Effect of Vibration Transmissibility on Fatigue Lifetime of Electronic Devices

Liu Yang[1,*], Ying Chen[1], Zenghui Yuan[1], and Liqun Chen[2]

[1] Science and Technology on Reliability and Environmental Engineering Laboratory, Beihang University, Beijing, China
[2] AVIC Aviation Motor Control System Institute Wuxi, Jiangsu, China
{yangliu92616,yuanzh6672,clq2272}@163.com, cheny@buaa.edu.cn

Abstract. Vibration fatigue is one of the main mechanisms which will cause the failures of electronic devices. If the natural frequency of a PCB and its case do not obey octave rule, the vibration of the PCB and the case will couple with each other, and stress applied on PCB will be amplified, resulting in early failure. With Steinberg vibration fatigue prediction models, this paper studies the effect of vibration transmissibility on fatigue lifetime of electronic devices with consideration of coupling. ADAMS software is used to simulate and analyze the vibration transmissibility of electronic devices. The correction of vibration transmissibility in Steinberg model is given. In case study, vibration fatigue lifetimes that compute with corrected Steinberg model and the model without consideration of vibration transmissibility are compared. Effect of vibration transmissibility on electronic devices' fatigue life is discussed.

Keywords: transmissibility, octave rule, vibration fatigue, coupling, lifetime.

1 Introduction

Vibration is one of main environmental conditions experienced by electronic devices, which will result in some failure mechanisms, such as random vibration fatigue, sinusoidal vibration fatigue, shock overstressing and so on. Analyzing vibration failure with Physics-of-Failure method and models has many advantages, including location of design weak location and formulation of improvement measures.

Vibration fatigue of electronic devices has been widely studied [1,2,3,4.5] by many researchers. The research on physics model of vibration fatigue failure can be traced back to 1970s. After many years of practical experience, Dave S. Steinberg proposed Steinberg model applied to lifetime estimation of electronic devices working under sinusoidal or random vibration conditions [6,7]. Although Manson model and other models [8] appeared in this field later, Steinberg model is still wildly used in engineering because of its obvious physical meaning. Dehbi.A et al. [9] studied the application of Steinberg model in tantalum capacitor. Through experiment, they

* Corresponding author.

M. Gen et al. (eds.), *Industrial Engineering, Management Science and Applications 2015*,
Lecture Notes in Electrical Engineering 349, DOI: 10.1007/978-3-662-47200-2_107

provided the S-N curve in different sinusoidal sweeping-frequency vibration conditions. Marksteind et al. [10] proposed some principles of electronic systems to withstand high vibration and shock conditions.

Wu et al. [11] analyzed PCB's vibration with Steinberg model in CalcePWA. Steinberg model was spilt into two separate models, stress analysis model and fatigue damage model. They established a rapid test method which can directly test the effect of new structure and material on lifetime of PCB. Wu gave a suggestion that the Steinberg model in CalcePWA software required correction work for PCB with new structure and material. Chen et al. [12] estimated fatigue lifetime of electronic components in PBGA package by test of vibration damage and FEA. Liu et al. [13] studied the dynamic response and reliability of lead-free solder ball in BGA package under different G values and frequencies on the basis of Steinberg model. Urgueira et al. [14] used a variety of life prediction models including Steinberg model and evaluated lifetime of the position with maximum stress.

From the above discussion, Steinberg model has been widely used in engineering. In this paper, the effect of vibration transmissibility on fatigue lifetime of electronic devices is studied by Steinberg model. Transmissibility factor in Steinberg model represents the coupling state of PCB and its case. It has a significant impact on vibration fatigue lifetime of electronic devices.

2 Theoretical Basis

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

$$Z = \frac{9.8 G_{out}}{f^2} = \frac{9.8 G_{in} Q}{f_n^2} \quad . \tag{1}$$

Where Z is dynamic single amplitude displacement of PCB's center, f_n is resonant frequency of PCB, G_{out} is the root mean square acceleration of output , G_{in} is the root mean square acceleration of input, Q is transmissibility.

