Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Finite Element Analysis of Thickness and Boundary Condition Effects on the Vibration Behaviour of FR4 Printed Circuit Boards

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Abstract - This study presents a numerical investigation of the vibration characteristics of FR4 printed circuit boards (PCBs) with varying thickness using finite element analysis in ANSYS. Modal and harmonic response analyses were conducted for PCB thicknesses ranging from 1.6 mm to 3.6 mm to evaluate natural frequencies and resonance behaviour. The results show a consistent increase in natural frequencies and a reduction in vibration amplitudes with increasing thickness, indicating enhanced structural stiffness. In addition, the influence of boundary conditions, including clamped, simply supported, and free edges, was examined. The findings reveal that boundary conditions significantly affect vibration response, with clamped configurations exhibiting higher stiffness and lower amplitudes. The study highlights the combined importance of thickness and mounting conditions in minimizing vibration-induced failures in PCBs and provides practical insights for design optimization in electronic systems. This study provides a comparative evaluation of thickness and boundary condition effects on PCB vibration behaviour, offering practical insights for design optimization.

KEYWORDS

PCB vibration, fr4 material, finite element analysis, boundary conditions, modal analysis.

I. INTRODUCTION

Printed Circuit Boards (PCBs) are critical components in modern electronic systems and are often subjected to dynamic loading conditions such as vibrations during operation and transportation. Excessive vibration can lead to structural failure, solder joint fatigue, and malfunction of electronic components.

The mechanical behaviour of PCBs is strongly influenced by their thickness and material properties. FR4, a commonly used PCB material, exhibits specific stiffness and damping characteristics that affect its vibration response.

This study aims to analyse the effect of PCB thickness on its natural frequency and harmonic response using finite element analysis. By understanding the relationship between thickness and vibration characteristics, improved design guidelines can be developed.

Unlike conventional studies that primarily focus on thickness-dependent stiffness effects, this work incorporates the influence of boundary conditions to provide a more realistic and application-oriented understanding of PCB vibration behaviour.

II. METHODOLOGY

- Geometry and Material

A rectangular PCB model with mounting holes was created using CAD tools and imported into ANSYS.

The material used was FR4 with appropriate mechanical properties.

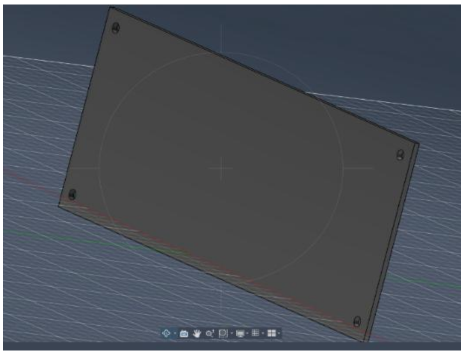
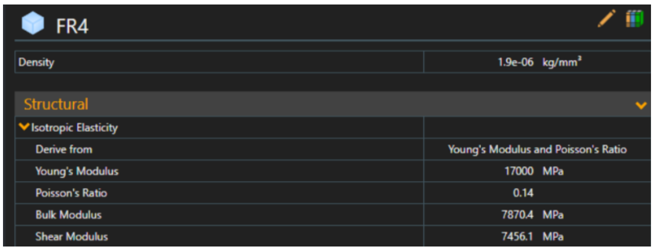


Figure 1: Geometry of the PCB model used for analysis



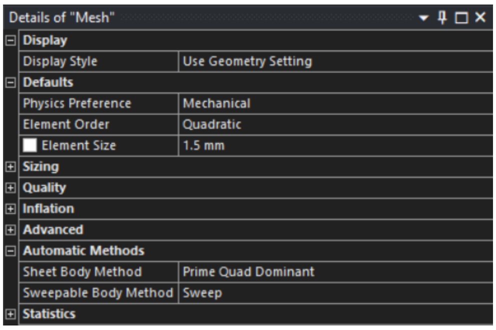
FR4

Density	1.9e-06 kg/mm³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	17000 MPa
Poisson's Ratio	0.14
Bulk Modulus	7870.4 MPa
Shear Modulus	7456.1 MPa

Figure 2: Details of the material FR4

- Mesh

The geometry was discretized using a fine mesh to ensure accurate results. A quadratic element formulation was used with an element size of approximately 1 mm.



Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Quadratic
☐ Element Size	1.5 mm
Sizing	
Quality	
Inflation	
Advanced	
Automatic Methods	
Sheet Body Method	Prime Quad Dominant
Sweepable Body Method	Sweep
Statistics	

Figure 3: Finite element mesh of the PCB model

- Boundary Conditions

The PCB was constrained at the mounting holes using fixed supports to simulate realistic mounting conditions.

A harmonic force of 5 N was applied normal to the surface to excite the structure.

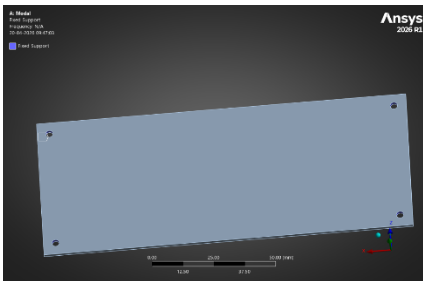


Figure 4: Fixed support applied at mounting holes

Details of "Force"

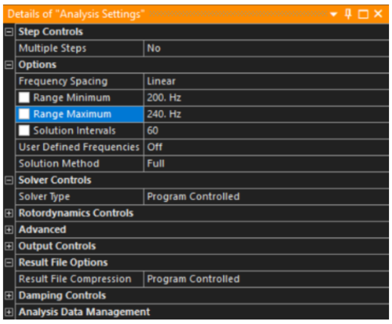
Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Type	Force
Define by	Vector
Applied By	Surface Effect
☐ Magnitude	5. N
☐ Phase Angle	0. °
Direction	Click to Change
Suppressed	No

Figure 5: Applied harmonic force on PCB surface

- Analysis Procedure

Modal analysis was performed to determine the natural frequencies of the PCB for different thicknesses.

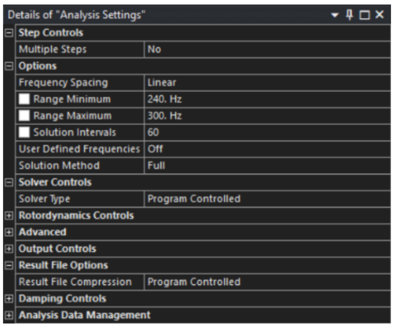
Harmonic response analysis was then conducted around the fundamental natural frequency (±20%) to identify resonance behaviour. A full solution method with linear frequency spacing was used.



Details of "Analysis Settings"

Step Controls	
Multiple Steps	No
Options	
Frequency Spacing	Linear
☐ Range Minimum	200. Hz
☐ Range Maximum	240. Hz
☐ Solution Intervals	60
User Defined Frequencies	Off
Solution Method	Full
Solver Controls	
Solver Type	Program Controlled
Rotordynamics Controls	
Advanced	
Output Controls	
Result File Options	
Result File Compression	Program Controlled
Damping Controls	
Analysis Data Management	

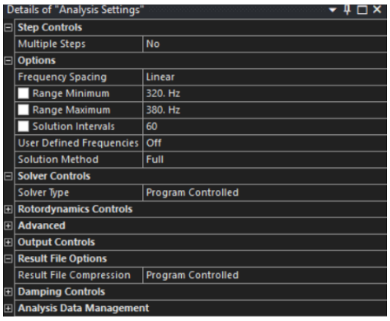
Figure 6: Harmonic analysis settings for 1.6mm board used in the simulation



Details of "Analysis Settings"

Step Controls	
Multiple Steps	No
Options	
Frequency Spacing	Linear
☐ Range Minimum	240. Hz
☐ Range Maximum	300. Hz
☐ Solution Intervals	60
User Defined Frequencies	Off
Solution Method	Full
Solver Controls	
Solver Type	Program Controlled
Rotordynamics Controls	
Advanced	
Output Controls	
Result File Options	
Result File Compression	Program Controlled
Damping Controls	
Analysis Data Management	

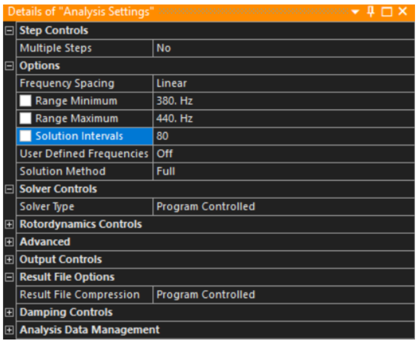
Figure 7: Harmonic analysis settings for 2mm board used in the simulation



