessary to study the applicability of the model. In addition, studying the influence of model parameters on the vibration fatigue life can provide a basis for improving vibration design.

The remainder of this paper is organized as follows. In SectionⅡthe derivation of Steinberg vibration fatigue model is studied. Section Ⅲ summarizes the applicability of the model. Section ⅣAnalyzes the influence of model parameters on the vibration fatigue life. Then Section Ⅴsummarizes the design guidelines for vibration. Lastly, Section Ⅵ gives our conclusions.

II. STEINBERG SINE/RANDOM VIBRATION FATIGUE MODEL

2.1 Vibration fatigue characteristic equation

The fatigue life of vibration system can be calculated by fatigue properties of components which bear most structural loads. These fatigue properties are usually obtained from controlled circle stress tests. The components and parts are made of the same material and have precise dimensional tolerances. Plot the components' fault data in a double logarithm coordinate system. Ordinate is stress, and abscissa is cycle time before failure. Fig. 1 indicates a straight line formed by the disperse data points.

The sloping part in curve can be expressed by an equation given by[9] (1).

978-1-4799-7958-5/14/$31.00 ©2014 IEEE

$$N_1 S_1^b = N_2 S_2^b \tag{1}$$

Where

N = stress cycle time before fatigue failure,

S = failure stress,

b = fatigue index related to slope.

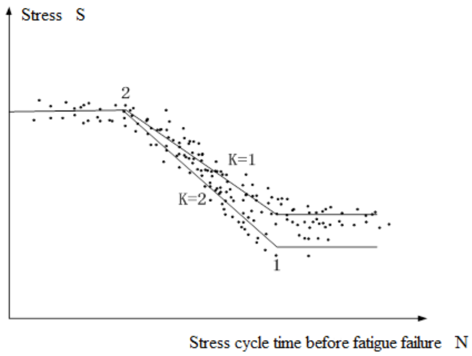

Figure 1.Typical fatigue characteristic curve

For linear systems, S is proportional to Z .

$$N_1 Z_1^b = N_2 Z_2^b \tag{2}$$

And,

$$N_2 = N_1 (\frac{Z_1}{Z_2})^b \tag{3}$$

2.2 Origin of N_1 and Z_1

Tests show that if the peak amplitude displacement of simply supported PCB equals the value in (4), the fatigue life of components can be calculated. In sinusoidal vibration environment, the fatigue life is about 1×10^7 stress circle times[10]. In random vibration environment, the fatigue life is about 2×10^7 stress circle times[11].

$$Z = \frac{0.00022B}{ChR_{xy}\sqrt{L}} \tag{4}$$

Where

B =length of PCB edge parallel to component,

L =length of electronic component,

h =height or thickness of PCB,

C =constant for different types of electronic components,

(C=1.0 for a standard dual inline package (DIP) ; C =1.26 for a DIP with side-brazed lead wires; C=1.26 for a pin grid array (PGA) with two parallel rows of wires extending from the bottom surface of the PGA; C=1.0 for a PGA with wires around the perimeter extending from the bottom surface of the PGA; C=2.25 for a leadless ceramic chip carrier (LCCC); C=1.75 for a ball grid array (BGA); C=0.75 for axial-leaded component resistors, capacitors, and fine pitch semiconductors)

R_{xy} =relative position factor of component on PCB, (R_{xy} =1.0 for component at the center of PCB; R_{xy} =0.707 for component at 1/2 point X and 1/4 point Y on a PCB supported on four sides; R_{xy} =0.5 for component at 1/4 point X and 1/4 point Y on a PCB supported on four sides)

2.3 Origin of Z_2

2.3.1 The displacement response under sinusoidal vibration Z_2

PCB can be approximated as a single degree of freedom system, when it vibrates under the fundamental resonance. The actual dynamic single amplitude displacement of PCB's center is given by:

$$Z = \frac{9.8G_{out}}{f^2} = \frac{9.8G_{in}Q}{f_n^2} \tag{5}$$

By testing on PCB with different boundary conditions, and collecting a large number of data, the transfer rate of a compact epoxy circuit board is given by[10]:

$$Q = \sqrt{f_n} \tag{6}$$

So, Z can be calculated as follows:

$$Z = \frac{9.8G_{in}}{f_n^{1.5}} \tag{7}$$

1.3.2 The displacement response under random vibration Z_2

In random vibration, the mean square displacement of PCB's center is given by:

