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Determination of Natural Frequencies for Multi-Layered Printed Circuit Boards using FEA Simulation

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Abstract— The goal of this project was to determine natural frequencies for several multi-layered Printed Circuit Board (PCB) designs using Modal analysis in Ansys Workbench. When a material is subjected to a vibrational frequency higher than its natural frequency, it can experience resonance, which in turn can cause deformation, malfunction or failure of a part, even if the stress it experiences is lower than its ultimate strength. Ansys™ software was used to perform modal analysis, which yields natural frequencies of a model. The designs studied typically consisted of three layers, the outside layers being varied between copper, aluminum, magnesium and gold, while the middle layer was kept constant as FR-4 composite material. The dimension of the of the PCB used was 150mm X 200mm X 0.1mm and the thickness of outer layer used was 0.035 mm. During meshing a method called Capture Proximity was used to obtain valid mesh in thin layers of materials. Transistors modeled out of silicon material were added to some designs to model somewhat realistic PCB. The closest realistic PCM model (Model 7 in Appendix A) showed higher natural frequencies for aluminum and magnesium as outer layers than either copper or gold.

Index Terms— Modal Analysis, Vibration, Ansys, PCB, Natural Frequency, FEA, Meshing Multilayer.

1 Introduction

EVERY material has what has been dubbed a "natural frequency," if the material vibrates at a frequency higher than its natural frequency, that is, a resonant frequency, it experiences resonance. Under resonance, it is possible for a structure or component to deform and fail, even if the static loads applied are well below than its maximum capacity. Vibrational testing has become a part of almost every industry as quality control departments seek to mitigate the risk of their manufactured parts failing under resonance. This testing even includes the electronics industry and many companies, often trying to avoid destruction testing, seek ways to predict, analyze and virtually simulate, the behavior of a component under vibrational loads. There are many engineering intellectual tools to perform this type of analysis but one of the most prevalent is modal analysis. Modal analysis is a powerful tool that allows researchers and developers to obtain physical properties of materials under a set of dynamic conditions, typically vibrations or freefall drops.

The virtual modeling of PCB is often done as a 2-D or a 3-D model using modeling software. The 3-D model is often referred to as "Package on Package" (POP) structures [1]. POP consist of a minimum of 2 plates with many small solder joints. These plates are usually a thick plate (.25mm +) of epoxy glass material joined with a thin plate (.035 +/- .002mm) of conductive material [2]. When there are conductive layers on both sides with holes connecting them, it could be called a double plated through hole PCB. Attached to the PCB are often different electrical components such as transistors. One way to design these components would be to get the size of some of them and model them out of a specific material such as plastic or silicone and attach them to the model as an assembly. Another way to account for the effects of added components, could be by simply increasing the young's modulus and the density of the model [3]. Design of a PCB can be done using Solid Works or Ansys as both software packages have design capabilities. One important thing to note is that while PCB often have internal circuits and pathways for the electricity, in this research, the area of interest was mainly the material selection aspect. For this reason, internal circuitry was ignored or not accounted for.

Modal analysis allows for properties of materials and components to be optimized to the dynamic motion that systems, or components, will be put through. In order to optimize dynamic performance, it makes use of a mathematical approximations to a system's behavior under specific input conditions. Ansys is one of the commercial programs that integrates modal analysis into their simulation package and uses Finite Element Method (FEM) to solve complex virtual problems. Using Ansys Modal analysis it can be found how the natural frequency of a PCB affected as the thickness varied [4]. It was found that the natural frequency of a PCB increases as the thickness increases. This is useful as it helps determine a correlation between material thickness and natural frequency, but it does not address the issue of what the effects of changing the material will have on the natural frequency.

The fact that PCB are present in almost every modern electronic device, makes this research even more crucial. In the case of cell phones for example, if a drop from a certain height causes a high amount of vibration, if could shatter the internal PCB components, even if the outside components remain intact.

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The goal of this project focused on the question: Can a certain material be used that would raise the natural frequency of a PCB model thus making the design more stable? Because different materials can be used in the fabrication of PCB, it is practical to find a correlation between the type of layer material and the natural frequency of the design. In this study, the layers that were varied between different materials were the conductive outer layers, while the middle laminate layer and transistors were kept constant as a control. This is useful information as it will show which materials could be used to raise the natural frequency of a PCB design, which in turn will make it harder for the PCB to experience resonance.

