SPECTRUM RESPONSE ANALYSIS FOR PCB WITH HEATING ICS IN DIFFERENT HEATING CONDITIONS

Bor-Tsuen Wang[1], Yau-Chang Lee[2], Yi-Shao Lai[3], Chang-Lin Yeh[3] ,Ying-Chih Lee[3]
[1]Professor, [2]Graduate Student
[1,2]Department of Mechanical Engineering
National Pingtung University of Science and Technology
[3]ASE GROUP Kaohsiung Stress-Reliability Lab
wangbt@mail.npust.edu.tw

ABSTRACT

Coupling effects of both thermal and vibration loadings on printed circuit board (PCB) are of interest. This paper aims to study the random vibration excitation of PCB with four heating ICs that are used to emulate the temperature elevation during operations. Two levels of heating conditions as well as without heating are considered in this work. The vibration tests according to JESD22-B103-B are carried out to measure the random vibration response of PCB under the conditions of both with and without heating. The finite element (FE) model of PCB with heating ICs is constructed and performed spectrum response analysis with and without thermal effects. The temperature distributions on PCB are first verified and shown good agreement between finite element analysis (FEA) and experiments. The power spectral density (PSD) functions of the acceleration on the PCB in heating are also obtained and compared for both FEA and experiments. The RMS accelerations on the PCB can be calculated and matched well between the analytical and experimental results. The fatigue evaluation due to coupling loadings from thermal and vibration effects on the PCB is also addressed. This work presents the systematic approaches in studying spectrum response analysis of PCB with both thermal and vibration coupling loads and shows a very good agreement results between FEA and experiments.

1. INTRODUCTION

Electronic devices become smaller and require high precision and performance. The printed circuit boards (PCBs) containing IC packages or electronic components subject to high temperature and environmental vibration effects are of concerns. The reliability of PCB regarding to thermal and vibration effects was drawn much attention in simulation to duplicate the dynamic behavior.

Yang *et al*. [1] applied experimental modal analysis (EMA) to calibrate the PBGA printed circuit board assemblies in different boundary conditions. They showed structural modal parameters can be affected by pre-stressed and fixture conditions. Wang and Tsao [2] combined finite element analysis (FEA) and EMA to perform model verification of a free-free rectangle plate. The validated FE model can be used for response prediction. Wang *et al*. [3] presented different FE modeling techniques to discuss the mass effect of accelerometer on PCB simulation analysis. Wang *et al*. [4] performed reproducibility test on a same PCB by two independent experiments to discuss the reliability of model verification of PCB. Results showed EMA is a reliable tools in calibrating the analytical model.

Wang *et al*. [5] conducted vibration tests on two PCBs with same specification to characterize the structural properties and performed spectrum response analysis to obtain acceleration and stress response for predicting possible area of fatigue failures. Wong *et al*. [6] experimentally studied the fatigue life and endurance of BGA solder joint subject to military vibration test standard. Yang *et al*. [7] applied FEA to obtain the vibration response of PBGA assemblies as well as observed by experiments. They found the fatigue failure may come from the solder joint at the four corners. Pitarresi *et al*. [8] focused on the theoretical and experimental analysis of personal computer motherboards. The simplified FE model is constructed to simulate the random vibration, only the lower modes dominating structural vibration response.

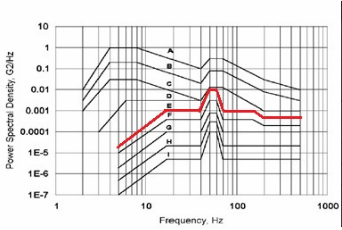
PCBs in high performance electronic device will encounter both environmental vibration as well as thermal effects. The coupling loadings of vibration and thermal effects on PCB are of interest. Wang *et al*. [9, 10] utilized the heating pad attached to the package to emulate the heating effect of ICs. Both FEA and EMA were conducted to validate the analytical model that can then be applied to response prediction in considering random excitation and elevated temperature. The heating pad is an additional component attached to the IC package and may not practically emulate the heating conditions. This paper presents the use of heating ICs mounted on the PCB for studying the compound loading effects of heating and random vibration.