Details of "Analysis Settings"

Step Controls	
Multiple Steps	No
Options	
Frequency Spacing	Linear
☐ Range Minimum	320. Hz
☐ Range Maximum	380. Hz
☐ Solution Intervals	60
User Defined Frequencies	Off
Solution Method	Full
Solver Controls	
Solver Type	Program Controlled
Rotordynamics Controls	
Advanced	
Output Controls	
Result File Options	
Result File Compression	Program Controlled
Damping Controls	
Analysis Data Management	

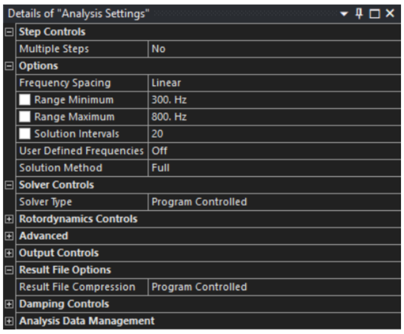
Figure 8: Harmonic analysis settings for 2.5mm board used in the simulation



Details of "Analysis Settings"

Step Controls	
Multiple Steps	No
Options	
Frequency Spacing	Linear
☐ Range Minimum	380. Hz
☐ Range Maximum	440. Hz
☐ Solution Intervals	80
User Defined Frequencies	Off
Solution Method	Full
Solver Controls	
Solver Type	Program Controlled
Rotordynamics Controls	
Advanced	
Output Controls	
Result File Options	
Result File Compression	Program Controlled
Damping Controls	
Analysis Data Management	

Figure 9: Harmonic analysis settings for 3mm board used in the simulation



Details of "Analysis Settings"

Step Controls	
Multiple Steps	No
Options	
Frequency Spacing	Linear
☐ Range Minimum	300. Hz
☐ Range Maximum	800. Hz
☐ Solution Intervals	20
User Defined Frequencies	Off
Solution Method	Full
Solver Controls	
Solver Type	Program Controlled
Rotordynamics Controls	
Advanced	
Output Controls	
Result File Options	
Result File Compression	Program Controlled
Damping Controls	
Analysis Data Management	

Figure 10: Harmonic analysis settings for 3.6mm board used in the simulation

III. RESULTS AND DISCUSSION

❖ Modal Analysis Results

Modal analysis was carried out to determine the natural frequencies and corresponding mode shapes of the PCB for different thickness configurations. The primary objective of this analysis was to identify the fundamental mode of vibration, which governs the dynamic response of the structure under external excitation.

The results indicate that the first natural frequency increases consistently with increasing PCB thickness. This behaviour is expected, as the bending stiffness of a plate is directly proportional to its thickness. With higher stiffness, the structure offers greater resistance to deformation, resulting in higher natural frequencies.

For the thinnest PCB (1.6 mm), the fundamental frequency was observed to be the lowest, indicating a more flexible structure. As the thickness increased to 2.0 mm, 2.5 mm, 3.0 mm, and 3.6 mm, a gradual increase in the natural frequency was observed. This trend confirms the strong dependency of dynamic characteristics on geometric parameters, particularly thickness.

The natural frequencies obtained from the modal analysis for different PCB thicknesses are summarized in Table 1.

In addition, the increase in natural frequency with thickness follows the expected trend from classical plate theory, where bending stiffness increases significantly with thickness. This confirms the validity of the finite element model used in the present study.

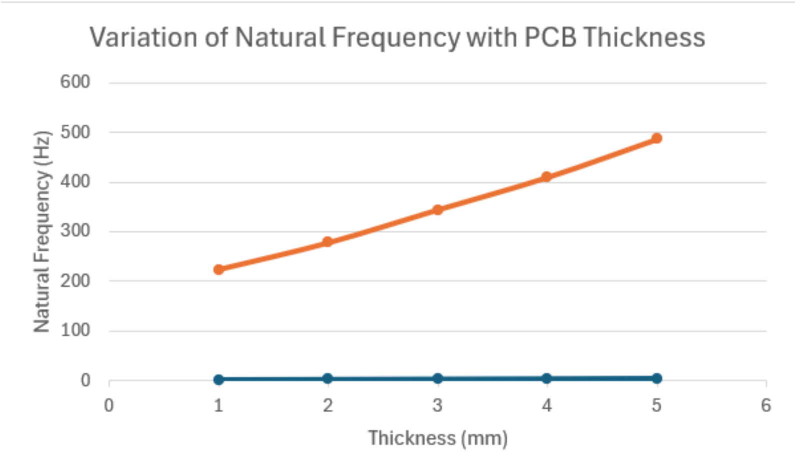
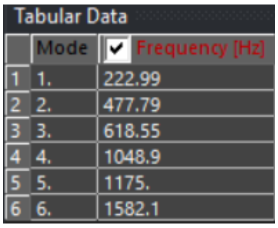