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

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

Where G_{RMS} is the root mean square acceleration.

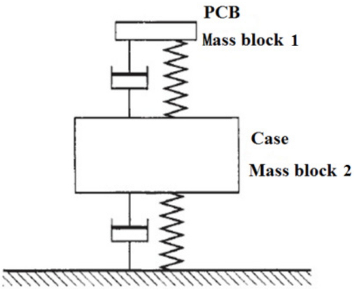
When the input PSD (Power Spectral Density) of random vibration is flat spectrum in resonance region, the root mean square acceleration response of a system is given by:

$$G_{out} = \sqrt{\frac{\pi}{2} P f_n Q} \left(RMS \right) . \tag{3}$$

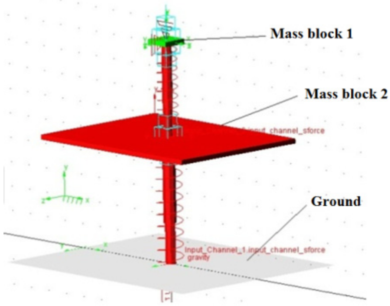
Where P is the input PSD at resonant frequency.

Usually, electronic device can be simplified as two degrees of freedom spring-mass system which consists of spring, damping and mass block, as shown in Fig. 1 a). Changing stiffness ratio of spring can change the ratio of natural frequencies of PCB and case. Changing the mass of PCB and case will change the weight ratio. Changing damping ratio can make the ratio of uncoupling natural vibration transmissibility change. With the purpose of obtaining acceleration value G on PCB, we analyze the energy transmission from case to PCB in condition of different dynamic combinations.

In order to get the relation of vibration transmissibility in two degrees of freedom system, Adams software is used to model two degrees of freedom spring-mass system, as shown in Fig. 1 b) Mass block 1 in the figure represents PCB, and mass block 2 represents its case. The connection between mass block 1 and mass block 2 is a spring-damping system. Similarly the connection between mass 2 and ground is also a spring-damping system.



a) Two degrees of freedom dynamic spring-mass system



b) ADAMS model

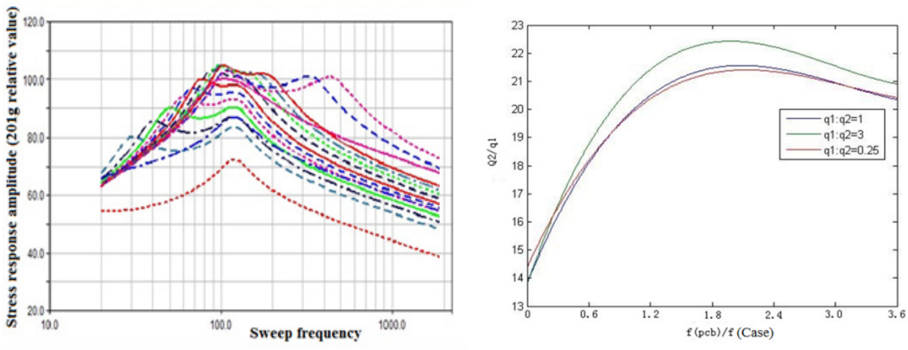
Fig. 1. Modeling PCB and the case

By regulating the mass of mass block 1 and mass block 2, the model is made to match the given condition of weight ratio between PCB and case. By regulating the elastic coefficient k and damping coefficient c of two spring-damping systems, the model is made to match the given condition of natural frequency ratio and natural transmissibility ratio between PCB and case. After that, the sinusoidal vibration load is applied on this system according to the given conditions. Stress response of mass block 1 under different conditions is shown in Fig. 2 a).