2 Methodology

The methodology for this project relied on simulation of modal analysis using Ansys Workbench. The process involved designing several PCB models and performing modal analysis on them. At first, the simplest design was used to demonstrate the steps in the analysis process. The first step was to design a thin plate model that was used for a basic simulation. From some research into PCB designs, the plate was given .035 mm thickness. The width and length chosen were 150 mm x 200 mm respectively. The dimensions were chosen arbitrarily as there are infinite possibilities of PCB sizes.

Table 1: Material Property Data [5]

	Material Properties		
Layer Materials	Young's Modulus (Pa)	Density (kg/m3)	Poisson's Ratio
FR-4 (X-direction)	2.84E+10	1840	0.11
FR-4 (Y-direction)	1.84E+10	1840	0.09
FR-4 (Z-direction)	1.50E+10	1840	0.14
Copper	1.10E+11	8300	0.34
Aluminum	7.10E+10	2770	0.33
Gold	7.72E+10	19320	0.42

Table 2: Details of seven different designs.

Design No.	Design Dimensions (mm)	Outer Layers (both sides, 0.035mm)	PCB plate
1	150 x 200 x 0.035	No layers	Individual plate of Al, Cu, Mg, Au
2	150 x 200 x 0.1	Cu, Al, Mg, Au	FR-4
3	150 x 200 x 0.1	Cu, Al, Mg, Au	FR-4, 4 bolt holes located at each corner.
4	150 x 200 x 0.1	Cu, Al, Mg, Au	FR-4, 4 bolt holes located at each corner, one transistor mounted on the PCB.
5	150 x 200 x 0.1	Cu, Al, Mg, Au	FR-4, 4 bolt holes located at each corner, one transistor mounted on the PCB, corners are rounded.
6	150 x 200 x 0.1	Cu, Al, Mg, Au	FR-4, 4 bolt holes located at each corner, four transistors mounted on the PCB, corners are rounded.
7	150 x 200 x 0.1	Cu, Al, Mg, Au	FR-4, 2 bolt holes located at each corner, four transistors mounted on the PCB, corners are rounded, few slots were created to mimic a real PCB.

This first design was then saved to be used in simulations to obtain its natural frequency. As this was a thin plate layer, it was used to compare thin outer layers of all four materials. The material property data used in the simulations is shown in the Table 1. The dimensions with explanation of each design are given in Table 2.

Once a material is assigned to the solid, the geometry can be meshed. In most instances, the default mesh was not sufficient, and the mesh settings needed to be changed to get a more accurate customized mesh. This concept is expanded upon in the results section under the heading "Mesh Optimization."

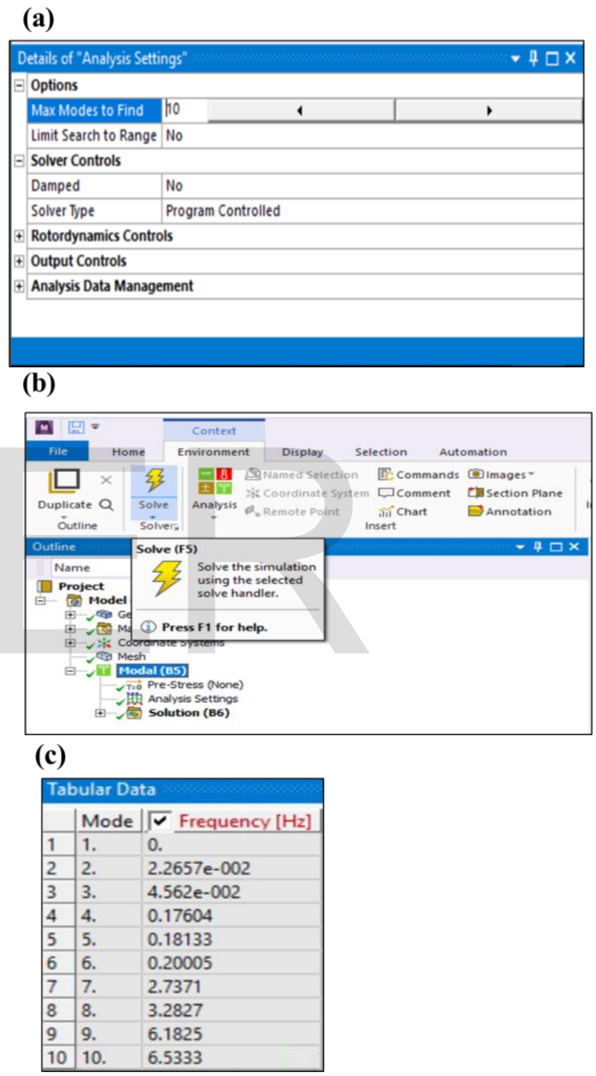

Fig. 1: Solving the Simulation, (a) to (d).

