A Refined Finite Element Model Verification for IC Packaged PCB with Thermal Effects†

Bor-Tsuen Wang[1]*, Xiu-Wei Liang[1], Fu-Xiang Hsu[1], Yi-Shao Lai[2], Chang-Lin Yeh[2], Ying-Chih Lee[2]
[1] Department of Mechanical Engineering, National Pingtung University of Science and Technology
[2] Central Product Solutions, Advanced Semiconductor Engineering, Inc.
*Email: wangbt@mail.npust.edu.tw

Abstract

A reliable and accurate analytical model is desired for the printed circuit board (PCB) with IC package to predict the system response due to loadings such as shock and vibration simulation or even with thermal effect. This work addresses the procedure of model verification by the adoption of experimental modal analysis (EMA) to validate the finite element (FE) model constructed by FE commercial software. The PCB with one package adhered with the heating pad to emulate the heat effect is first considered for completely free boundary condition. The refined FE model of the PCB consists of detail components, such as the chip, substrate, compound and solder balls. The thermal effect on the PCB is simulated to conduct the temperature field analysis as well as the thermal stress. The modal analysis on the PCB with the heating in steady state is then performed to obtain the structural modal parameters, i.e. natural frequencies and mode shapes. The EMA is also carried out to determine the system modal properties that are used to update the analytical FE model. Through the comparison of frequency response functions and modal parameters between the analytical FE model and the real PCB structure, the refined FE model can be verified for material properties and thermal boundary conditions. The same procedure for model verification is then conducted via both EMA and FEA on the PCB in the fixed boundary that complies with the test fixture for the random vibration test of JEDEC specification. The verified equivalent FE model of the PCB can then be adopted to perform spectrum response analysis accordingly.

Keywords: Finite element; Experimental modal analysis; Printed circuit board; Vibration; Thermal

1. Introduction

Various kinds of electronic devices become popular and demand high quality and reliability. The printed circuit boards (PCBs) that are the major components of 3C products become smaller and more strictly encountered severe environments such as shock and vibration as well as thermal effects due to operating condition or even in transportation. The PCBs subject to thermal and vibration coupling loadings can be expected. This work aims to deal with the analysis for the vibration characteristics of PCBs with thermal effects. In particular, this paper addresses the idea of model verification by the integration of finite element analysis (FEA) and experimental modal analysis (EMA) to construct the reliable FE model of PCBs considering the thermal effect. Therefore, the analytical model can be utilized for further analysis such as the coupling loadings of random excitation and thermal inputs.

The analytical approach is of great interest in PCB design, specially regarding to environmental vibration excitation. FEA is a fine tool but needs careful validation procedure to ensure the correctness of simulation. EMA is the commonly used technique in engineering structural design and can also be applied to PCB study as well as other electronic products. Gibson and Wen [1] tested three types of composite plates in free boundary and found that using flexible strings to suspend the plates can reasonably emulate the boundary condition and result in good validation of structural modal properties. Yang *et al.* [2] conducted EMA on the PBGA PCB assemblies in different boundaries and showed the effect of transducer's mass on the accuracy of measuring structural natural frequencies. Wang *et al.* [3] also presented different FE modeling methods to study the simulation of accelerometer mass and found that the mass elements distributed covering the sensor area can practically match the real structure.

The board level testing for PCBs has been regulated by JEDEC [4], especially for random vibration tests. The analytical study of PCB under vibration test is desired and required the validation of theoretical models. Wang *et al.* [5] combined the FEA and EMA to verify the FE model of PCB by matching the theoretically and experimentally obtained modal parameters. The simplified PCB FE model was validated and used for response prediction due to random vibration excitation. Wu *et al.* [6] also performed

