Modeling and Characterization for Vibration

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Abstract— A methodology to correlate finite element (FE) models of component and circuit board assemblies, developed in ANSYS, with experimentally derived vibration characterization data, is described. The correlated models can be used to predict the response of assemblies under dynamic loading. The correlation procedure is based on modal measurements (natural frequency and mode shape information). This information is used to fine-tune the FE model (e.g., modify material properties and boundary conditions) of the assembly. This technique results in a methodical means for developing accurate models accounting for both actual material properties and boundary conditions. Using this methodology, mode shape and frequency estimates from the model are within a few percent of those measured for the test board used in this study. Moreover, the transmissibility during random vibration testing was also correlated with excellent accuracy. The developed model can be used to study strain, stress, and displacement for the assembly and can also be employed for studies involving stress in the solder joints to be used in conjunction with measured failure data to develop S-N curves for various solder alloys under dynamic loading.

1 INTRODUCTION

Vibration loading can be exerted on an electronic assembly during shipping, handling, manufacturing, and end-use. Therefore, vibration-induced solder joint reliability assessment in electronic packaging has become a major concern in the industry. For this reason, researchers developed several methodologies and techniques to predict the solder joint fatigue life experimentally and via computer simulations (e.g., finite element methods). Although it is an approximation technique, the finite element method has been shown to be an effective tool to characterize the dynamic response of printed circuit boards (PCB) and assemblies and for the evaluation of stress induced in the solder joints [1,2].

One difficultly in building an effective finite element model of a board-level package is due to complex structure and range of geometric scale of the various parts. For example, the PCB contains copper layers, woven fabrics, plated-through holes, and so forth. In addition to the modeling demands of including such details, the mechanical behavior will typically be non-isotropic. Therefore, it is often acceptable to obtain equivalent orthotropic material properties and use them in the simulation. Similar complexities arise from modeling of the package and solder joints. Consequently, approximations and simplifications of both the geometry and material properties are often exploited in order to reduce the complexity of the resulting finite element models.

To facilitate these simplifications, Pitarresi, et al., [3-5] considered various finite element modeling techniques of assemblies subjected to vibration loading. Specifically, they explored methodologies for the correlation of the experimentally derived data with computer simulations to produce accurate models of reasonable complexity. Zhang, et al. [6] extended this approach and obtained the equivalent orthotropic properties using statistical methods to provide best fit between FEA results and the experimental observations. Yu, et al. [7] and Yafawi [8] presented an assessment methodology to predict solder joint fatigue in electronics from vibration testing and FEA.

The objective of this report is to provide an accurate methodology for developing finite element models of electronic test assemblies. The primary tool for achieving this result is to correlate the finite element results with experimental measurements, by comparing natural frequencies and mode shapes (eigenvalues and eigenvectors) of the system. This leads to a logical and systematic adjustment process whereby first the material properties are adjusted (using free-mode results and simulations) and then the boundary conditions (i.e., the fixity conditions at supports) are adjusted. At each step, the goal is to produce high-fidelity models vetted through correlation with modal measurements.

2 FINITE ELEMENT MODELING

Table 1 presents the dimensions of the printed circuit board, solder joint, and component for the test assembly used in this study. The initial material properties used in this model for the PCB and component are listed in Table 2, these values were taken from [8].

TABLE 1
DIMENSIONAL PARAMETERS

Parameter	Dimension
PCB width*Length	76.2*76.2 mm^2
PCB Thickness	1.0 mm
Solder joint height	0.5 mm
Solder joint diameter	0.762 mm
Pitch	1.27 mm
Component width*length	30*30 mm^2
Component thickness	1.5 mm

SAC305 properties are shown in Table 3, these values from ref. [9]. Note that the PCB and component substrate are FR-4 material and SAC305 is the solder joint alloy. All the previously mentioned materials are assumed to be linear elastic.

TABLE 2
INITIAL MATERIAL PROPERTIES FOR PCB AND COMPONENT

Material Property	PCB	Component
E_x	25.8 GPa	22.4 GPa
E_y	25.8 GPa	22.4 GPa
ν_{xy}	0.136	0.136
G_{xy}	12.1 GPa	12.1 GPa
Density	3030 Kg/m^3	2000 Kg/m^3

TABLE 3
MATERIAL PROPERTIES FOR SAC305

Material Property	Value
E_x	90.0 GPa
ν_{xy}	0.36
Density	7400 Kg/m^3

The element type used in the FE model is ANSYS element "Solid45," shown in Figure 1. This element is defined by eight nodes; each node has 3 translational degrees of freedom, namely, u_x, u_y and u_z. This element was attributed to PCB, solder joints, copper pads and component.