Once the model was meshed, the final step in the process was to solve for the natural frequencies. For this analysis it was determined that ten results would be sufficient for each model. This was done by editing the "analysis settings" to find ten modes. In some cases, depending on the model, less natural frequencies would be enough but ten seemed to give good results for all the models. The process to solve the simulations is shown in the Fig. 1. The final step in obtaining results was to generate "mode shapes" for the different natural frequencies as shown in Fig. 2. This was done by highlighting the table

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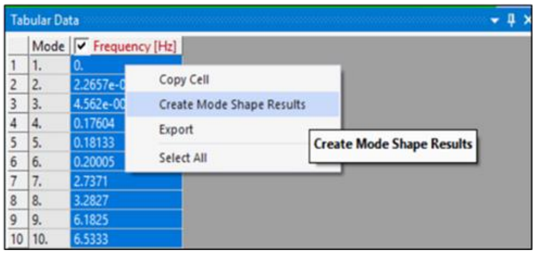
with the ten mode values, right clicking, and selecting "Create Mode Shape Results." This created a table for each of the frequencies in the data set.

(a)



(b)

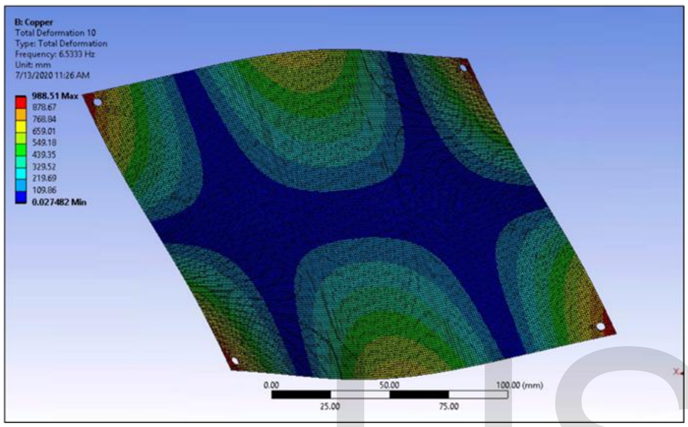


Fig. 2: Generating Mode Shape Results, (a) and (b).

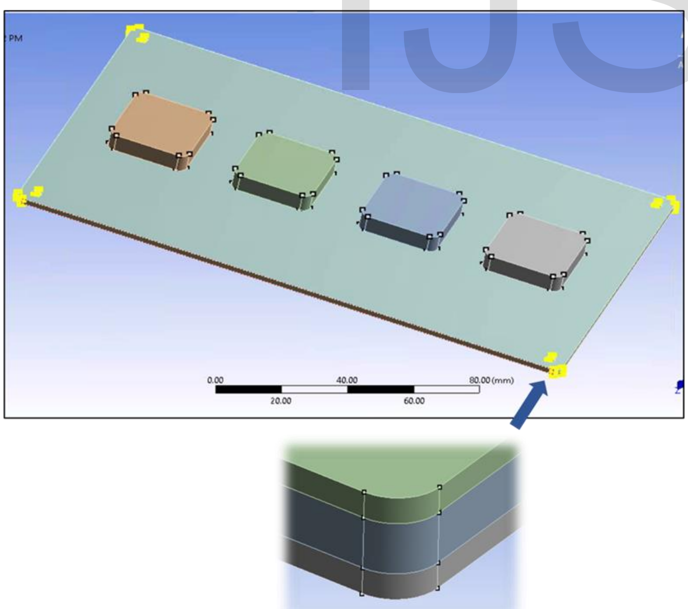


Fig. 3: Model with 4 transistors.