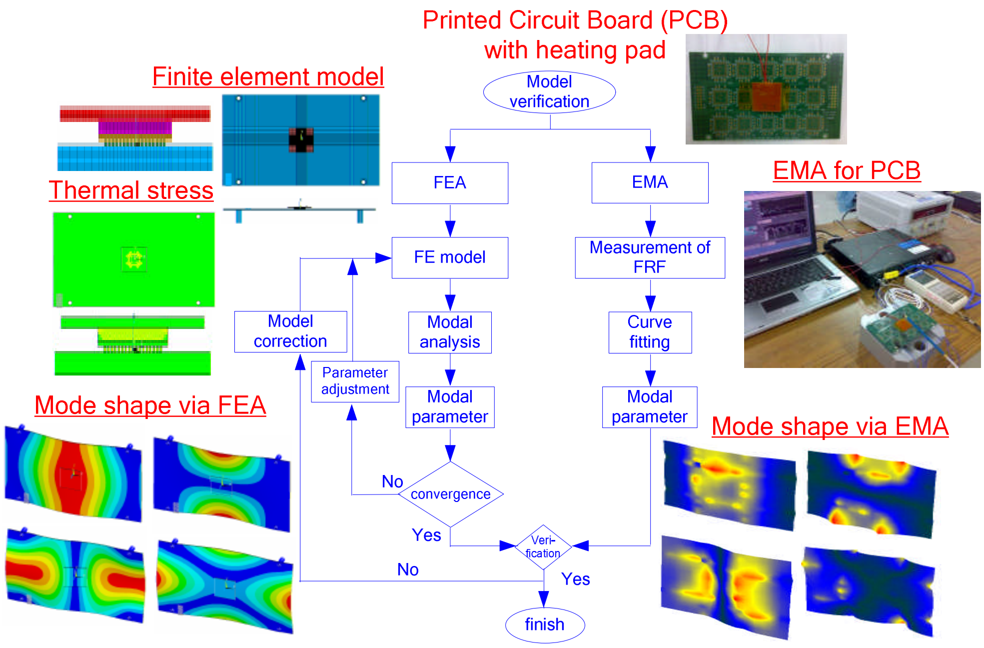


Fig. 1: Model verification procedure for PCB

FEA and EMA on medical devices to calibrate the FE model for vibration study. Wang *et al.* [7] used the microphone instead of the accelerometer as the sensor for EMA to calibrate the PBGA FE model that was integrated with PCB for further analysis. Wang *et al.* [8] presented the analysis for PCB with different numbers of IC packages in simulating the stress fields under random vibration tests. The single packaged PCB resulted in higher stress concentration near the package than those of others. Pitarresi *et al.* [9] conducted mechanical excitation and measured random vibration response for finding the equivalent FE model of personal computer mother boards.

The random vibration induced fatigue failure for PCB is also of concern. Wang *et al.* [10] experimentally measured the acceleration and strain on the PCB during vibration tests. The theoretical simulation was also conducted and shown reasonable agreement. They also presented the fatigue failure evaluation by adopting Goodman diagram under the assumption of normal distribution for structural random response. Wang *et al.* [11] constructed the simplified model of PCB neglecting package details for the spectrum response analysis with random vibration and thermal effects. The simple FE model was verified by EMA and utilized for response prediction. This paper builds the refined model for the PCB including details of packages and shows the model verification results.

The adoption of FEA and EMA techniques to validate the PCB analytical model that can be useful for response prediction is quite promising. This work will present the idea and procedure for model verification of PCB in Section 2. The refined FE model of the PCB consisting of detail components is built for theoretical modal analysis (TMA) for both free and fixed boundaries, respectively in Sections 3 and 4, in considering thermal loading with heating effect. The EMA for the PCB with thermal effects are also carried out. By the comparison of theoretical and experimental modal parameters, the PCB FE model can be validated and applied for further analysis, such as response prediction due to random excitation as well as thermal effects.

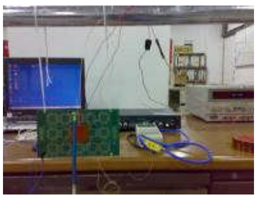
2. Model Verification

Fig. 1 shows the flow chart and basic principle for model verification by the integration of FEA and EMA. In FEA, the FE model of PCB is properly constructed according to the need of analysis objectives. In this work, the refined model is built and consists of details of IC package, including IC, substrate, solder balls and the specially designed heating pad that is adhered on the top of package to heat the PCB for the thermal input with constant temperature in steady state. Since the PCB FE model is aimed to be used for random vibration response simulation in fixed boundary, the model verification for free boundary is first conducted to calibrate the material constants. The fixed boundary model of PCB is then constructed to validate the spring constants for modeling the fixed boundary.