By studying two degrees of freedom spring-mass system under three conditions, the mass ratio of PCB and case is confirmed as 1:4. The ratio of PCB's uncoupling transmissibility q_2 and case's uncoupling transmissibility q_1 is determined as 0.25, 1 and 3. The ratio of PCB's coupling transmissibility Q_2 and case's uncoupling transmissibility q_1 varies with the ratio of two natural frequencies. (Fig.2 b))

The trend of Fig. 2 b) rises at first and then goes down. When the natural frequencies of PCB and case are very close, the vibration transmissibility reaches the peak. At this time, there is resonance phenomenon between PCB and case. A general equation of vibration transmissibility is shown in equation (4).

$$Q = A\left[\frac{f_n}{(G_{in})^{0.6}}\right]^{0.76}. \tag{4}$$



a) Stress response of mass block 1 under the condition of permanent mass ratio and transmissibility ratio (Different lines represent ratios of natural frequency)
b) Variation of vibration transmissibility

Fig. 2. ADAMS simulation results

The letter A is a constant related to structural support of electronic devices. When electronic device is girder structure, A=1.0. When it is periphery fixed PCB or plug-in mounting PCB, A=0.5. When it is a small sealed electronic case, A=0.2. f_n is resonant frequency. G_{in} is the root mean square acceleration of input. Q is transmissibility.

In the practical engineering calculation, Steinberg model can be simplified as shown in equation (5).

$$Q = c\sqrt{f_n} \; . \tag{5}$$

The value of c ranges from 0.5 to 2 which is a constant related to excitation amplitude and natural frequency. Generally for a PCB whose first-order natural frequency is in middle frequency band (200Hz-300Hz), the value of c is 1. And for an electronic case, the value is 0.5.

3 Case Study

3.1 PCB and Case Obey the Octave Rule in Design

An electronic device consists of two plug-in PCBs and a case. The device is conducted modal analysis by ANSYS Workbench. The first-order resonant frequency of case is 699.34Hz and the value of PCB-A is 86Hz, as shown in Fig. 3.

The frequency of random vibrational spectrum ranges from 10 Hz to 2000Hz and the power spectral density is 1.5g. In this case, prediction for failure time of components' interconnection due to vibration fatigue is given by CalcePWA, as shown in Fig. 4a). And the failure position is shown in Fig. 4 b).

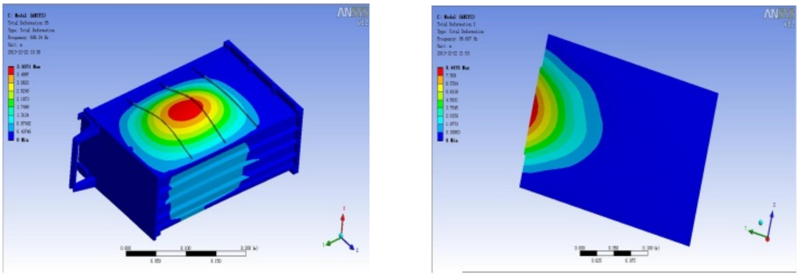
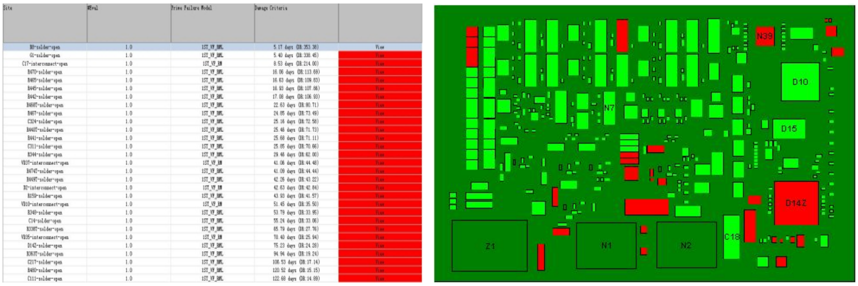


