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Design and Analysis of Avionics Rack for Space Application

Chiranjeevi T S[1], *Dr.Annapoorna T.L*[2]
[1]*PG Scholar, Department of ME, Sri Siddhartha Institute of Technology, Tumkur, Karnataka, India.*
[2]*Associate Professor, Department. of ME, Sri Siddhartha Institute of Technology, Tumkur, Karnataka, India.*
Emails: *chiranjeevits1412@gmail.com*[1], *annapurnababu94@gmail.com*[2]

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Abstract

The avionics rack is a critical structural component used to support and protect electronic systems in spacecraft. The design must ensure structural integrity, vibration resistance, and reliability under launch and operational conditions. In this project, an avionics rack assembly was designed and analyzed using Siemens NX. The rack structure and its components were modelled and assembled to represent a realistic system configuration. Finite Element Analysis (FEA) was performed to evaluate the structural behavior of the rack under static loading and dynamic Loading conditions. The meshing process was carried out using tetrahedral elements for structural components and 2D shell elements for printed circuit boards (PCBs). Modal analysis was carried out to identify the modes and mode shapes of the structure. Random vibration Analysis was carried out to study how structure responds under unpredictable vibrations. Static structural analysis was conducted to determine deformation and stress distribution. The results obtained from the simulations help verify that the avionics rack design is capable of withstanding mechanical loads and vibration environments typically encountered in aerospace applications.

1. Introduction

Space missions today depend a lot on avionics systems. These systems help the spacecraft to communicate, navigate, and control spacecraft functions. During a mission, avionics equipment has to work in extreme environments. It faces high vibration during launch, temperature variations, vacuum conditions, and radiation. Because of this, giving proper support and protection to avionics equipment is extremely important for a successful mission.

1.1. About Rack

An avionics rack is a structure that holds and supports electronic equipment in the correct position. It helps to remove heat, reduces vibration, and makes installation and maintenance easier. While designing an avionics rack, it is important to satisfy mass, strength, stiffness, and thermal performance requirements, and it must meet space mission safety requirements. This project is about designing and studying the structural integrity of an avionics rack for space use. The rack is made to survive launch forces, shocks, and temperature changes without getting damaged. Avionics racks are very important parts of a spacecraft. They hold key electronic units such as computers, power units, communication systems, and data handling devices. When designing racks for space missions, many things must be considered, such as keeping weight low, making the structure strong, thermal management, handling vibration and shock, avoiding electrical interference, and making the system reliable and easy to maintain [1].

1.1.1. Functional Role of Avionics Rack in Spacecraft

The avionics rack connects electronic equipment to the main structure of the spacecraft. Studies show that racks must hold equipment firmly, keep everything properly aligned, and help move heat away from electronics. Using standard rack designs helps make assembly easier, improves repairs, and allows systems to be upgraded, especially in satellites and crewed spacecraft.

1.2. Structural Design Considerations

1.2.1. Load Environment

During launch, spacecraft go through very strong forces such as heavy vibrations, loud noise, and sudden shocks. Avionics racks must be designed to withstand these forces without excessive deformation or failure.

1.2.2. Stiffness and Vibration

Avionics racks must be stiff so they do not vibrate too much during launch. If the rack vibrates at certain frequencies, it can be dangerous. Engineers study this using vibration analysis to make sure the rack vibration frequency is high enough. The main challenge is making the rack stiff while keeping it lightweight.

1.2.3. Materials and Manufacturing

Aluminium alloy is commonly used because of its machinability, strength-to-weight ratio, and thermal conductivity [2].

1.3. Thermal Design and Heat Management

Thermal control is one of the most important parts of avionics rack design. Since there is no air in space, heat is mainly removed by conduction. The rack helps transfer heat from electronic units to cooling systems or radiators. Engineers use thermal models like cold plates to make sure the temperature stays within safe limits. Some designs use heat pipes or special materials to improve heat flow.

1.4. Finite Element Analysis and Simulation

1.4.1. Structural Analysis

FEA analysis is widely used to check whether the rack can handle launch loads and vibrations. Static analysis is used for steady forces, while vibration and shock analysis are used to study movement and impact effects. Comparing the results with real test results helps confirm that the design is correct.