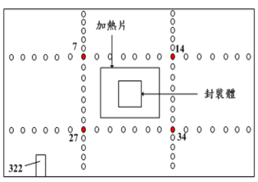
For experiments, the conventional EMA was carried out to measure the structural frequency response functions (FRFs) that are applied to do curve-fitting for determining the structural modal parameters. Then, both theoretically and experimentally obtained modal data can be compared. If they are matched to each others, the analytical FE model can be considered equivalent to the practical structure. The convergence of FE model and model correction may be required to update and calibrate the analytical model. The main idea and benefit of model verification are the modal data is compared, i.e. the system model information is independent of system input and output. Through the model verification, the equivalent analytical FE model can be calibrated properly and used for further response prediction, such as random excitation and thermal coupling loadings.

This work considers the IC packaged PCB with heating effect. The theoretical modal analysis on the PCB with thermal input is conducted. The thermal field analysis needs to be analyzed first, and then the structural modal analysis can be performed including the pre-stress effect of thermal deformation determined from thermal analysis. By examining the temperature comparison between analysis and experimental results, the thermal boundary conditions can also be calibrated.

This work performs the conventional EMA procedure for the PCB experiments. Figs. 2(a) and 2(b) shows the experimental setup for PCB EMA in free and fixed boundaries, respectively, while Fig. 2(c) reveals the 80 measurement grid points.



(a) (b)



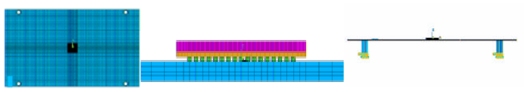
(c)

Fig. 2: Experimental setup for EMA of PCB: (a) for free boundary; (b) for fixed boundary; (c) grid points for EMA

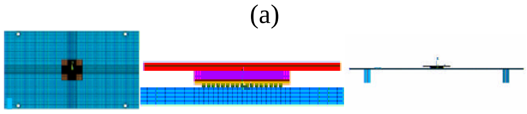
The impact hammer is used as the actuator to excite the PCB, while the accelerometer is fixed at the corner to measure the response. A series of FRFs from the impact modal testing can be obtained and used to extract the modal parameters by curve-fitting software, ME'ScopeVES. The PCBs with and without the heating pad are tested, respectively. Different heating temperatures were controlled by charging the heating pad at different levels of voltage inputs and used to heat the PCB for thermal effects emulation. The effect of thermal input on the PCB vibration characteristics is theoretically studied and compared with the experiments.

3. Model Verification of PCB with Thermal Effects in Free Boundary

Since this work aims to study the vibration characteristics of the PCB with the thermal input by the adhered heating pad on the top of packages as shown in Fig. 3, the analytical procedures involve several steps to validate the FE model in conjunction with EMA experiments. The FE model for the structural field analysis is first constructed for both the PCB without and with the heating as shown in Figs. 3(a) and 3(b), respectively. The eight-node brick element (SOLID45) is used to build the detail geometry of IC packaged PCB, while the mass element (MASS21) is used for the simulation of accelerometer mass at the bottom left corner. The EMA for both the PCB without and with heating pad is, respectively, conducted to validate the FE model. At the first stage of model verification, material constants for the IC packaged PCB can be calibrated. Especially, the heating pad modeling can also be verified.



(a)



(b)

Fig. 3: FE models for PCB: (a) without heating pad; (b) with heating pad

Tables 1 and 2 show the comparisons of natural frequencies and mode shapes between EMA and FEA for the PCB without thermal effects in free boundary. That the natural frequency errors are generally less than 3% indicates the calibration of model material constants being very good. In addition, the PCB with the heating pad has the additional mass effect and results in the smaller natural frequencies in general. Figs. 4(a) and 4(b) show the FRFs comparisons obtained from FEA and EMA and reveal reasonable agreement. For the implement of thermal effect, the heating pad is heated at constant temperature at 75^{o}C.

Table 1: Comparison of natural frequencies for PCB without thermal effects in free boundary

(a) PCB without heating pad

EMA		FEA		Freq. Error (%)
Mode	Natural Freq. (Hz)	Mode	Natural Freq. (Hz)	
E-01	118.08	F-01	115.15	-2.481
E-02	157.38	F-02	156.73	-0.413
E-03	288.56	F-03	280.15	-2.914
E-04	426.01	F-04	429.39	0.793
E-05	454.32	F-05	452.67	-0.363