Fig. 3. The first-order modals of case and PCB-A



Site	#Eval	Prime Failure Model	Damage Criteria	
N8-solder-open	1.0	1ST_VF_BML	5.17 days (DR:353.38)	View
G1-solder-open	1.0	1ST_VF_BML	5.40 days (DR:338.45)	View
C17-interconnect-open	1.0	1ST_VF_BM	8.53 days (DR:214.00)	View
R470-solder-open	1.0	1ST_VF_BML	16.06 days (DR:113.69)	View
R465-solder-open	1.0	1ST_VF_BML	16.63 days (DR:109.83)	View
R445-solder-open	1.0	1ST_VF_BML	16.93 days (DR:107.86)	View
R442-solder-open	1.0	1ST_VF_BML	17.08 days (DR:106.93)	View
R468T-solder-open	1.0	1ST_VF_BML	22.63 days (DR:80.71)	View
R46T-solder-open	1.0	1ST_VF_BML	24.85 days (DR:73.49)	View
C324-solder-open	1.0	1ST_VF_BML	25.16 days (DR:72.58)	View
R440T-solder-open	1.0	1ST_VF_BML	25.46 days (DR:71.73)	View
R441-solder-open	1.0	1ST_VF_BML	25.68 days (DR:71.11)	View
C311-solder-open	1.0	1ST_VF_BML	25.85 days (DR:70.66)	View
R344-solder-open	1.0	1ST_VF_BML	29.46 days (DR:62.00)	View
VD37-interconnect-open	1.0	1ST_VF_BM	41.06 days (DR:44.48)	View
R474T-solder-open	1.0	1ST_VF_BML	41.09 days (DR:44.44)	View
R449T-solder-open	1.0	1ST_VF_BML	42.26 days (DR:43.22)	View
D2-interconnect-open	1.0	1ST_VF_BM	42.63 days (DR:42.84)	View
R159-solder-open	1.0	1ST_VF_BML	43.93 days (DR:41.57)	View
VD10-interconnect-open	1.0	1ST_VF_BM	51.45 days (DR:35.50)	View
R348-solder-open	1.0	1ST_VF_BML	53.79 days (DR:33.95)	View
C14-solder-open	1.0	1ST_VF_BML	55.24 days (DR:33.06)	View
R338T-solder-open	1.0	1ST_VF_BML	65.79 days (DR:27.76)	View
VD35-interconnect-open	1.0	1ST_VF_BM	70.40 days (DR:25.94)	View
D142-solder-open	1.0	1ST_VF_BML	75.23 days (DR:24.28)	View
R363T-solder-open	1.0	1ST_VF_BML	94.94 days (DR:19.24)	View
C217-solder-open	1.0	1ST_VF_BML	108.53 days (DR:17.14)	View
R480-solder-open	1.0	1ST_VF_BML	120.52 days (DR:15.15)	View
C111-solder-open	1.0	1ST_VF_BML	122.68 days (DR:14.89)	View

a) Failure prediction of PCB-A b) Potential failure location of PCB-A

Fig. 4. Failure prediction of PCB-A with CalcePWA

In Fig. 5, the ordinate axis represents the ratio between coupling transmissibility of PCB and uncoupling transmissibility of case. The abscissa axis represents the ratio between natural frequencies of PCB and case.

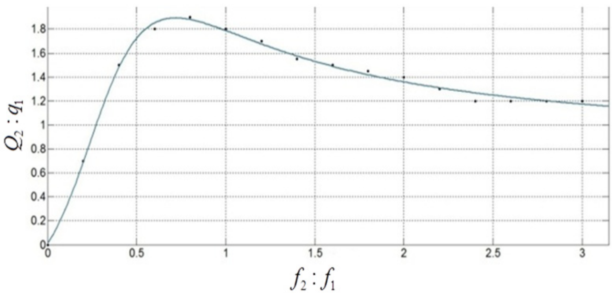


Fig. 5. The relation between two ratios

The fitting expression of above figure is equation (6).

$$y = \frac{6005x^2 + 7615x - 16.15}{x^3 + 8266x^2 - 3525x + 2805} \quad . \tag{6}$$