The designs that followed were increasing in complication with some of them including transistors modeled out of silicon material. One of the more complicated models is shown in the As shown in Fig. 3, the other models contained 3 layers of materials. The middle layer was always kept constant as FR-4 composite material, while for each model, the outer layers were varied between copper, aluminum, magnesium and gold. Each material was chosen as it may have some advantages over other materials even if there are some tradeoffs. Copper is the most common and cost-effective conductive material used in PCB, while magnesium is lighter than the rest [6]. Aluminum can be used in applications where heat needs to be dissipated quickly [7], and gold can be used in high performance circuits due to its high conductivity [8]. Each material can have an advantage over the others depending on the application and now, in the results section, it is explained how this analysis can predict how each will perform under vibrational loadings.

3 Results and Discussions

Before discussing the results, it is important to note how the type and number of nodes and elements will affect the accuracy of the modal analysis results. In this section, the mesh optimization is analyzed by comparing results of simulations run with a default mesh with varying levels of complexity (number of nodes and elements), and simulations run with a custom mesh again with varying complexity levels. The basics of what makes a default mesh is the fact that it allows the program to control the sizing of the mesh elements which is called "adaptive sizing." By lowering or raising the adaptive sizing level, one can obtain a simpler or more complex mesh. In contrast, customized meshes allow the user to adjust the complexity by changing the size and type of elements manually. It also allows for an option called "Proximity Capture" which forces a mesh to have multiple elements pass through the thickness of a model, default meshes do not always do this. The Fig. 4 shows the different statistics and options and how the custom mesh differs from a default mesh. In this case, the meshes being compared are the most complex custom mesh (left) vs the most complex default mesh (right).

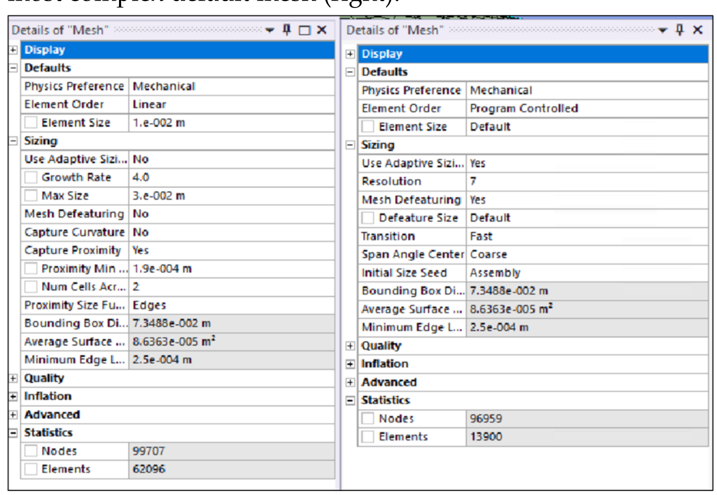


Fig. 4: Mesh Options and Statistics

As the Fig. 4 shows, the most complex meshes both have about the same number of nodes but a vastly different number of elements. This is partly because the customized mesh is more effective at creating elements and junctions which results in higher number of elements. The "Capture Proximity" also allows the mesh to have more elements pass through the thickness of the model. The way this works is shown in the

Fig. 5.

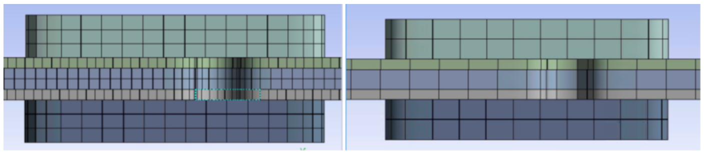


Fig. 5: Mesh Elements Through Model Thickness

The mesh on the left of Fig. 5 is the custom mesh while the right one is a default mesh. On the left, it is easily noticeable how many more elements are created compared to the right. The left mesh also has two elements passing through the thickness of the middle plate while on the right there is only one. The Transistors on the left have three elements going through them while the right mesh only has two. This option becomes very important when dealing with thin plates such as PCB.

As discussed earlier, when meshing complex geometries, it is typically better to use a custom mesh as opposed to a default one. In this instance, both types were used to compare the results of their respective simulations. In the final results, however, every mesh was customized to obtain the best results possible. To perform this study, the design used was the final design which is model seven in the appendix A. The outer layers were modeled out of copper and the middle layer was modeled out of FR-4 composite material. The eight transistors were modeled out of Silicon Anisotropic material. The modal simulation was performed with each mesh type beginning with the simplest default mesh and ending with the most complex customized mesh. Each simulation determined ten results of which the highest one was taken as the natural frequency of the model. The results for each mesh type are shown in the Table 3 and Table 4.