(b) PCB with heating pad

EMA		FEA		Freq. Error (%)
Mode	Natural Freq. (Hz)	Mode	Natural Freq. (Hz)	
E-01	118.6	F-01	115.40	-2.701
E-02	149.16	F-02	151.56	1.609
E-03	283.62	F-03	278.90	-1.663
E-04	421.39	F-04	426.34	1.175
-	-	F-05	443.22	-
E-05	519.52	F-06	507.35	-2.343

Table 2: Comparison of mode shapes for PCB without thermal effects in free boundary

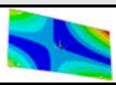
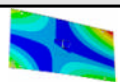
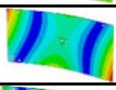
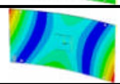
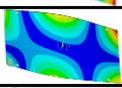
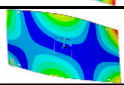
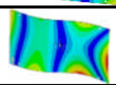
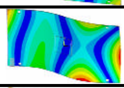
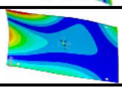
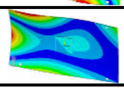
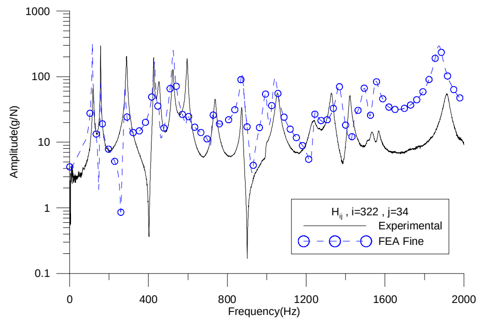
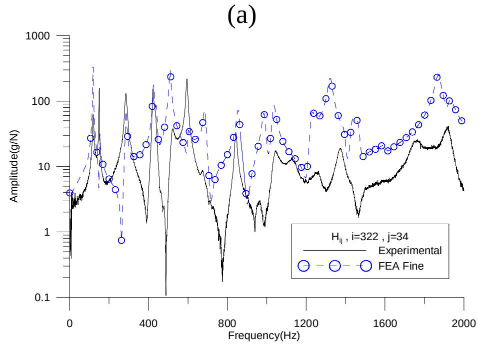
PCB without heating pad		PCB with heating pad	
Mode	mode shape	Mode	mode shape
F-01		F-01	
F-02		F-02	
F-03		F-03	
F-04		F-04	
F-05		F-06	

Table 3 shows the temperature fields distributions from experiments and FEA, respectively. For thermal field analysis, the FE model shown in Fig. 3(b) is adopted. The eight-node brick conduction element (SOLID70) is used to perform steady state thermal analysis. From Table 3, one can observe that both experimental and FEA temperature curves coincide to each others. In this stage, the thermal boundary specified in the FE model for thermal analysis can be calibrated. The free convection coefficient for all surfaces on the PCB is $h_f = 22(\mathrm{W/m^2 \cdot K})$, and the bulk temperature is 27°C.

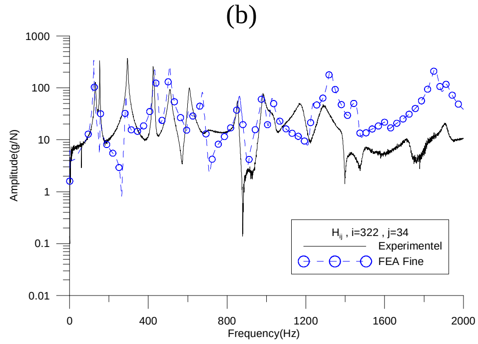
The PCB with thermal deformation due to the heating can then be included as the pre-stress effect for structural modal analysis. The modal characteristics of the PCB with the heating effect can be determined and compared with those from EMA. Table 4 shows the comparison of modal parameters for the PCB with the heating pad at 75°C in free boundary, and Fig. 4(c) is the



(a)



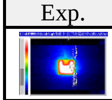
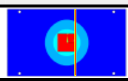
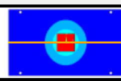
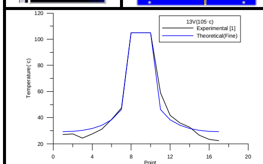
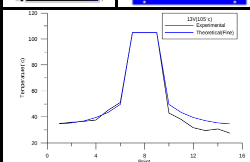
(b)



(c)

Fig. 4: FRF comparison for PCB in free boundary: (a) without heating pad; (b) with heating pad; (c) with heating pad at 75°C