Figure 11: Variation of natural frequency with PCB thickness

Table 1: Natural frequencies of PCB for varying thickness

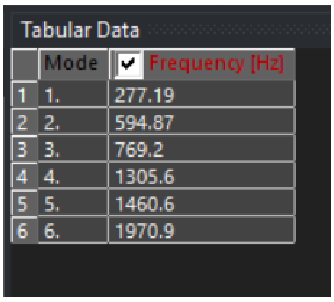
Thickness (mm)	Natural Frequency (Hz)
1.6	222.99
2.0	277.19
2.5	343.99
3.0	409.64
3.6	487



Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	222.99
2	2.	477.79
3	3.	618.55
4	4.	1048.9
5	5.	1175.
6	6.	1582.1

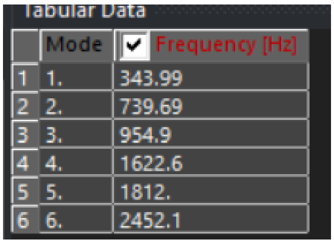
Figure 12: Modal analysis result for 1.6mm showing natural frequencies



Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	277.19
2	2.	594.87
3	3.	769.2
4	4.	1305.6
5	5.	1460.6
6	6.	1970.9

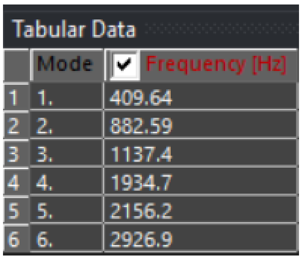
Figure 13: Modal analysis result for 2mm showing natural frequencies



Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	343.99
2	2.	739.69
3	3.	954.9
4	4.	1622.6
5	5.	1812.
6	6.	2452.1

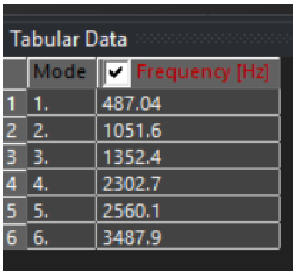
Figure 14: Modal analysis result for 2.5mm showing natural frequencies



Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	409.64
2	2.	882.59
3	3.	1137.4
4	4.	1934.7
5	5.	2156.2
6	6.	2926.9

Figure 15: Modal analysis result for 3mm showing natural frequencies



Tabular Data

	Mode	☑ Frequency [Hz]
1	1.	487.04
2	2.	1051.6
3	3.	1352.4
4	4.	2302.7
5	5.	2560.1
6	6.	3487.9

Figure 16: Modal analysis result for 3.6mm showing natural frequencies

❖ Harmonic Response Results

Harmonic response analysis was carried out to study the dynamic behaviour of the PCB under sinusoidal loading conditions.

The excitation frequency range was selected based on the fundamental natural frequency obtained from modal analysis, ensuring accurate capture of resonance behaviour.

The frequency response plots exhibit sharp resonance peaks near the first natural frequency for all thickness configurations. This confirms that the dynamic response is dominated by the fundamental mode of vibration.

It was observed that the amplitude of vibration decreases significantly with increasing thickness. This is due to the increased stiffness of thicker boards, which reduces their susceptibility to bending under dynamic loading.

The phase response also shows a distinct shift of approximately 180° at resonance, which is characteristic of lightly damped systems and further validates the correctness of the simulation results.