When $f_2 : f_1 = 0.12$, the value of $Q_2 : q_1$ is about 0.39. By using sinusoidal vibration fatigue model in equation (1), component D10 in PCB is predicted its failure considering vibration coupling. If $Q_2 : q_1 = R$, substitute $Q_2 = R \cdot q_1$ into equation(1). Z can be expressed as shown in equation (7)

$$Z = \frac{9.8G_{out}}{f^2} = \frac{9.8Q_2G_{in}}{f^2} = \frac{9.8Rq_1G_{in}}{f^2} \quad . \tag{7}$$

Relevant parameters of D10 and PCB are brought into sinusoidal vibration fatigue model. By calculation, the fatigue life is $N_2 = 4.47 \times 10^{13}$. However the result calculated by CalcePWA is 1.1645×10^{12}. Obviously the former is far greater than the latter. In other words, lifetime calculated without considering coupling is shorter than that considering coupling. The main reason is that the natural frequency of PCB is much smaller than case's, and they obey the octave rule. Therefore, this situation reflected on Fig. 5 is that the two frequencies have been away from dangerous area where serious coupling is much possible. In the circumstances, Q_2 calculated by $R \cdot q_1$ maybe be smaller than the approximate value which is square root of PCB's natural frequency.

When the input is random vibration, natural frequency of PCB is 86Hz, and natural frequency of case is 699.34Hz. According to the empirical formula, when PCB is excited at its natural frequency, the uncoupling transmissibility of PCB is $\sqrt{86} \approx 9.27$. The PCB should also be considered the additive energy which is gained from case coupling at 86Hz. And when forced frequency f_f is 86Hz, resonant frequency of case f_n is 699.34Hz, the ratio of forced frequency and resonant frequency of case R is 0.12, transmissibility of PCB can be calculated in equation (8)

$$Q = \frac{1}{1 - R^2} = 1.01 \, . \tag{8}$$

So the coupling transmissibility of PCB at 86Hz can be calculated by $Q_p = 1.01 \times 9.27 = 9.3627$, where Q_p represents coupling transmissibility.

The case's second resonance peak at 699.34Hz can be estimated. The uncoupling transmissibility of case is about 13.22. And the uncoupling transmissibility of PCB at 699.34Hz can be calculated by equation (8), the result is -0.0146. The minus means that the responses at 699.34Hz and 86Hz are in opposite direction. So coupling transmissibility of PCB at 699.34Hz is 0.193.

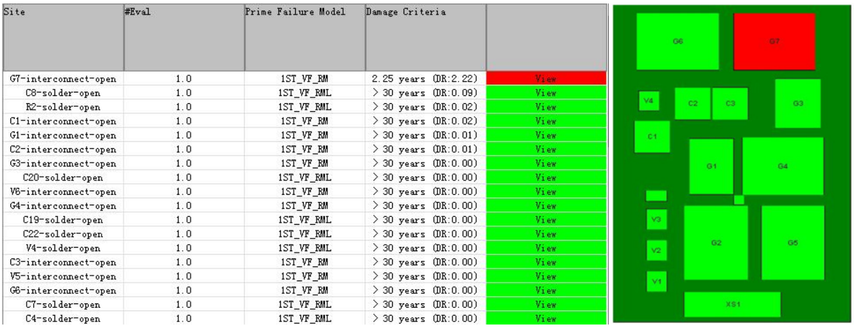
The PCB's resonance peaks at 86Hz and 699.34Hz are regarded as resonance peaks with single degree of freedom. Root mean square of the response in PCB's center is,

$$G_{RMS} = \sqrt{\frac{\pi}{2} \times 0.2 \times 86 \times 9.3627 + \frac{\pi}{2} \times 0.2 \times 699.34 \times 0.0146} = 16.005 \quad . \tag{9}$$

Relevant parameters of D10 and PCB are put into random vibration fatigue model. Fatigue life of component D10 is obtained as 2.45×10^{6} hours, which is smaller than 5.53×10^{7} hours which is estimated by CalcePWA. The result can be explained by slight coupling of PCB and case in random vibration condition. Fortunately, the coupling degree is low enough. So displacement of PCB is not over enlarged, and the decrease of PCB's fatigue life is unconspicuous. Because the design of PCB-A and case is in strict conformance with octave rule.