Table 3: Temperature comparison for PCB with heating pad and thermal effect (75°C) in free boundary

Exp.	FEA	Exp.	FEA
			
			

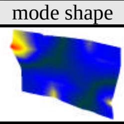
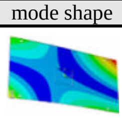
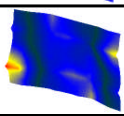
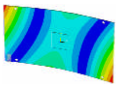
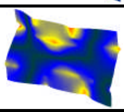
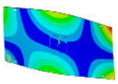
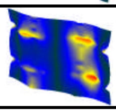
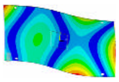
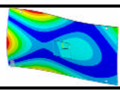
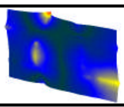
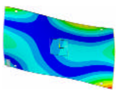
FRF comparison. Results show the natural frequencies agree well except mode F-05 is not measured in EMA, and the mode shapes obtained from EMA and FEA correspond to each others for the MAC values are mostly near 1. It is noted that the MAC value is between 0 and 1 for estimating the similarity of two vectors. The MAC value equals to 1 means two mode shape vectors are in perfect match and 0 means the two mode shapes are in orthogonal. One can also observe both FRFs obtained from FEA and EMA match very good in Fig. 4(c). In this stage of model verification, the structural and thermal field coupling effects are again validated and shown very good calibration of system model parameters as well as thermal boundary conditions.

Table 4: Comparison of modal parameters for PCB with heating pad and thermal effect (75°C) in free boundary

(a) Natural frequencies

EMA		FEA		Freq. Error (%)
Mode	Natural Freq. (Hz)	Mode	Natural Freq. (Hz)	
E-01	129.53	F-01	122.31	-5.574
E-02	152.78	F-02	155.52	1.793
E-03	293.70	F-03	285.57	-2.768
E-04	424.08	F-04	431.22	1.684
-	-	F-05	446.71	-
E-05	510.28	F-06	507.99	-0.449

(b) Mode shapes

EMA		FEA		MAC
Mode	mode shape	Mode	mode shape	
E-01		F-01		0.95
E-02		F-02		0.93
E-03		F-03		0.95
E-04		F-04		0.77
-	-	F-05		-
E-05		F-06		0.78

4. Model Verification of PCB with Thermal Effects in Fixed Boundary

Through the above model verification procedure step by step in Section 3, the geometry and material constants of the system model as well as the thermal boundaries can be well calibrated for the PCB in free boundary. Next, the above procedures are applied again in the fixed boundary. From the side view of Fig. 3, there are spring elements applied at the corners of PCB to simulate the boundary conditions for screwing. The model verification of the PCB FE model has been well validated in free boundary. For practical random vibration testing, the PCB is fixed at the fixture as shown in Fig. 2(b). The calibration of spring constants for those spring elements in the fixed boundary is required to ensure the analytical model suitable for future application to spectrum response analysis. This section shows the step-by-step results to convey the idea and process of model verification.

The PCB without thermal effects in fixed boundary is first studied. Tables 5 and 6 show the comparison of natural frequencies and mode shapes up to the frequency range about 500 Hz that is the highest frequency in random vibration test. The natural frequency errors between EMA and FEA are lest than 2% for the PCB without the heating pad and 5% for with the heating pad. The PCB reveals typical plate mode shapes as shown in Table 6.

Table 5: Comparison of natural frequencies for PCB without thermal effects in fixed boundary

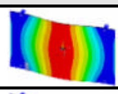
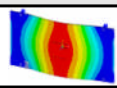
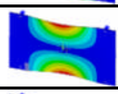
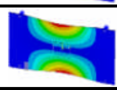
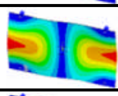
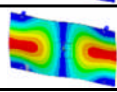
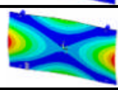
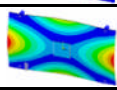
(a) PCB without heating pad

EMA		FEA		Freq. Error (%)
Mode	Natural Freq. (Hz)	Mode	Natural Freq. (Hz)	
E-01	192.02	F-01	191.65	-0.208
E-02	298.1	F-02	298.89	0.265
E-03	461.9	F-03	465.65	0.812
E-04	507.48	F-04	499.78	-1.517