This work considers a PCB with four heating ICs that can generate heat with direct current inputs to emulate the thermal effect of ICs on PCB. The JEDEC random vibration test [11] is conducted on the PCB for both with and without thermal effects. The finite element model of PCB is constructed to perform spectrum response analysis. The acceleration PSD can be obtained and compared with experimental data to validate the analytical solutions. The stress PSD can also be predicted and used for possible fatigue failure evaluation. This paper addresses the simulation techniques for PCB subject to random vibration and thermal loadings. The methodology for fatigue failure evaluation is also presented.

2. RANDOM VIBRATION TESTS OF PCB IN DIFFERENT HEATING CONDITIONS

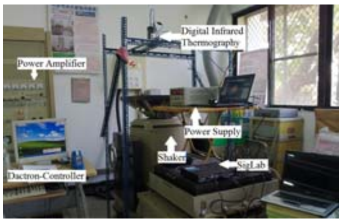
This work conducts the random vibration tests for the PCB with four heating ICs that are applied DC current to elevate the temperature in each ICs for emulating different heating conditions. Figure 1 shows the specification of random vibration test from JEDS-B103-B [11]. The E-Level is adopted in this work to perform random vibration test on the PCB with four heating ICs.

Figure 2(a) shows the experimental setup for random vibration test, while Figure 2(b) shows the PCB mounted on the fixture that is attached to the head expander of vibration test machine. The digital infrared thermograph (DIT) is used to capture the temperature distribution of PCB during tests. The accelerometer is applied on the PCB at Points A-E as shown in Figure 3 to record the acceleration response due to the random excitation in different heating conditions.

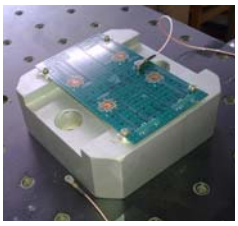


JEDEC Freq	E-level PSD(G^2/Hz)
5	0.00002
17	0.001
40	0.001
50	0.01
60	0.01
70	0.001
150	0.001
200	0.0005
500	0.0005

FIGURE 1. JEDEC STANDARD FOR RANDOM VIBRATION TEST [11]



(a) Experimental test equipments



(b) PCB on the fixture

FIGURE 2. EXPERIMENTAL SETUP FOR MODAL TESTING OF PCB

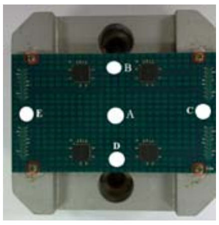
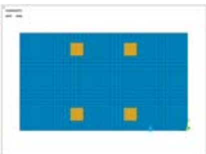
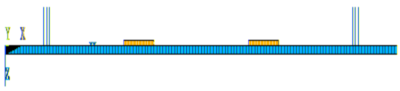


FIGURE 3. MEASUREMENT LOCATIONS ON THE PCB



(a) Top view



(b) Side view

FIGURE 4. FE MODEL FOR THE PCB WITH HEATING ICS IN FIXED BOUNDARY

This work considers both with and without heating for the PCB in random vibration tests. Three types of thermal conditions are no heating effect, ICs heated at 75℃ (with 5.3 V input) and 100℃ (with 6.7 V input). The PCB is heated until in steady state and carried out for random vibration test.

3. SPECTRUM RESPONSE ANALYSIS OF PCB SUBJECT TO RANDOM EXCITATION

This section presents the finite element modeling for the PCB with and without heated for the ICs subject to random excitation by adopting ANSYS software. The PCB due to the coupling effects of random vibration and thermal loadings are studied.

For the coupling loadings of thermal and random vibration on the PCB, the analysis can be divided into three steps. The first step is to perform thermal field analysis on the PCB with the heating effects in ICs so as to obtain the temperature distribution of PCB in steady state. The structural field analysis including the thermal deformation can then be carried out to obtain the pre-stressed condition of PCB with thermal effects. Finally, spectrum response analysis of PCB subject to random vibration excitation as shown in Figure 1 with pre-stressed effect due to thermal loading is activated to obtain the acceleration and stress power spectral density (PSD) functions for further evaluation.