3.2 PCB and Case Disobey the Octave Rule

Another electronic device has two power modules, two input output interface modules and two interface cards. Modal analysis of the electronic device is conducted by ANSYS workbench software. Through analyzing, the first resonant frequency of case is 579.6Hz. The first resonant frequency of module B is 219.8Hz. And other modules' first resonant frequencies are over 1000 Hz. Natural frequencies of module B and its case do not obey the octave rule, which may result in dynamic coupling. By CalcePWA, there is no weak link under sinusoidal vibration. When the input is random vibration, result of vibration fatigue life calculated by CalcePWA is shown in Fig. 6 a), and the failure position is shown in Fig. 6 b).



Site	#Eval	Prime Failure Model	Damage Criteria	
G7-interconnect-open	1.0	1ST_VF_RM	2.25 years (DR:2.22)	View
C8-solder-open	1.0	1ST_VF_RML	> 30 years (DR:0.09)	View
R2-solder-open	1.0	1ST_VF_RML	> 30 years (DR:0.02)	View
C1-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.02)	View
G1-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.01)	View
C2-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.01)	View
G3-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.00)	View
C20-solder-open	1.0	1ST_VF_RML	> 30 years (DR:0.00)	View
V6-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.00)	View
G4-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.00)	View
C19-solder-open	1.0	1ST_VF_RML	> 30 years (DR:0.00)	View
C22-solder-open	1.0	1ST_VF_RML	> 30 years (DR:0.00)	View
V4-solder-open	1.0	1ST_VF_RML	> 30 years (DR:0.00)	View
C3-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.00)	View
V5-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.00)	View
G6-interconnect-open	1.0	1ST_VF_RM	> 30 years (DR:0.00)	View
C7-solder-open	1.0	1ST_VF_RML	> 30 years (DR:0.00)	View
C4-solder-open	1.0	1ST_VF_RML	> 30 years (DR:0.00)	View

a) Failure prediction of module B b) Potential failure location of module B

Fig. 6. Failure prediction of module B with CalcePWA

In Fig. 7, the ordinate axis represents the ratio between coupling transmissibility of module B and uncoupling transmissibility of case. The abscissa axis represents the ratio between natural frequencies of module B and case.

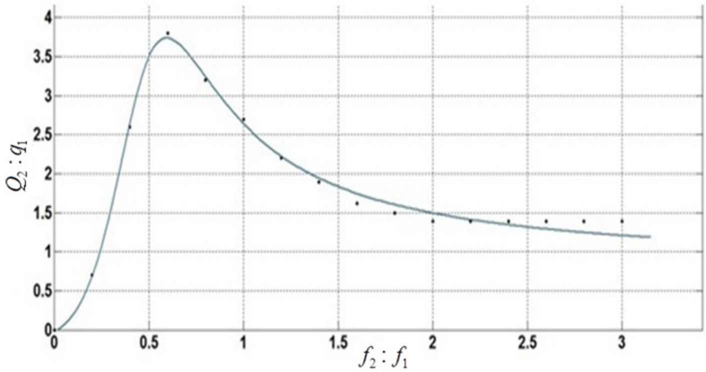


Fig. 7. The relation between two ratios

By using sinusoidal vibration fatigue model considering vibration coupling, fatigue life of G7 is calculated $N_2 = 1.15\times10^{12}$. It is slightly smaller than 1.5372×10^{12} which is the result from CalcePWA. Because the ratio of PCB's and case's natural frequency is about 1.5. They disobey the octave rule to some extent. The coupling effect can enlarge the displacement of PCB and shorten its fatigue lifetime. Seen from the Fig.7, frequencies' ratio 1.5 is at the edge of dangerous zone. Therefore, the reduction of fatigue lifetime is to a small extent.