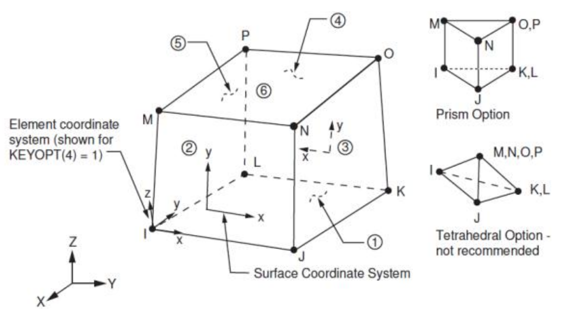

Figure 1. ANSYS Solid45 3D element [10].

The modeling procedure was started by building a "unit solder" model as shown in Figure 2. This unit was copied as needed for the geometry of the assembly (20×20 Perimeter, 256 I/O package). The remaining portions of the component and PCB are then extruded up to the desired dimension. The total number of elements for this model is 147,468. Figure 3 shows the isometric view of the full model.

The modeling in this effort is focused on modal analysis (mode shape and natural frequency extraction) and forced vibration analysis (harmonic and random excitation). With the methods described herein, the resulting models can be then used to explore the dynamic response of the assembly to a wide range of load conditions.

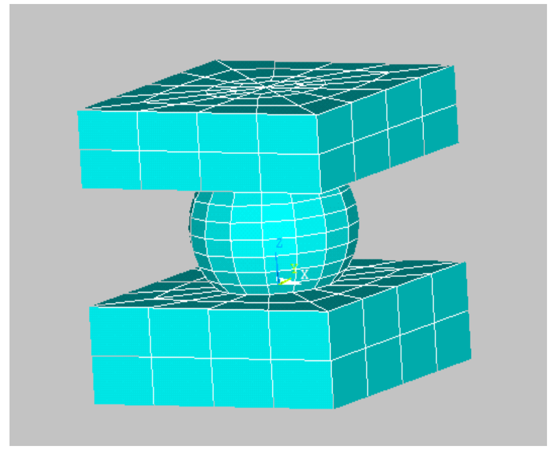

Figure 2. Typical solder joint unit.

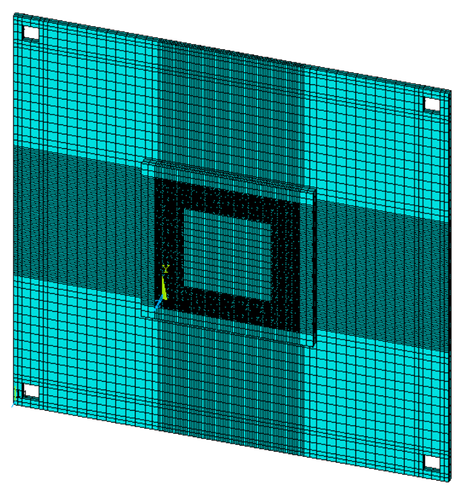

Figure 3. Full model mesh.

3 CORRELATION PROCEDURE

In order to build a FE model of the assembly that faithfully captures the essential dynamic characteristics, i.e., mode shapes and natural frequencies, it is necessary to employ an appropriate model "adjustment" technique so that any changes made to the model can be traced to a physical source of justification. The two primary reasons for making adjustments to the model include uncertainty with the material behavior and the boundary conditions.

The correlation methods used herein are based on systematically comparing the modal characteristics (i.e., the natural frequencies and mode shapes) of the first few lower modes of the assembly from both the FE model and dynamic measurements from physical samples. Specifically, the method is employed in two steps. The first step correlates the modal characteristics for a "free-edge" boundary condition (i.e., the test piece is modeled and measured with free boundary conditions on all edges). This effectively eliminates any uncertainty regarding the degree of fixity of the boundary conditions from the model so that any adjustments made are focused on material property changes in the FE model. Second, after the material properties are adjusted as best as possible, the test piece is mounted in the testing fixture (e.g., screw fasteners through holes drilled in the PCB). This second round of correlation is therefore focused on the effect of the boundary conditions on the modal characteristics. Again, adjustments are made to the "fixity" of nodes in the FE model to improve the mode shape and natural frequency correlation. Note: in this phase, the material properties are not adjusted – the focus of the second phase is on the boundary conditions only.