1.4.2. Thermal and Structural Effects

Studies look at both heat and structure together to understand how temperature changes can cause stress or deformation. This is important for long missions and high-power electronics, where heat differences can affect performance.

1.5. Electrical Interference and Grounding

Research shows that avionics racks help reduce electrical interference between electronic units. Good grounding and bonding are needed to avoid unwanted electrical noise. The rack often acts as a common grounding point, so good contact between parts is very important.

1.6. Assembly and Maintenance

Many designs focus on making racks modular so electronic units can be easily installed or removed. For crewed missions, easy access and repair are very important. Designers also consider how easily astronauts can reach components and handle connectors.

1.7. Testing Qualification

Avionics racks are tested using vibration, shock, and temperature tests to make sure they can survive space conditions.

1.8. Research Gaps and New Trends

Even though aluminium racks are widely used, research continues to find ways to reduce weight and improve design efficiency. New ideas like design optimization, digital models, and virtual testing are becoming more popular.

2. Literature Review

- Previous studies highlight the importance of thermal and structural design in avionics racks.
- Advanced cooling methods using micro-channel airflow improve temperature distribution in racks.
- Space station racks require independent thermal control systems due to varying experiment conditions.
- Modular rack systems like EXPRESS Rcak

3. Design of Avionics Rack

3.1. Design Considerations

The avionics rack design focuses on:

- Structural strength
- Component arrangement
- Thermal control [3]
- Vibration resistance
- Reliability and durability

3.2. CAD Modelling

The model is created using Siemens NX:

- Sketching base geometry
- Extrusion to form solids
- Adding holes and mounting features
- Applying fillets
- Assembling components using constraints

3.3. Components of Rack

Key components include:

3.3.1. Rack structure

Rack is a structure that supports and protects the electronic equipment in the correct position Shown in Figure 1.

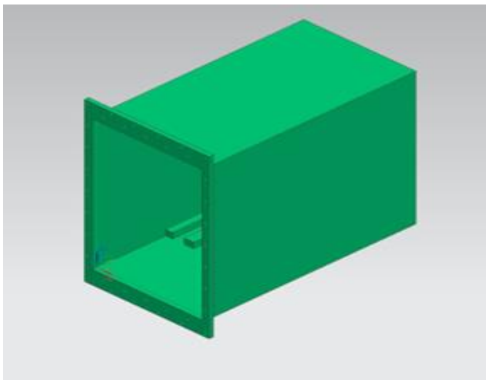

Figure 1 Isometric View of Rack

3.3.2. Motherboard Cover

The cover protects motherboard and helps harness connectors to get mounted and engaged with the corresponding connectors on motherboard Shown in Figure 2.

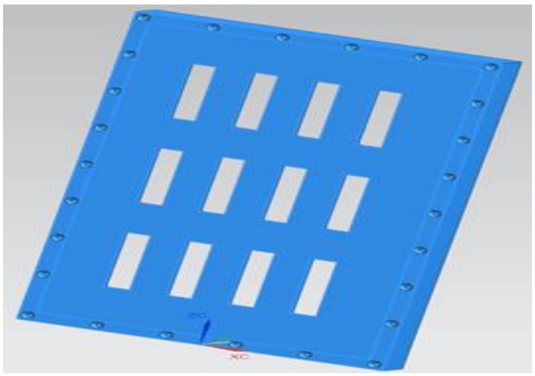

Figure 2 Isometric view of Mother Board

3.3.3. Primary covers

The primary cover is a metallic cover which covers primary (or top) side of the PCB. It protects the PCB structurally; it helps to achieve EMI/EMC specification of PCB module. It acts as a thermal sink for high dissipating components of PCB as well Shown in Figure 3.

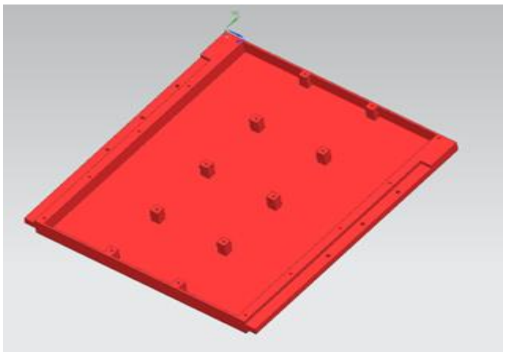

Figure 3 Isometric view of Primary Cover

3.3.4. Secondary covers

The secondary cover is a metallic cover which covers secondary (or bottom) side of the PCB [4]. It protects the PCB structurally; it acts as an EMI/EMC cover Shown in Figure 4.