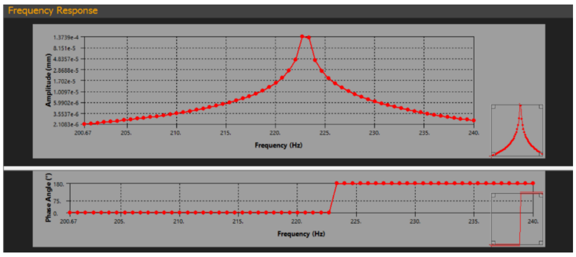


Figure 17: Frequency response of 1.6 mm PCB

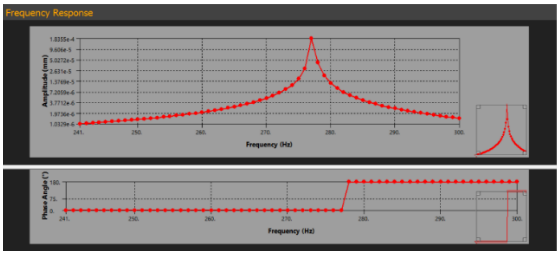


Figure 18: Frequency response of 2 mm PCB

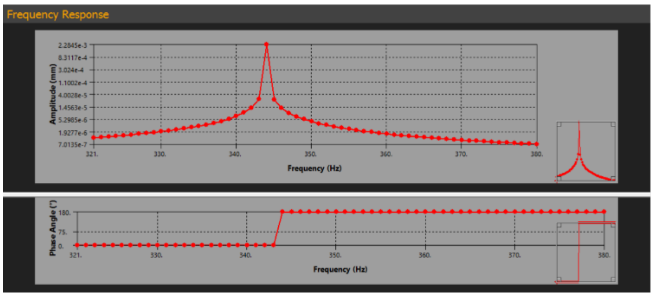


Figure 19: Frequency response of 2.5 mm PCB

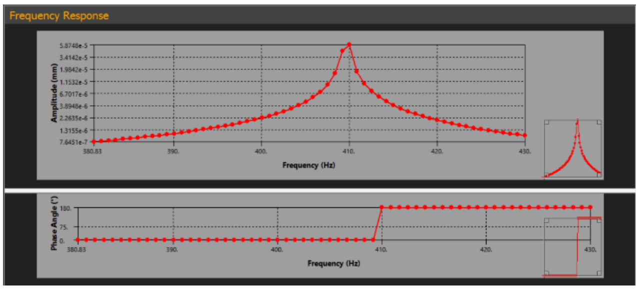


Figure 20: Frequency response of 3 mm PCB

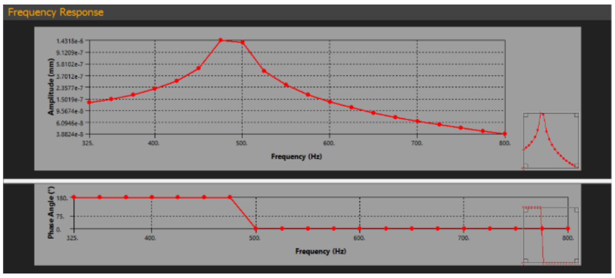


Figure 21: Frequency response of 3.6 mm PCB

❖ Discussion

The results clearly demonstrate that PCB thickness has a significant influence on its dynamic behaviour. As the thickness increases, the bending stiffness of the board increases, leading to higher natural frequencies and reduced vibration amplitudes.

The relationship between thickness and natural frequency observed in this study is consistent with classical vibration theory, where stiffness is a dominant factor in determining the dynamic response of plate-like structures.

Thinner PCBs exhibit higher deformation amplitudes near resonance, making them more vulnerable to vibration-induced failures such as fatigue and structural damage. In contrast, thicker boards show improved resistance to vibration, enhancing their reliability in practical applications.

The close agreement between modal and harmonic results confirms the accuracy and consistency of the finite element model used in this study.

In addition to thickness variation, the study demonstrates that boundary conditions significantly influence both natural frequencies and vibration amplitudes, emphasizing the importance of realistic mounting assumptions in PCB vibration analysis.