$$Z_{RMS} = \frac{9.8G_{RMS}}{f^2} \tag{8}$$

According to the stress level 3σ in random vibration, the maximum dynamic single amplitude displacement of PCB's center is three times of the mean square displacement which is as follows:

$$Z = 3\times\frac{9.8G_{RMS}}{f_n^2} \tag{9}$$

When the input PSD of random vibration is flat spectrum in resonance region, the mean square root acceleration response of a system is given by:

$$G_{out} = \sqrt{\frac{\pi}{2}Pf_nQ}(RMS) \tag{10}$$

So, Z can be calculated as follows:

$$Z = \frac{36.85\sqrt{P}}{f_n^{1.25}} \tag{11}$$

III. THE APPLICABILITY OF STEINBERG VIBRATION FATIGUE MODEL

There are some assumptions and simplifications in the derivation of Steinberg vibration fatigue model. According to studying these assumptions or simplifications, several applicabilities of this model are as follows:

1. The resonance frequency of the case and PCB should meet octave law. Then PCB can be considered a single degree of freedom system;

2. The system should be a slight damping system. Because for a slight damping system, the relationship between damping ratio and transfer rate is $\frac{c}{c_c}=\frac{1}{2Q}$. Therefore, the mean square root acceleration response is $G_{out}=\sqrt{\frac{\pi}{2}P_{in}f_nQ}(RMS)$;

3. The input PSD of random vibration should be flat spectrum in resonance region so that G_{out} can be expressed by $G_{out}=\sqrt{\frac{\pi}{2}P_{in}f_nQ}(RMS)$.

4. For a rectangular PCB, if it is supported on four sides, with evenly distributed load, and the vibration occurs in the direction perpendicular to the surface, the response displacement changing with PCB's coordinates can be expressed by[10],

$$Z=\sum_{m=1.3.5\ldots}^{\infty}\sum_{n=1.3.5\ldots}^{\infty}A_{mn}\sin\frac{m\pi X}{a}\sin\frac{n\pi Y}{b} \tag{12}$$

A lot of vibration test data shows that: most faults occur in resonant mode which has maximum displacement and stress[12]. Therefore, the above equation can be simplified as:

$$Z=Z_0\sin\frac{\pi X}{a}\sin\frac{\pi Y}{b} \tag{13}$$

5. It should not consider the coupling transfer rate. Then the transfer rate of PCB is approximately $Q=\sqrt{f_n}$.

IV. PARAMETER ANALYSIS OF STEINBERG VIBRATION FATIGUE MODEL

Substitute (4) and (7) into (3). Then N_2 can be expressed as follows:

$$N_2=10^7\times\left(\frac{0.00022B}{ChR_{xy}\sqrt{L}}\cdot\frac{f_n^{1.5}}{9.8G_{in}}\right)^{6.4} \tag{14}$$

Substitute (4) and (11) into (3). Then N_2 can be expressed as follows:

$$N_2=2\times10^7\times\left(\frac{0.00022B}{ChR_{xy}\sqrt{L}}\cdot\frac{f_n^{1.25}}{36.85\sqrt{P}}\right)^{6.4} \tag{15}$$

It can be seen from the two formulas that when the input value and resonant frequency are certain (i.e., $Z_2=\frac{9.8G_{in}}{f_n^{1.5}}$ and $Z_2=\frac{36.85\sqrt{P}}{f_n^{1.25}}$ are certain values), the influence of parameters on fatigue life can be translated into the influence on $Z_1=\frac{0.00022B}{ChR_{xy}\sqrt{L}}$. Then take sine vibration fatigue model for instance. And the influence of B, L, h, C and R_{xy} on vibration fatigue life is analyzed.