In thermal field analysis, the 8-node brick conduction element (SOLID70) is adopted to construct the finite element (FE) model of PCB and heating ICs. The FE model neglecting the solder joints between ICs and PCB is built with 10564 elements and 21232 nodes as depicted in Figure 4. The ICs are specified as the constant temperature for both heating conditions at 75℃ and 100℃, respectively. The temperature distributions over the PCB can be predicted and compared with those measured by DIT. Table 1 shows the good agreement in comparison of temperature distributions of PCB between FEA and experiments when the four heating ICs are at 75℃.

In structural field analysis, the 8-node brick structural elements (SOLID45) are used to replace the conduction elements. The mounted boundary is simulated by the 3D spring element (COMBIN14), and the mass element (MASS21) is also applied at where the accelerometer is attached on the PCB to simulate the mass effect. Modal analysis is first performed to characterize the structural modal parameters that are used to carry out the spectrum response analysis by mode superposition method. When the thermal effect is considered, the pre-stressed option is turned on for both modal analysis and spectrum response analysis to include the thermal effect in vibration analysis. In particular, the E-level PSD distribution shown in Figure 1 is specified as the input for the simulation of random excitation. Table 2 shows the operational deflection shape (ODS) of the first three modes of PCB. There is only a slight difference on the structural natural frequencies for different heating conditions, and the ODSs reveal similar. The measurement points as shown in Figure 3 are selected base on the maximum response of each ODS.

TABLE 1. HEATING ICS : 5.3 V (75℃) TEMPERATURE DISTRIBUTION FOR PCB

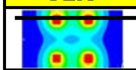
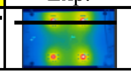
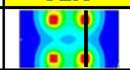
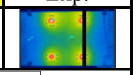
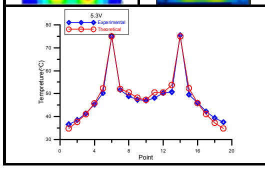
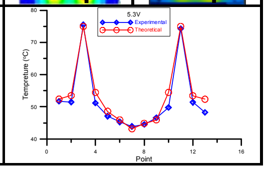
(1) horizontal		(2) vertical	
FEA	Exp.	FEA	Exp.
			
			

TABLE 2. ODS FOR PCB

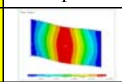
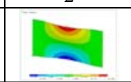
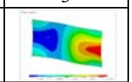
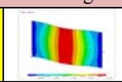
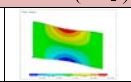
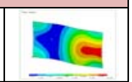
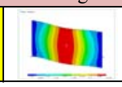
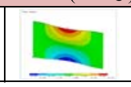
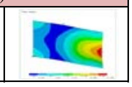
No Heating			
mode	1	2	3
ODS			
Heating ICs : 5.3 V (75℃)			
ODS			
Heating ICs : 6.7 V (100℃)			
ODS			

TABLE 3. ACCELERATION PSD RESPONSE FOR THE PCB WITH THERMAL AND RANDOM VIBRATION LOADINGS

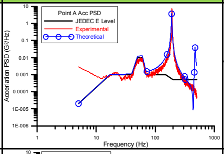
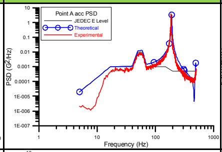
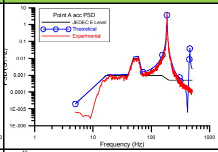
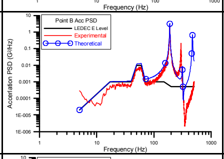
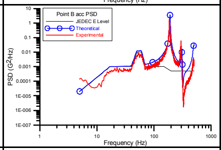
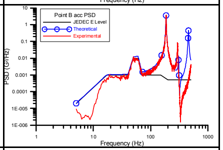
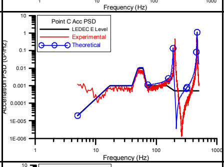
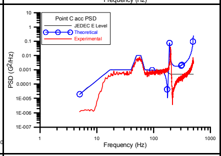
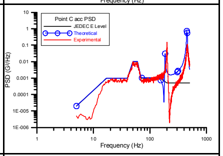
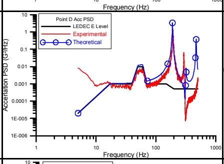
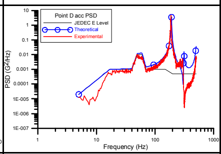
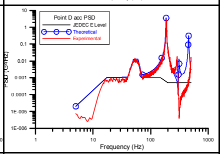
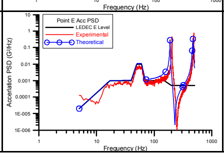
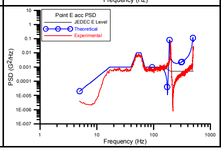
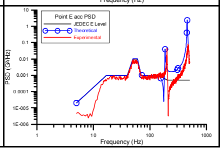
Pt	No heat effect	Heating ICs : 5.3 V (75℃)	Heating ICs : 6.7 V (100℃)
A			
B			
C			
D			
E			