Similarly, by using random vibration fatigue model, fatigue life of G7 considering vibration coupling is 411.37 hours. It is about a quarter of 1640 hours calculated by CalcePWA. PCB and case disobey the octave rule, so dynamic coupling effect quickly reduces components' fatigue life. If their natural frequencies are seriously contrary to octave rule, the effect of dynamic coupling will be more serious and the reducing of fatigue life will be more quickly.

4 Discussion and Conclusion

In this paper, fatigue lifetime of electronic devices is studied with Steinberg model considering transmissibility. The result is compared with that calculated by CalcePWA without considering vibration coupling. It is found that in sinusoidal vibration environment, lifetime considering vibration coupling is not always smaller than the lifetime without considering coupling. Only when the PCB and case seriously disobey octave rule, namely the ratio of their natural frequency is at dangerous zone, the calculation considering coupling is smaller. If the ratio of their natural frequency is away from dangerous zone, the calculation without considering coupling is smaller. In a general way, if the ratio of their natural frequency ranges from 0.75 to 1.25, it is defined as dangerous zone.

Compared with sinusoidal vibration, coupling in random vibration is more likely to enlarge the displacement of PCB. It is due to different characteristics of sinusoidal vibration and random vibration. In sinusoidal vibration, the natural frequencies of PCB and case are excited respectively. However in random vibration, they are excited simultaneously. If natural frequencies of PCB and case are more close to each other, they will disobey octave rule more seriously, and the effect of dynamic coupling will be more serious. Accordingly fatigue life is smaller than that without considering dynamic coupling, and the gap will be larger.

References

1. Dehbi, A., et al.: Vibration lifetime modelling of PCB assemblies using Steinberg model. Microelectronics Reliability 45(9-11), 1658–1661 (2005)
2. Markstein, W.H.: Designing electronics for high vibration and shock. Electron. Packag. Prod., 40(3) (1987)
3. Chin, I., et al.: A mechanical fatigue assessment methodology to study solder joint reliability. In: 2008 33rd IEEE/CPMT International. Electronic Manufacturing Technology Symposium (IEMT), Penang (2008)
4. Wu, M.L.: Vibration-induced fatigue life estimation of ball grid array packaging. Journal of Micromechanics and Microengineering 19(0650056) (2009)
5. Li, R.S.: A Methodology for Fatigue Prediction of Electronic Components Under Random Vibration Load. Journal of Electronic Packaging 123(4), 394–400 (1999)
6. Steinberg, D.S.: Vibration Analysis for Electronic Equipment, 3rd edn., p. 440. Wiley, New York (2000)
7. Chen, Y., Yang, L., Liu, B., Xue, D.: Applicability Study of Steinberg Vibration Fatigue Model in Electronic Products. In: IEEE 2014 Prognostics and System Health Management Conference, Zhangjiajie (2014)
8. Liu, F., Meng, G.: Random vibration reliability of BGA lead-free solder joint. Microelectronics Reliability 54(1), 226–232 (2014)
9. Chesné, S., Deraemaeker, A.: Damage localization using transmissibility functions: A critical review. Mechanical Systems and Signal Processing 38(2), 569–584 (2013)
10. Steenackers, G., Devriendt, C., Guillaume, P.: On the use of transmissibility measurements for finite element model updating. Journal of Sound and Vibration 303(3-5), 707–722 (2007)
11. 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
12. Manson, S.S.: Fatigue: a complex subject – some simple approximations. Exp. Mech. 5(3), 202 (1965)
13. Wang, D.: Study on simulation case of random vibration test at board level electronic products. Beihang University (2010)
14. Urgueira, A.P.V., Almeida, R.A.B., Maia, N.M.M.: On the use of the transmissibility concept for the evaluation of frequency response functions. Mechanical Systems and Signal Processing 25(3), 940–951 (2011)