For our investigation, the above described correlation method was implemented, resulting in four cases:

1- Unpopulated PCB with free BC's.
2- Unpopulated PCB with fixed BC's (mounted).
3- Assembly with free BC's.
4- Assembly with fixed BC's (mounted).

The correlation between simulated and measured mode shapes was compared using the Modal Assurance Criterion (MAC) metric. MAC can be thought of as the dot product or linear regression coefficient between the FE and measured modal vectors. It takes the range between zero (no correlation) and one (perfect correlation). This relation is mathematically expressed as:

$$[MAC(\{\Phi_e\}_j, \{\Phi_f\}_k)] = \frac{\left|\{\Phi_e\}_j{}^T, \{\Phi_f\}_k\right|^2}{\{\Phi_e\}_j{}^T\{\Phi_e\}_j\{\Phi_f\}_k{}^T\{\Phi_f\}_k} \quad (1)$$

Where:

$\{\Phi_e\}_j$: is the experimental mode shape vector from *j=0* to *j= no. of mode shapes*.

$\{\Phi_f\}_k$: is the finite element mode shape vector from *k=0* to *k= no. of mode shapes*.

As discussed in the previous section, the initial material properties used in the FE model (Table 2) were adjusted using the two-step process to improve the correlation with the experiment. The first step in the adjustment was done on the unpopulated sample (either PCB or assembly) using free boundary conditions; this step is mainly to determine the orthotropic properties of the sample while neglecting the effect of the fixture/attachment BC's. The same procedure was followed to tune-up the properties of the assembly. The resulting updated material properties are given in Table 4. As can be seen (when compared to the initial properties from Table 2), slight modifications to the properties were made to improve the modal correlation. This will be presented in the next section. What is critical is that these changes to the properties were made to specifically improve the correlation to the measurements. That is, the modal data serves as a test method for determining the mechanical properties.

TABLE 4
UPDATED MATERIAL PROPERTIES FOR THE PCB AND COMPONENT

Material Property	PCB	Component
E_x	35.1 GPa	20.4 GPa
E_y	35.1 GPa	20.4 GPa
ν_{xy}	0.136	0.136
G_{xy}	12.7 GPa	6.9 GPa
Density	3030 Kg/m^3	2000 Kg/m^3

4 RESULTS

4.1 Natural Frequencies and mode shape correlation

The modal characteristics were measured using a small, light-weight accelerometer attached to the sample and an instrumented impact hammer to provide dynamic input. The resulting transfer functions were captured using the Puma hardware and the Star modal analysis software and then processed to produce the natural frequencies, mode shapes, and damping estimates for the sample. The free-edge boundary condition was approximated by simply suspending the sample by light-weight fishing line.

4.1.1 Unpopulated PCB with Free Boundary Conditions

Due to the free-edge BC's, the material properties can be adjusted with the focus on their influence on the modal characteristics. The initial results of this method are shown in Table 5. Here, we can see that the initial estimate of the material properties results in reasonable correlation.

TABLE 5
INITIAL NATURAL FREQUENCIES AND MAC FOR FREE-EDGE UNPOPULATED PCB

Mode Number	FEA Freq. (Hz)	Exp. Freq. (Hz)	%Error	MAC
1	363	369	-1.6	0.98
2	498	552	-9.7	0.96
3	553	715	-22.6	0.97
4	893	986	-9.4	0.38

From the above table, the MAC metrics shown indicates good correlation for the first three modes and poor matching for fourth mode. We can also observe that the FE natural frequencies are less than the measured frequencies, so there is a need to increase the stiffness of the PCB by increasing elastic and shear moduli. To understand this further, we need to observe the behavior of each mode shape and how the corresponding modulus affects its motion. The mode shapes are shown in Figure 4

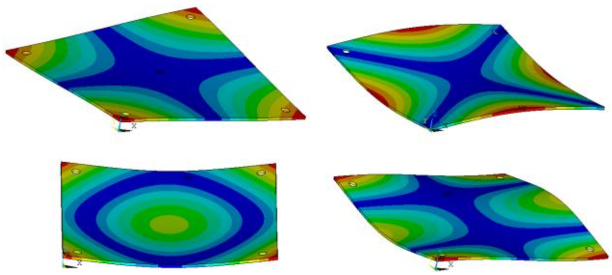

Figure 4. Unpopulated PCB Free Boundary conditions mode shapes (1st: top left, 2nd: top right, 3rd: bottom left, 4th: bottom right).