TABLE 4. ACCELERATION RMS VALUES ON PCB

Point	No Heating		Heating ICs : 5.3V (75℃)		Heating ICs : 6.7V (100℃)	
	FEA (g)	EMA (g)	FEA (g)	EMA (g)	FEA (g)	EMA (g)
A	4.34	4.33	4.21	3.83	4.41	4.21
B	4.46	3.60	4.38	3.24	4.97	4.09
C	3.19	2.44	2.03	1.81	3.84	2.72
D	4.56	3.13	4.38	4.03	4.75	3.84
E	2.25	2.68	2.03	1.92	4.07	2.28

4. RESPONSE PREDICTION AND VERIFICATION OF PCB SUBJECT TO RANDOM EXCITATION IN DIFFERENT HEATING CONDITIONS

The PCB acceleration responses due to random vibration and with different heating conditions are studied in this section. Both simulation and experimental measurement data are compared and verified for response prediction by FEA. Table 3 shows the acceleration PSD functions at different locations as well as different heating conditions. Table 4 summarizes the acceleration rms value a_{rms} that are computed as follows:

$$a_{rms} = \sqrt{\int_{f_1}^{f_2} G_{aa}(f)df} = SD_a \qquad (1)$$

where $G_{aa}(f)$ is the acceleration PSD function on the monitored point; SD_a is the standard deviation and equal to a_{rms} for zero mean; f_1 and f_2 are lower and upper bounds of frequency range, i.e. 5-500 Hz as shown in Figure 1 for E-level. Note that Equation (1) is also valid for stress evaluation to obtain stress rms and standard deviation values.

From Tables 3 and 4, some observations and discussions are as follows:

1. Three curves of acceleration PSDs are shown in each plot. The theoretical PSD is nearly overlapped with the base excitation spectrum at low frequency range and appears two or three peak values due to structural resonances. The prediction for acceleration PSD is reasonable.
2. At Point A right on the center of PCB where is the maximum response of the first mode and near the nodal points for the second and third modes, the peak values of acceleration PSD appear at the first mode as expected.
3. One can observe Points B and D, as shown in Figure 3 and referred to Table 2, are not nodal points for the first three modes; therefore, there are three peak values of acceleration PSD at Points B and D.
4. There are only two peak values of acceleration PSD at Points C and E because they are right on the nodal points of the second mode.
5. One can observe that the experimental acceleration PSDs generally match very well with the theoretical ones. The acceleration rms values obtained from FEA and experiments also agree very well as shown in Table 4.

5. FATIGUE FAILURE ANALYSIS AND PREDICTION

Previous section shows the response prediction for acceleration PSDs and rms values in comparison with those from experiments and reveals good verification between FEA and experiments. This section will present the methodology for fatigue failure analysis of PCB subject to random excitation, especially with thermal coupling loadings.