Table 3: Natural frequencies of design 7 using default meshes.

	Lowest # Nodes <- -> Highest # Nodes (Frequency in Hz)					
	Default Mesh 1	Default Mesh 2	Default Mesh 3	Default Mesh 4	Default Mesh 5	Default Mesh 6
# Nodes	8633	12124	15508	47767	73237	96959
# Elements	1029	2209	1939	7175	13006	13900
Narural Frequency 1	0	0	0	0	0	0
Narural Frequency 2	0	0	0	0	0	0
Narural Frequency 3	0	0.00E+00	1.26E-02	3.93E-03	0	0
Narural Frequency 4	3.60E-02	1.57E-02	2.53E-02	2.32E-02	0	2.49E-02
Narural Frequency 5	4.42E-02	3.54E-02	3.43E-02	3.53E-02	1.56E-02	4.40E-02
Narural Frequency 6	5.74E-02	4.82E-02	4.90E-02	4.04E-02	3.53E-02	7.05E-02
Narural Frequency 7	1300.5	1194.6	1154.4	1136.7	1150.6	1119.7
Narural Frequency 8	2357.2	2140.9	2066.9	1995.2	2045.9	1940.8
Narural Frequency 9	4156.4	3572.9	3402.4	3305.1	3368.4	3231.1
Narural Frequency 10	5487.8	4999	4882.5	4630.9	4784.7	4499

Table 4: Natural frequencies of design 7 using customized meshes.

	Lowest # Nodes <- ->Highest # Nodes (Frequency in Hz)						
	Custom Mesh 1	Custom Mesh 2	Custom Mesh 3	Custom Mesh 4	Custom Mesh 5	Custom Mesh 6	Custom Mesh 7
# Nodes	23842	45428	55740	66982	77352	87201	99707
# Elements	10682	24169	31406	39065	46244	53106	62096
Narural Frequency 1	0	0	0	0	0	0	0
Narural Frequency 2	0	0	0	0	0	0	0
Narural Frequency 3	0	0	0	0	0	0	0
Narural Frequency 4	2.73E-02	0	1.42E-02	3.16E-02	0.10797	0.10912	0.11072
Narural Frequency 5	5.55E-02	2.50E-02	3.11E-02	0.24239	0.20378	0.15584	0.17727
Narural Frequency 6	8.51E-02	7.53E-02	4.59E-02	0.41999	0.38494	0.25231	0.25348
Narural Frequency 7	4419.1	5556.9	4081.5	4774.1	4892.1	5953.5	5110
Narural Frequency 8	5735.1	6568.6	6447.5	6099	5732.4	6749.4	6108.5
Narural Frequency 9	11142	11401	11037	11951	10446	10537	10845
Narural Frequency 10	12575	13562	12521	12775	12731	13799	13376

Even though the custom meshes vary in complexity, they are usually more efficient than the default meshes when it comes to complex geometries such as the ones modeled for this project. For this reason, the values obtained from the custom mesh are considered to be closer to the real-world value of the natural frequency for these models. The mesh convergence occurred after custom mesh 6 (Table 4). The results in Fig. 4 obtained from custom meshes that captured proximity with multiple elements through the thickness of the models and are assumed to be the most accurate values obtainable from simulations. For each model designed, the highest natural frequency obtained was plotted and the graphs are shown in Fig. 6.