From the figure above it is seen that the first mode shape is a twisting motion that is directly related to the shear modulus of the PCB material. The second is a bending mode so the elastic modulus in either *x* and *y* directions are to be tuned. The material properties were adjusted until better correlation was achieved, as shown in Table 6. The adjusted material properties were summarized previously in Table 4.

TABLE 6
NATURAL FREQUENCIES COMPARISON AND MAC FOR ADJUSTED MATERIAL FREE UNPOPULATED PCB

Mode Number	FEA New Freq. (Hz)	Exp. Freq. (Hz)	%Error	MAC
1	372	369	0.8	0.98
2	586	552	5.9	0.98
3	650	715	-9.0	0.98
4	968	986	-1.8	0.85

From Table 6, it is now demonstrated that the material property adjustment process has significantly improved the simulation correlation with the measured results.

4.1.2 Unpopulated PCB with Fixed Boundary Conditions

After tuning-up the material properties and getting good correlation, the next step is to adjust the boundary conditions imposed in the FE model. Modeling of realistic boundary conditions is very difficult. The degree of physical restraint on regions of the actual sample is difficult to translate into easily applied BCs on the FE model. Therefore, this phase of the correlation process “locks-in” the material properties and makes adjustments to fixity of nodes in the region of the fasteners.

The original BC’s where imposed by fixing the internal surface of the PCB mounting holes in all directions. A new modal analysis is performed, both via FEA and measurement, resulting in a new set of mode shapes and natural frequencies for comparison. The new modal analysis results are summarized in Table 7.

TABLE 7
INITIAL NATURAL FREQUENCIES AND MAC METRICS FOR FIXED UNPOPULATED PCB

Mode Number	FEA Freq. (Hz)	Exp. Freq. (Hz)	%Error	MAC
1	494	550	-10.0	0.99
2	879	931	-6.0	0.88
3	996	1019	-2.2	0.91
4	1500	1530	-2.0	0.94

The above indicates good mode shape correlation between however the frequencies require some fine-tuning to improve the correlation.

A new proposed BC’s set is to add the “washer effect” of the fastener by restricting nodes on the top and the bottom of the PCB near the holes in finite element model that fall under the “shadow” of the washer. After applying the new set of BC’s a new modal analysis is conducted and its results are in Table 8.

TABLE 8
NATURAL FREQUENCIES COMPARISON AND MAC FOR ADJUSTED BC’S FOR MOUNTED UNPOPULATED PCB

Mode Number	FEA New Freq. (Hz)	Exp. Freq. (Hz)	%Error	MAC
1	536	550	-2.5	0.99
2	940	931	0.9	0.81
3	1068	1019	4.5	0.91
4	1542	1530	0.7	0.94

As can been seen in Table 7, the frequency correlation has improved while the MAC is essential the same as previous showing good correlation for the modal parameters. Therefore, this new BCs set will be used in the FE models of the assembly. The FE mode shapes of the PCB are shown below in Figure 5.

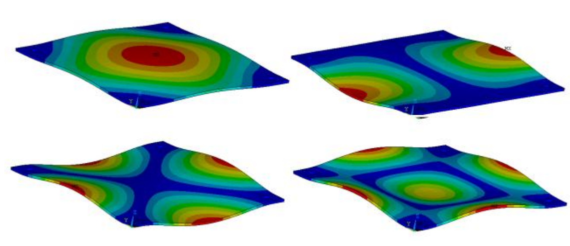

Figure 5. Unpopulated PCB Fixed Boundary conditions mode shapes (1st: top left, 2nd: top right, 3rd: bottom left, 4th: bottom right).