4.1 The influence of B and R_{xy} on component's vibration fatigue life

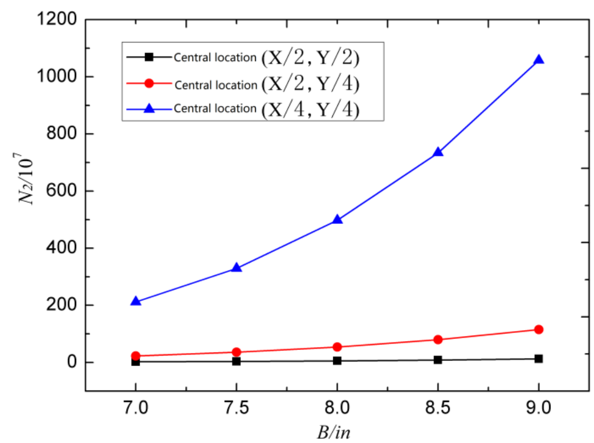

Figure2. The vibration fatigue life of component in different positions vs parameter *B*

As shown in Fig. 2, as the parameter B increases, the vibration fatigue life of components increases too. In other words, the longer PCB's edge length that parallels to the components, the longer the vibration fatigue life of components will be. By comparing vibration fatigue life of components in different positions, it is indicated that component in center of PCB has the shortest vibration fatigue life. The closer to the edge of PCB, the longer vibration fatigue life will be. It is found from this figure that component's position has great influence on vibration fatigue life. The difference even reaches up to two orders of magnitude.

4.2 The influence of L and C on component's vibration fatigue life

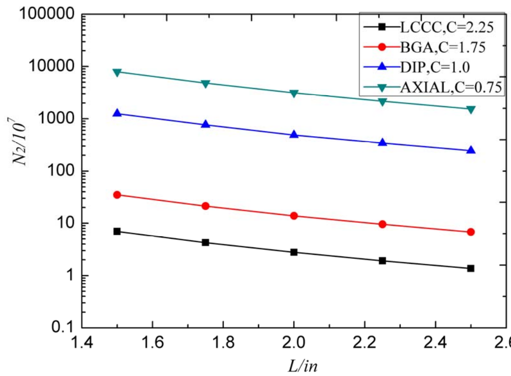

Figure3. The vibration fatigue life of component with different packages vs parameter *L*

As shown in Fig. 3, the longer components are, the shorter vibration fatigue life will be. The vibration fatigue life of axial lead package (AXIAL) is the longest. The second one is dual in-line package (DIP). The third one is ball grid array package (BGA). The last one is leadless ceramic chip carrier (LCCC). Obviously, there is large difference of vibration fatigue life between different packaging components is large, up to three orders of magnitude.

4.3 The influence of h on component's vibration fatigue life

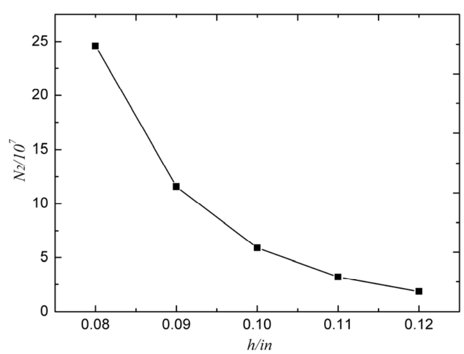

Figure4. The vibration fatigue life vs parameter *h*

As shown in Fig. 4, the larger parameter *h* is, the shorter vibration fatigue life will be. The vibration fatigue life of components decreases with the increase of PCB's thickness.

V. VIBRATION DESIGN GUIDELINES

By studying the influence of model's parameters on vibration fatigue life, several vibration design guidelines can be summarized to make component's vibration fatigue life longer.

1. PCB and its supporting structure should meet the octave law. The larger the difference between the frequencies is, the smaller coupling effect will be. Because PCB is connected with supporting structure, the dynamic response of supporting structure becomes the input of PCB. In any kind of dynamic vibration environment, natural frequencies of supporting structure and PCB are affected by the excitation. If the natural frequency of PCB is close to the natural frequency of the supporting structure, their transfer rate Q may be coupling. This means that their Q values will be multiplied. This will force the response acceleration G to be magnified, leading to a rapid failure of PCB. Therefore, the ratio of PCB's natural frequency and supporting structure's natural frequency must be greater than two. Coupling effect in this case will be sharply reduced. From the relation $Q = \frac{1}{1-(f_f / f_n)^2}$, it can be seen that if $f_f < f_n$, the smaller the ratio is, the smaller Q will be; if $f_f > f_n$, the bigger the ratio is, the smaller absolute value of Q will be.

2. Components with large mass should not be put in the center of PCB as far as possible. Fig. 2 illustrates that when component's position is in the center of PCB, the vibration fatigue life is the shortest. Because if the frequency of four-edge supported PCB is fundamental resonant frequency, the curvature in center of PCB changes rapidly, while the curvature at the edge of PCB changes slowly, as shown in Fig. 5.