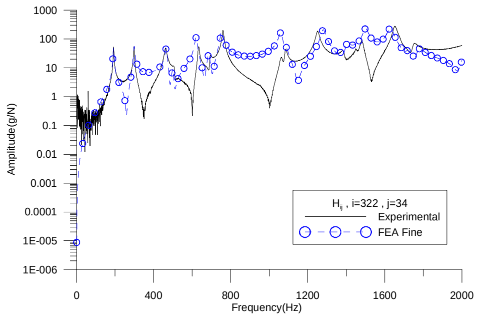
(b) PCB with heating pad

EMA		FEA		Freq. Error (%)
Mode	Natural Freq. (Hz)	Mode	Natural Freq. (Hz)	
E-01	162.99	F-01	169.71	4.123
E-02	287.93	F-02	291.67	1.299
E-03	447.71	F-03	455.76	1.798
E-04	514.32	F-04	494.32	-3.889

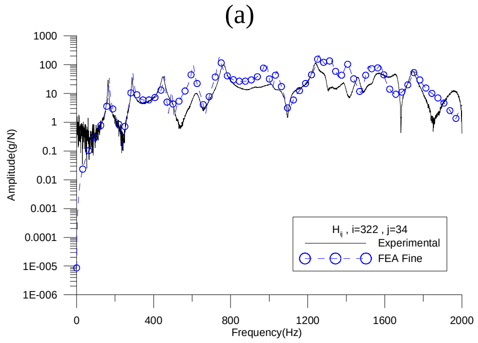
Table 6: Comparison of mode shapes for PCB without thermal effects in fixed boundary

PCB without heating pad		PCB with heating pad	
Mode	shapes	Mode	shapes
F-01		F-01	
F-02		F-02	
F-03		F-03	
F-04		F-04	

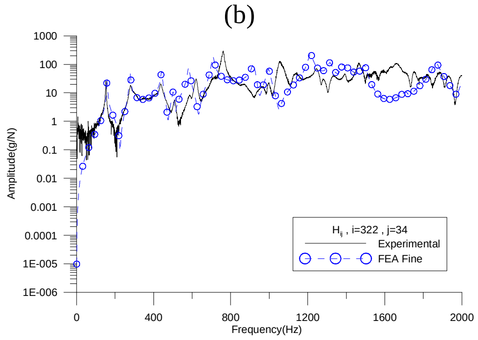
Figs. 5(a) and 5(b) show the FRF comparisons for both the PCB without and with the heating pad. The agreement of FRFs between FEA and EMA is very good up to 1000 Hz, though there is a little discrepancy at high frequency range. At this stage, the boundary spring constants can be calibrated for the FE model of fixed conditions.



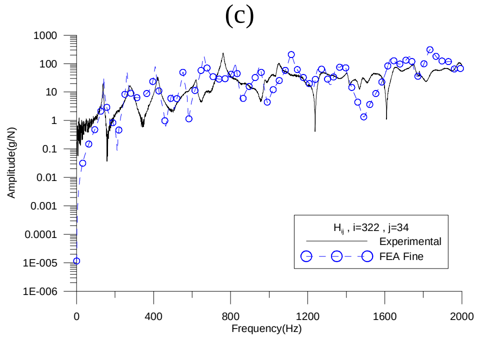
(a)



(b)



(c)



(d)

Fig. 5: FRF comparison for PCB in fixed boundary: (a) without heating pad; (b) with heating pad; (c) heating at 75°C; (d) heating at 125°C

The PCB without thermal effects in fixed boundary is first studied. Tables 5 and 6 show the comparison of natural frequencies and mode shapes up to the frequency range about 500 Hz that is the highest frequency in random vibration test. The natural frequency errors between EMA and FEA are lest than 2% for the PCB without the heating pad and 5% for with the heating pad. The PCB reveals typical plate mode shapes as shown in Table 6. Figs. 5(a) and 5(b) show the FRF comparisons for both the PCB without and with the heating pad. The agreement of FRFs between FEA and EMA is very good up to 1000 Hz, though there is a little discrepancy at high frequency range. At this stage, the boundary spring constants can be calibrated for the FE model of fixed conditions.

The PCB with the heating pad heated at 75°C and 125°C are studied, respectively. Table 7 shows the temperature comparisons between experiments and FEA and reveals very good agreement. The thermal field analysis in the fixed boundary is again validated and can be included for structural modal analysis for the pre-stress effect of thermal deformation.