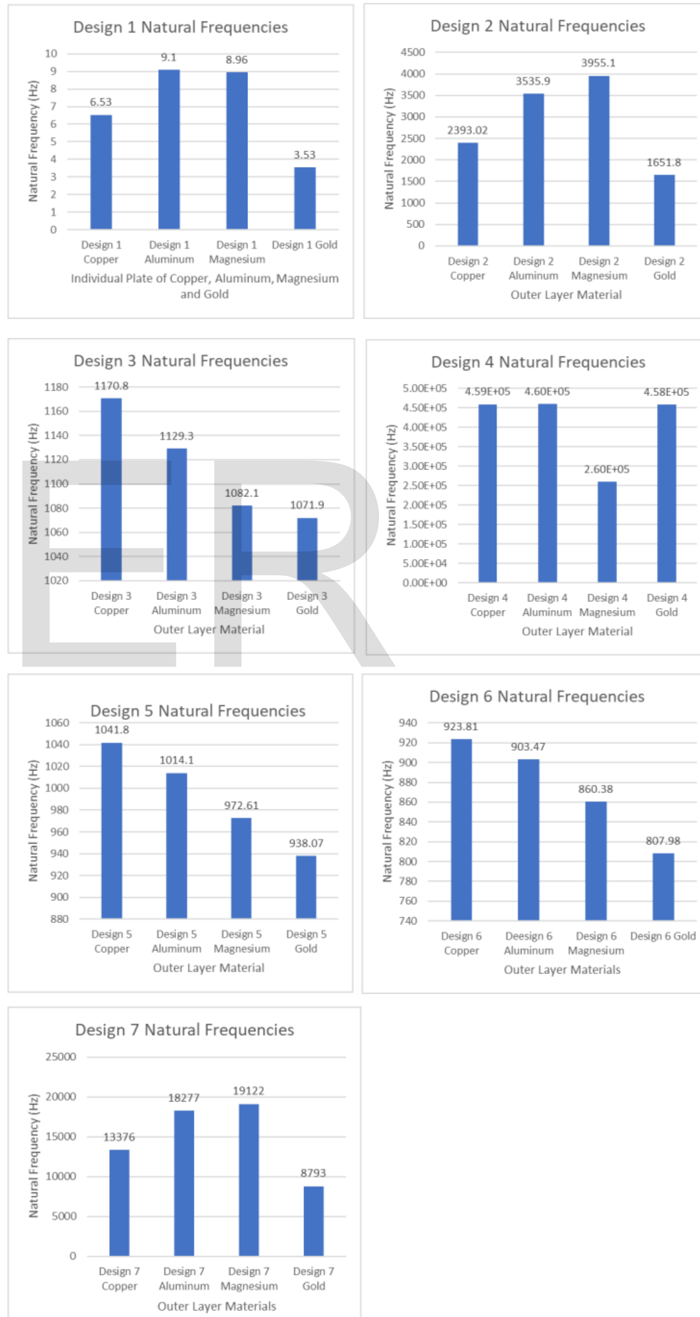


Fig. 6: Natural frequency vs. outer layer material.

Due to the variations in natural frequency, a perfect pattern or correlation was not established. By simply looking at the results in Fig. 6, one can see that sometimes the highest natural frequency happened with copper as the outer layer material, other times it was aluminum and one time it was magnesium. order to better parse the results, the distribution of the highest natural frequency was plotted, and the graph is shown Fig. 7.

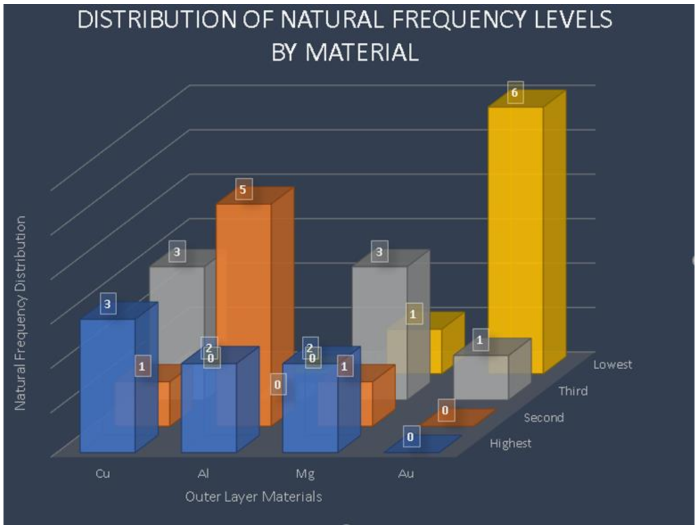


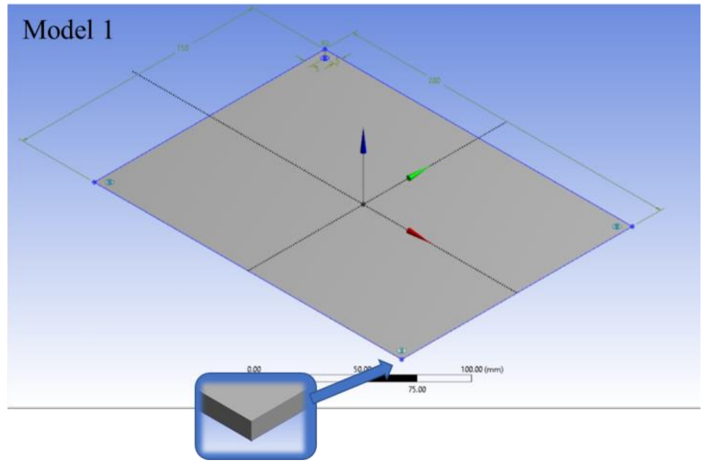
Fig. 7: Natural Frequency Distribution per Outer Layer Material