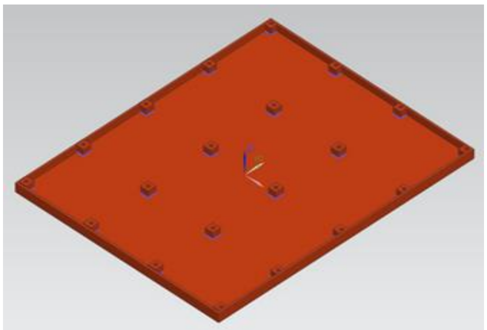

Figure 4 Isometric view of Secondary Cover

3.3.5. PCB

Printed Circuit Board (PCB) as the name suggests is where the electronic circuits are getting printed.

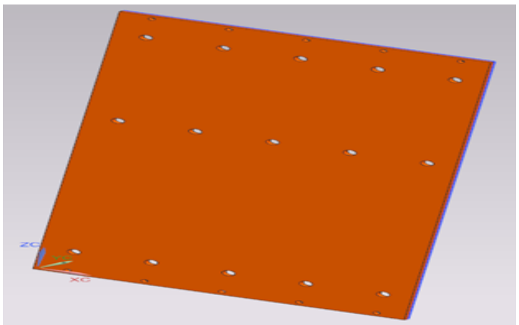

Figure 5 Isometric View of PCB

It's a multi-layer board where routings as per schematics are laid out [5]. It houses electronic components on both and top sides Shown in Figure 5.

3.3.6. Mother Board

Printed Circuit Board (PCB) as the name suggests is where the electronic circuits are getting printed [6]. It's a multi-layer board where routings as per schematics are laid out. It houses electronic components on both and top sides Shown in Figure 6.

Figure 6 Isometric View of Mother Board

3.3.7. Wedge lock

A wedgw lock is a mechanical system used to hold someting tightly in place by using pressure and friction. It eases process of assembly & dis-assembly. It facilitates replace-ability and reparability Shown in Figure 7 – 10.