Table 7: Temperature comparison for PCB with heating pad and thermal effects in fixed boundary

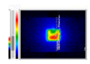
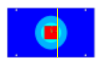
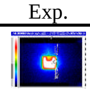
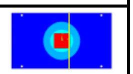
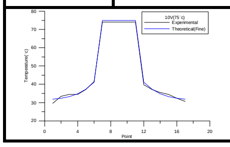
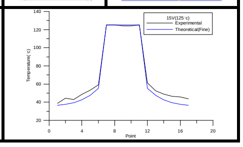
(a) heating pad at 75°C			(b) heating pad at 125°C	
Exp.	FEA		Exp.	FEA
				
				

Table 8 shows the comparisons of natural frequencies. One can see that the natural frequency errors are within 4% at 75°C and 5.17% at 125°C.

Table 8: Comparison of natural frequencies for PCB with heating pad and thermal effects in fixed boundary

(a) heating at 75°C

EMA		FEA		Freq. Error (%)
Mode	Natural Freq. (Hz)	Mode	Natural Freq. (Hz)	
E-01	152.5	F-01	158.47	3.915
E-02	280.49	F-02	277.56	-1.045
E-03	436.13	F-03	441.73	1.284
E-04	509.23	F-04	502.09	-1.402

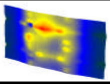
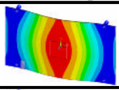
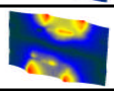
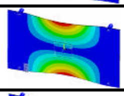
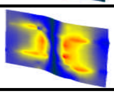
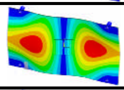
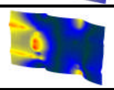
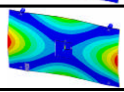
(b) heating at 125°C

EMA		FEA		Freq. Error (%)
Mode	Natural Freq. (Hz)	Mode	Natural Freq. (Hz)	
E-01	136.22	F-01	141.81	4.10
E-02	276.48	F-02	261.53	-5.41
E-03	419.55	F-03	408.32	-2.68
E-04	524.43	F-04	497.6	-5.17

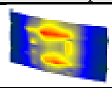
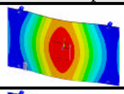
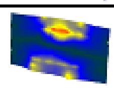
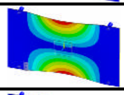
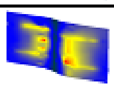
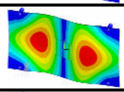
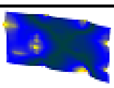
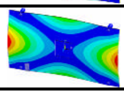
Table 9 reveals the mode shape comparisons corresponding to those modes in Table 8. From the MAC values and the mode shape pictures, the modal characteristics agree reasonably well. Figs. 5(c) and 5(d) also reveal the good prediction of FRFs matching well with those from EMA.

Table 9: Comparison of mode shapes for PCB with heating pad and thermal effects in fixed boundary

(a) heating at 75°C

EMA		FEA		MAC
Mode	Mode shapes	Mode	Mode shapes	
E-01		F-01		0.86
E-02		F-02		0.89
E-03		F-03		0.94
E-04		F-04		0.72

(b) heating at 125°C

EMA		FEA		MAC
Mode	Mode shapes	Mode	Mode shapes	
E-01		F-01		0.86
E-02		F-02		0.89
E-03		F-03		0.94
E-04		F-04		0.72

5. Conclusions

This paper applies FEA and EMA techniques to perform model verification of PCB with and without thermal effects. The refined PCB FE model is constructed and validated for both free and fixed boundary conditions, especially for the PCB in heating effect. The modal characteristics of PCBs can be well interpreted and shown reasonable agreement between FEA and EMA. The major outcome is summarized as follows:

1. The PCB with and without thermal loadings are first analyzed for the thermal field response and calibrated for the thermal boundary conditions, in particular the free convection coefficient is verified.
2. The thermal boundary for the PCB with heating effect is well calibrated, and the vibration characteristics of PCB with and without thermal inputs are well interpreted.
3. The PCB in free and fixed boundaries are, respectively, tested and analyzed to obtain structural modal parameters, including natural frequencies and mode shapes, as well as FRFs. The reasonable agreement of modal parameters between FEA and EMA indicates the success for the model verification.
4. The FE model of PCB with the heating pad simulating the thermal inputs is well validated and can be adopted for future response prediction followed by the JEDEC random vibration test specification with coupled thermal inputs.

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