4.1.3 Assembly with Free Boundary Conditions

Here, we again repeat the two-step correlation process, first concentrating on free BC modeling then on the mounted case. At this level of analysis, there are more material properties engaged throughout the process, such as the package properties and the solder joint alloy properties. Since the package substrate is made from FR4 material, a separate modal analysis was completed on the package with free BC's in order to get tuned material properties. This was similar what we have done for the PCB at free BC's level. From this analysis we were able to make minor adjustments to the material properties of the package as previously reported in Tables 2 and 3.

Table 9 present the modal correlation summary after adjusting the package material properties. It can be seen that the FE model correlates well with the measurements using free conditions, providing an excellent "base" for the minor adjustments needed to account for the boundary conditions when the assembly is attached to the test fixture (the results are presented in the next sub-section).

TABLE 9
NATURAL FREQUENCIES COMPARISON AND MAC FOR ASSEMBLY WITH FREE BC'S

Mode Number	FEA Freq. (Hz)	Exp. Freq. (Hz)	%Error	MAC
1	525	504	4.1	0.98
2	760	771	-1.4	0.94
3	827	822	0.6	0.77
4	1048	1048	0.0	0.82

4.1.4 Assembly with Fixed Boundary Conditions

Similar to the fixed unpopulated PCB, the washer effect of the BC has been applied to the model and the results are listed in Table 10. The modal characteristics now show strong correlation in terms of natural frequencies and mode shapes for the assembly. Because of the careful approach to building and vetting the model, it can now be used to simulate the dynamic response under a variety of loading conditions such as harmonic excitation and random vibration.

TABLE 10
NATURAL FREQUENCIES COMPARISON AND MAC FOR ASSEMBLY WITH BC'S

Mode Number	FEA Freq. (Hz)	Exp. Freq. (Hz)	%Error	MAC
1	541	540	0.2	1.00
2	961	965	-0.4	0.90
3	1320	1215	8.6	0.88
4	1736	1717	1.1	0.89

4.2 Dynamic Response

With a well-correlated and tuned FE model, it is now possible to simulate the dynamic response of the assembly to various types of loads. The metric for comparison is the transmissibility (the ratio of input to output). It describes how motion is transmitted from the base (fixture) to the system (response). Shown below in Figure 6 is the comparison between measured behavior and the FE model of the transmissibility due to random base excitation input.

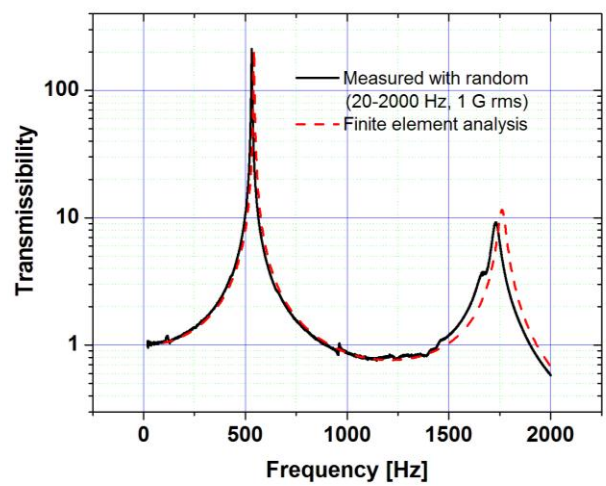

Figure 6. Transmissibility function correlation.

From the above figure, the FE transmissibility values are in strong agreement with measured values. Therefore, the FE model developed and presented is well-correlated with experimental measurements; this provides confidence in the conducted methodology and in the FE model.

CONCLUSIONS

The details of the correlation methodology have been presented. The methodology was based on comparing the results extracted from the finite element models (built using ANSYS), with the experimentally obtained modal and forced vibration results. Specifically, natural frequencies and mode shapes were the basis for the first phase of the model correlation. During this process, the material properties of the PCB and the component were finely-tuned for the free-condition cases. The second phase accounted for the boundary conditions which were adjusted to account the effect of the washer/fastener used in the experiment. After this tuning procedure, the natural frequencies and mode shapes from simulations and measurement were in excellent correlation. Finally, the transmissibility functions were also compared with random input (PSD) between measurement and FE model. The FE results were strongly correlated to the measurements. The presented methodology can be further used to verify the accuracy of FE models before extracting the stresses and strains at points of interest. Future work will be focused on obtaining stresses in solder joint to generate S-N curves from measured vibration-induced failure data.

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