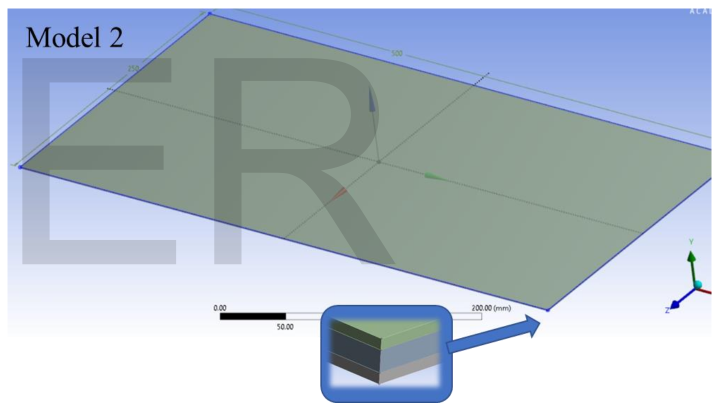
By looking at the distribution of the highest natural frequencies, a general trend could be established. It is shown that Copper had the highest natural frequency the most times, while Aluminum had the second highest natural frequency 5 times. Magnesium on the other hand, had the highest natural frequency only once, and the third highest 3 times. Gold had the lowest natural frequencies most often than the other materials. Parsing these results, the general trend would indicate that having copper or aluminum as outer layers on a PCB, may help raise the natural frequency of it, thus making it more stable under vibrational loads. Making use of Gold or Magnesium in turn, may come with tradeoffs in vibrational stability. If one needs a lighter PCB, or a highly conductive PCB, one may be trading vibrational stability for higher performance, or lighter weight. In the end, engineering is often about tradeoffs and optimization, thus these results can be helpful in determining a way to make a PCB more vibrationally stable.

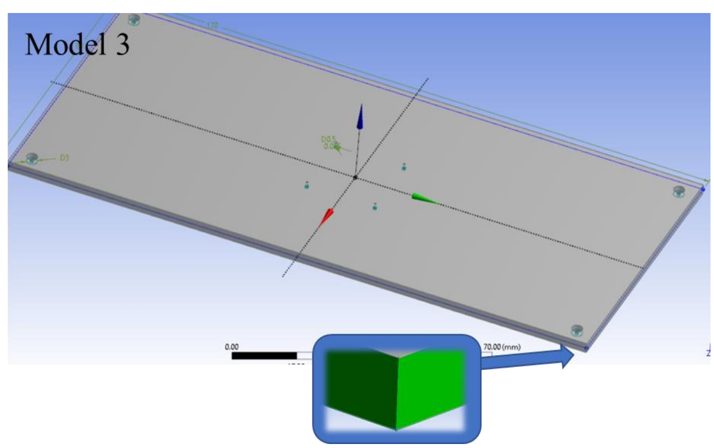
4 Conclusion

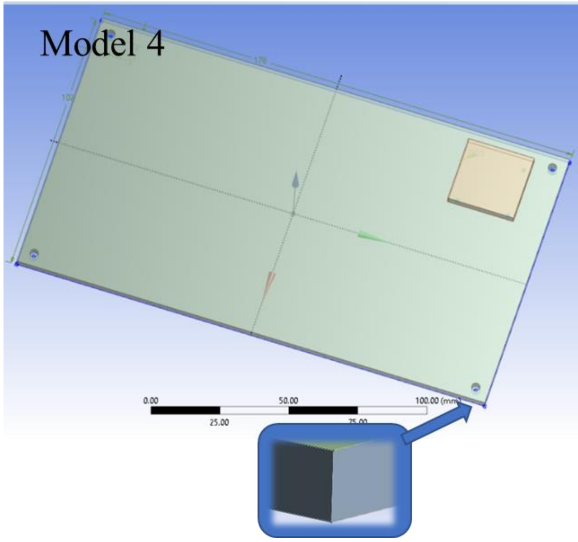
In conclusion, the goal of this project was to determine a way to raise the natural frequency of a PCB model in order to make designs more vibrationally stable. To study this problem, it was determined that several models could be studied by varying the outer layers of the models while keeping the middle layer constant as FR-4 composite material. After performing the simulations for 7 different models, a general trend was established. This trend suggested that the use of Copper and Aluminum for the outer layers of a PCB, may raise the natural frequency of the design while magnesium and gold may lower it. If someone needs to make a PCB withstand higher vibrations, it may be prudent to use Copper or Aluminum for the outer layers. If a PCB needs to be lighter, or highly conductive, then Magnesium or Gold may be used but the model will likely not be able to withstand the level of vibrations that Copper or Aluminum could withstand.