As shown in Equation (1), the rms and standard deviation values can be obtained from the PSD function for zero mean condition. Figure 5 shows the probability density function of normal distribution of a random process and reveals the percentages for different ranges. There contains 99.7% for three times of standard deviation ranges. The maximum and minimum stress values can be reasonably assumed as follows:

$$\sigma_{\max} = 3SD_\sigma = 3\sigma_{\text{rms}} \qquad (2)$$

$$\sigma_{\min} = -3SD_\sigma = -3\sigma_{\text{rms}} \qquad (3)$$

Figure 6 shows the Goodman line for the evaluation of fatigue failure of the PCB subject to random excitation. The horizontal axis is for the mean stress, and the vertical axis is for the stress amplitude. The Goodman line is defined by the material endurance limit (S_e) and ultimate strength (S_{ut}). For the random response of PCB, the mean stress σ_m and stress amplitude σ_a can be obtained as follows:

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} = 3SD_\sigma = 3\sigma_{\text{rms}} \qquad (4)$$

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} = 0 \qquad (5)$$

If the combination of mean stress and stress amplitude is located below the Goodman line, there is no fatigue failure, and vice versa.

Table 5 shows the typical principal stress (σ_1) and von Mises stress (σ_{eqv}) distributions for PCB with thermal and random vibration loadings. The maximum stress values appear as shown in Points I and II. Table 6 shows stress PSD functions for different heating conditions as well as the maximum and minimum stress values from Equations (2) and (3). One can observe the high stress area is near the fixed boundary.

6. CONCLUSIONS

This work presents the simulation techniques for the PCB subject to coupling loadings of thermal effect and random excitation and verifies the simulation results with those from experiments. The simplified FE model consisting of the PCB and heating ICs is constructed to simulate the thermal effect to determine the temperature distribution and validated by experimentally captured thermograph. The structural field responses due to random excitation according to JEDEC vibration test with and without thermal effects are also obtained and compared with experimentally measured acceleration response. Results show the acceleration PSD and rms values agree very well. The validated structural model can then be adopted to evaluate the fatigue failure by Goodman line. This work lays out the methodology for the study of PCB in random vibration test in conjunction with thermal loadings from heating ICs. Possible fatigue failures can also be predicted through simulation and useful for PCB design.

REFERENCES

[1] Yang, Q. J., Lim, G. H., Lin, R. M., Yap, F.F., Pang, H. L. J. and Wang, Z. P., 1997, "Experimental Modal Analysis of PBGA Printed Circuit Board Assemblies," *IEEE/CPMT Electronic Packaging Technology Conference*, pp. 290-296.

[2] Wang, B. T., and Tsao, W. C., 2002, "Application of FEA and EMA to Structural Model Verification," *The Tenth National Conference on the Society of Sound and Vibration*, pp. 131-138. (In Chinese)

[3] Wang, B. T., Tao, C. C., Lai, Y. S., Yeh, C. L., and Li, Y. C., 2007, "Evaluation and Verification of Accelerometer Mass Effect on Theoretical Simulation," *The 15th National Conference on Sound and Vibration*, Taipei, Paper No.: B-12. (in Chinese)

[4] Wang, B. T., Tsai, Y. Y., Li, Y. C., Lai, Y. S., and Yeh, C. L., 2006, "Reproducibility of Experimental Modal Survey on a Printed Circuit Board," *The 30th National Conference on Theoretical and Applied Mechanics*, Changhwa, Taiwan, Paper No.: H2-6. (in Chinese)

[5] Wang, B. T., Tao, C. C., Lee, P. W., Lai, Y. S., Yeh, C. L., and Li, Y. C., 2007, "Repeatability Discussions on Model Verification and Response Prediction of Printed Circuit Board," *Proceedings of 2007 Taiwan ANSYS/Fluent User's Conference*, Taoyuen, pp. 15-30. (In Chinese)

[6] Wong, T. E., Palmieri, F. W., and Fenger, H. S., 2002, "Under-filled BGA Solder Joint Vibration Fatigue Damage," *Thermal and Thermomechanical Phenomena in Electronic Systems*, California, pp.961-966.

[7] Yang, Q. J., Pang, H. L. J., Wang, Z. P., Lim, G. H., Yap, F. F., and Lin, R. M., 2000, "Vibration Reliability Characterization of PBGA Assemblies," *Microelectronics Reliability*, Vol. 40, pp.1097-1107.