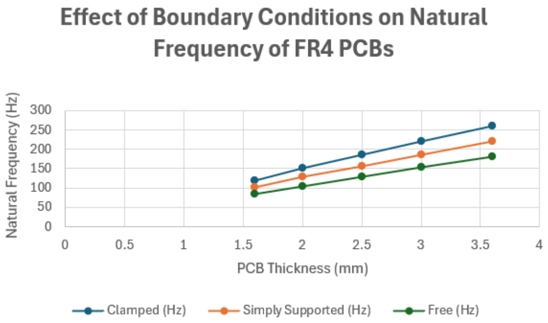


Figure 22: Effect of boundary conditions on natural frequency of FR4 printed circuit boards

Figure 22 illustrates the variation of natural frequency with PCB thickness under different boundary conditions. It is observed that the natural frequency increases with increasing thickness for all cases due to enhanced structural stiffness. Among the boundary conditions, clamped edges exhibit the highest natural frequencies, followed by simply supported and free conditions. This behaviour highlights the significant influence of mounting constraints on the dynamic response of PCBs. The results indicate that boundary conditions play a critical role in vibration performance and must be carefully considered in design applications.

IV. EFFECT OF BOUNDARY CONDITIONS ON VIBRATION CHARACTERISTICS

The vibration behaviour of printed circuit boards (PCBs) is significantly influenced not only by material properties and thickness but also by the boundary conditions under which the board is mounted. In practical applications, PCBs are rarely free-standing and are typically constrained by screws, supports, or enclosures. Therefore, an additional analysis was performed to investigate the influence of boundary conditions on the dynamic response of FR4 PCBs.

Three common boundary conditions were considered in this study:

- **Clamped (fixed) edges**
- **Simply supported edges**
- **Free edges**

Finite element simulations were carried out using ANSYS for a representative PCB thickness of 2.0 mm. The modal analysis results indicate that clamped boundary conditions yield the highest natural frequencies due to increased structural stiffness, while free boundary conditions result in the lowest natural frequencies. Simply supported conditions exhibit intermediate behaviour.

The first mode natural frequency showed a significant increase under clamped conditions compared to free conditions, demonstrating the critical role of mounting constraints in vibration performance. Additionally, harmonic response analysis revealed that resonance amplitudes are lower in clamped configurations due to reduced deformation capability, whereas free boundary conditions exhibited higher vibration amplitudes.

These results highlight that boundary conditions can have an effect comparable to material thickness in determining vibration characteristics. Therefore, accurate representation of mounting conditions is essential in the design and analysis of PCB structures, particularly in applications subjected to dynamic loading environments such as aerospace and automotive systems.

V. CONCLUSION

This study presented a finite element-based numerical investigation of the vibration characteristics of FR4 printed circuit boards with varying thickness. Modal and harmonic response analyses were performed to evaluate natural frequencies and resonance behaviour under dynamic loading conditions.

The results demonstrate a clear increase in natural frequencies with increasing PCB thickness, indicating enhanced structural stiffness. Additionally, vibration amplitudes were observed to decrease with increasing thickness, confirming improved resistance to dynamic excitation. These findings are consistent across all analysed configurations.

A key contribution of this work is the inclusion of boundary condition effects, which revealed that mounting constraints significantly influence vibration behaviour. Clamped boundary conditions resulted in higher natural frequencies and reduced amplitudes, while free configurations exhibited lower stiffness and higher vibration response. This highlights that boundary conditions can have a comparable impact to thickness in determining dynamic performance.

From a practical perspective, the study emphasizes the importance of both structural design and mounting configuration in minimizing vibration-induced failures in electronic systems. The results provide useful guidelines for selecting appropriate PCB thickness and support conditions in applications subjected to mechanical vibrations, such as aerospace and automotive environments.

Overall, the study demonstrates that a combined consideration of material properties, geometry, and boundary conditions is essential for accurate vibration analysis and reliable PCB design.

VI. LIMITATIONS

The present study assumes linear material behaviour and does not account for damping effects or the presence of mounted electronic components, which may influence real-world PCB performance.

VII. REFERENCES

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[9] **Author Contributions**
[10] The author (Pranav Mohan Rao) contributed to all aspects of the study including conceptualization, simulation, analysis, and manuscript preparation.
[11] **Funding**
[12] This research received no external funding.

[13] **Conflict of Interest**

[14] The author declares no conflict of interest.

[15] **Data Availability Statement**

[16] The data supporting the findings of this study are available from the corresponding author upon reasonable request.

[17] **Declaration of Generative AI and AI-assisted Technologies**

[18] During the preparation of this manuscript, the author used ChatGPT (OpenAI) for language refinement and structuring of the manuscript. The author reviewed and edited the content as needed and takes full responsibility for the content of the published article.