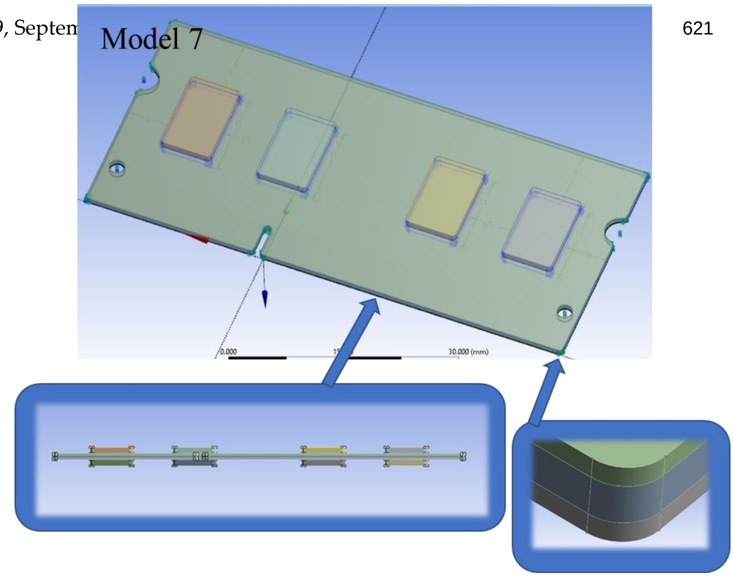
5 Appendix

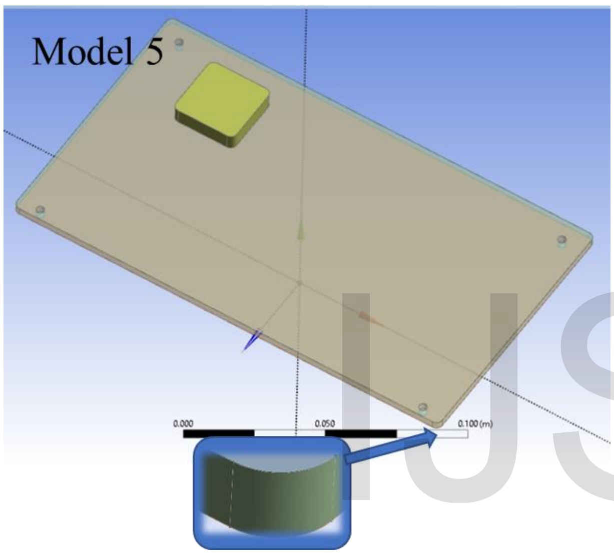


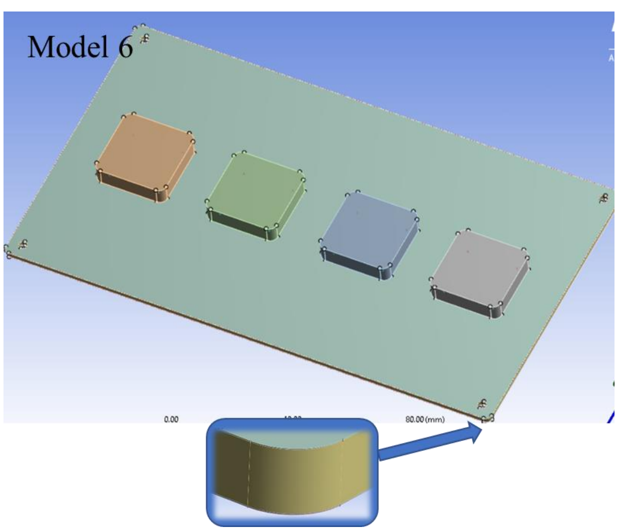












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