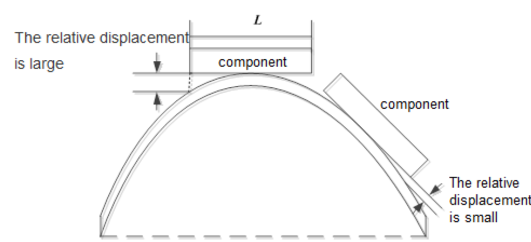

Figure5. The relative displacement of components in different position

3. The direction of component with large size should not parallel to the PCB's short edge. Fig. 2 illustrates that the longer PCB's edge length that parallels to the components, the longer the vibration fatigue life of components will be. If components parallel to the short edge, parameter *B* will decrease, and the vibration fatigue life will be shorter. The reason is that the curvature of PCB's short edge changes more rapidly than the curvature of PCB's long edge, as shown in Fig. 6. There will be a large relative motion between PCB and components. It will increase the stress in lead and solder joint, and reduce the fatigue life of components.

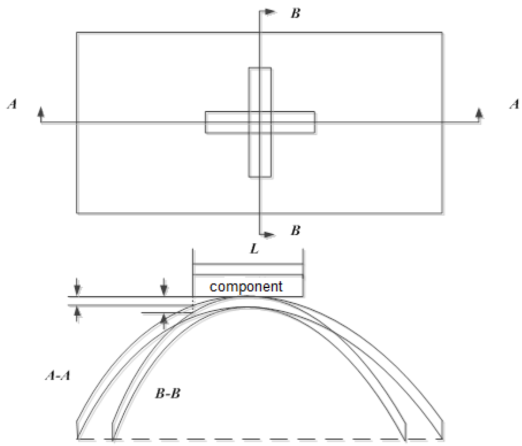

Figure6. The relative displacement of components in different direction

4. On the premise of meeting the functional requirements, we should use AXIAL package components preferentially, and try to avoid using LCCC package components. The life of AXIAL package is longer than LCCC package up to three orders of magnitude.

6. On the premise of meeting the functional requirements, the thickness of PCB can be properly reduced to prolong component's fatigue life.

VI. CONCLUSION

By studying the derivation, assumptions and simplifications of Steinberg vibration fatigue model, applicabilities are summarized. By analyzing the influence of B , L , h , C and R_{xy} on vibration fatigue life, several vibration design guidelines are concluded.

REFERENCES

[1] Yang Feibing. Dynamic Analysis Electronic Equipment and Vibration Control[D]. Xidian University, 2012.

[2] Chen Ying, Gao Lei, Kang Rui. Research on Reliability Simulation Prediction of Electronic Product Based on Physics of Failure Method [J]. Journal of CAEIT, 2013(5).

[3] Johnson, T.J. and D.E. Adams, Transmissibility as a Differential Indicator of Structural Damage. Journal of Vibration and Acoustics, 2002. 124(4): p. 634-641.

[4] Chesné, S. and A. Deraemaeker, Damage localization using transmissibility functions: A critical review. Mechanical Systems and Signal Processing, 2013. 38(2): p. 569-584.

[5] Lin, R.M. and J. Zhu, Finite element model updating using vibration test data under base excitation.Journal of Sound and Vibration, 2007. 303(3–5): p. 596-613.

[6] Wang Dongmei, Study on simulation case of random vibration test at board level electronic products, 2010, Beihang University.

[7] Urgueira, A.P.V., R.A.B. Almeida and N.M.M. Maia, On the use of the transmissibility concept for the evaluation of frequency response functions. Mechanical Systems and Signal Processing, 2011. 25(3): p. 940-951.

[8] Lim, J.H., A correlation study of satellite finite element model for coupled load analysis using transmissibility with modified correlation measures. Aerospace Science and Technology, (0).

[9] Steinberg & Associates. Assessment of Vibration on Avionic Design [M].Dayton：OH, 1984

[10] M. Vet. Vibration Analysis of Thin Rectangular Plates [M]. Mach : Des. Mag, 1967

[11] D. S. Steinberg. Circuit Component vs. G Forces [M]. Mach : Des. Mag, 1971

[12] Dave S. Steinberg. Vibration Analysis for Electronic Equipment [M]. New York：Wiley, 2000