[8] Pitarresi, J., Geng, P., Beltman, W., and Ling, Y., 2002, "Dynamic Modeling and Measurement of Personal Computer Motherboards," *Electronic Components and Technology Conference*, San Diego, pp.597-603.

[9] Wang, B. T., Hsu, F. X., Liang, X. W., Hung, C. H., Lai, Y. S., Yeh, C. L., and Li, Y. C., 2009, "Response Prediction and Verification for PCB with Package due to Thermal and Random Vibration Coupling Effects," *The 4th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT 2009)*, Taipei, Taiwan, Paper No.: TW135-1, pp.401-404.

[10] Wang, B. T., Liang, X. W., Hsu, F. X., Lai, Y. S., Yeh, C. L., Lee, Y. C., 2010, "A Refined Finite Element Model Verification for IC Packaged PCB with Thermal Effects," *The 5th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT2010)* , Taipei, Taiwan, Paper No.: TW159-1.

[11] JEDEC, 2001, *JESD22-B103-B: Vibration, Vibration Frequency*, JEDEC Solid State Technology Association.

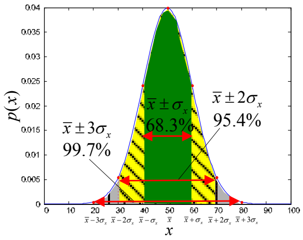


FIGURE 5. ILLUSTRATION OF NORMAL DISTRIBUTION

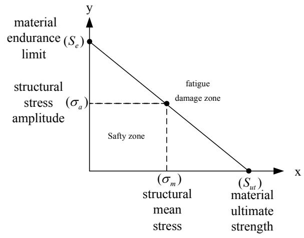


FIGURE 6. ILLUSTRATION OF GOODMAN LINE FOR FATIGUE EVALUATION

TABLE 5. STRESS DISTRIBUTIONS FOR PCB WITH THERMAL AND RANDOM VIBRATION LOADINGS

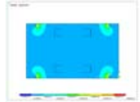
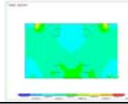
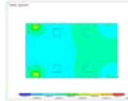
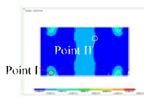
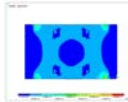
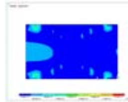
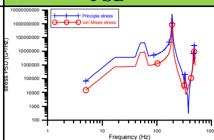
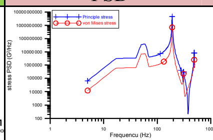
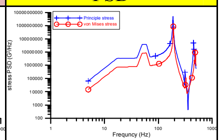
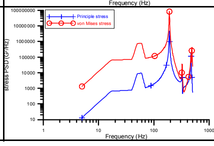
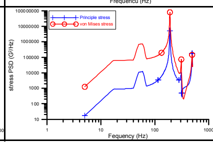
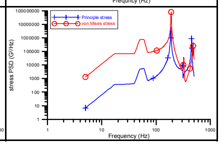
ODS \ Mode	Mode 1	Mode 2	Mode 3
σ_1			
σ_{eqv}			

TABLE 6. PREDICTION OF STRESS PSD, RMS VALUES AND RANGES FOR PCB WITH THERMAL AND RANDOM VIBRATION LOADINGS

(a) Stress PSD

pt	No heating	Heating ICs : 5.3 V (75℃)	Heating ICs : 6.7 V (100℃)
	PSD	PSD	PSD
I			
II			

(b) Stress values (KPa)

Point	$\sigma_{1,rms}$	$\sigma_{eqv,rms}$	$\sigma_{1,max}$	$\sigma_{eqv,max}$
No Heat				
I	164.84	70.05	494.52	210.15
II	5.01	21.17	15.03	63.51
Heating ICs : 5.3 V (75℃)				
I	155.42	62.12	466.26	186.36
II	5.44	20.86	16.32	62.58
Heating ICs : 6.7 V (100℃)				
I	160.27	70.05	480.81	210.15
II	6.42	21.17	19.26	63.51