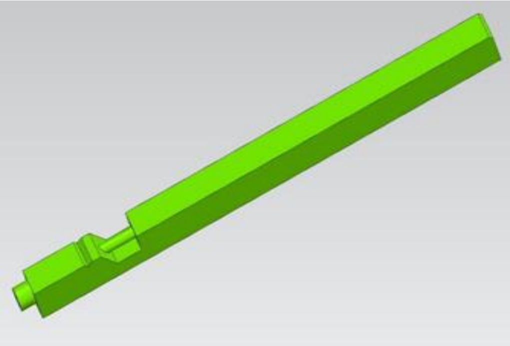

Figure 7 Isometric View of Wedge Lock

3.4. Assembly of Avionics Rack

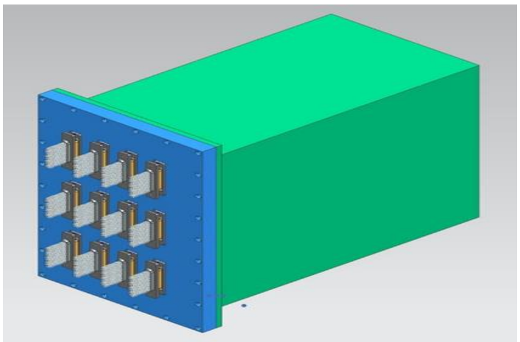

Figure 8 Isometric View of the Rack Assembly

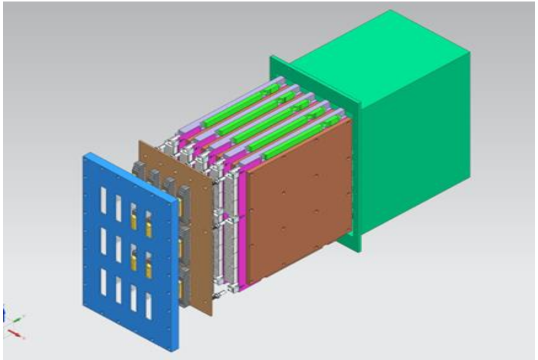

Figure 9 Exploded View of the Rack

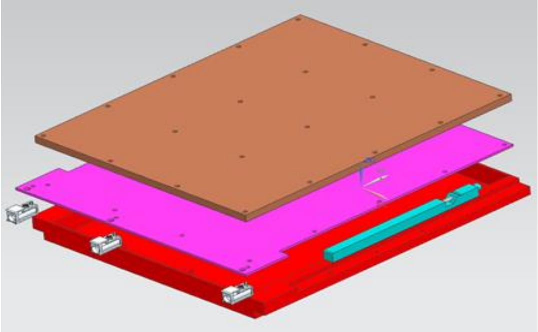

Figure 10 Exploded view of PCB module

4. Meshing

Meshing is a fundamental and critical step in Finite Element Analysis (FEA), where a complex geometric model is discretized into a finite number of smaller elements interconnected by nodes. This discretization converts the physical structure into a mathematical model, enabling numerical evaluation of structural behavior under different loading conditions. A well-defined mesh allows accurate prediction of key parameters such as stress distribution, deformation, strain, and overall structural stability. The quality of the mesh directly influences the accuracy, convergence, and reliability of simulation results. Poor mesh quality may lead to numerical instability, inaccurate results, or solver failure [7]. For aerospace structures like the avionics rack, meshing plays a vital role due to the need to withstand extreme launch loads, vibrations, and operational stresses. Therefore, careful selection of mesh type, element size, and quality parameters is essential.

4.1. Assembly Preparation and FEM Modeling

Prior to meshing, the complete avionics rack assembly was created in Siemens NX, incorporating all major components such as the rack frame, motherboard, PCB modules, and protective covers. The assembly ensures correct spatial positioning and interaction between components. Each component was then converted into a Finite Element Model (FEM), where mesh parameters, element types, and discretization strategies were defined.

4.2. Meshing Techniques Adopted

Two meshing techniques were employed based on the geometry and thickness of components:

- **3D Tetrahedral Meshing:** Three-dimensional tetrahedral elements were used for solid and components such as the rack structure, motherboard cover, and protective enclosures. These elements are well-suited for complex geometries and enable accurate representation of structural behavior.
- **2D Surface Meshing:** Two-dimensional elements were used for thin components such as PCBs and motherboard plates. Since thickness is negligible compared to planar dimensions, 2D meshing reduces computational effort while maintaining accuracy [8].
- **Element Size Selection:** An element size of 10 mm was selected to balance computational efficiency and accuracy. Smaller elements improve geometric representation and stress resolution but increase computational time, whereas larger elements reduce accuracy. The chosen size ensures sufficient detail while maintaining reasonable simulation time.
- **Mesh Quality Evaluation**

Mesh quality was assessed using key parameters such as:

- Aspect Ratio
- Skewness
- Jacobian
- Warpage

These parameters ensure that elements are well-shaped and suitable for numerical computation. High-quality mesh leads to stable solutions and accurate stress predictions, while poor-quality elements may cause distortion and unreliable results.

4.3. Assembly FEM (AFEM) and Connections

After meshing individual components, an Assembly FEM (AFEM) model was created to integrate all parts into a single simulation environment. Assembly constraints were retained to ensure realistic positioning. Mechanical connections such as bolt connections were defined to simulate real fastening conditions. Additionally, spider connections were used to distribute loads effectively from bolt locations to surrounding nodes, improving realism in load transfer.

4.4. Material Assignment

Material properties were assigned to each component:

- Aluminum Alloy (Al6061) for structural components due to its high strength-to-weight ratio and corrosion resistance
- FR-4 Epoxy Laminate for PCBs due to its insulation properties and thermal stability
- These properties enable accurate calculation of stress, strain, and deformation.
- Each component is designed to ensure structural stability and ease of assembly.

5. Boundary and Loading Conditions

The boundary conditions were defined to realistically simulate the mounting configuration of the avionics rack in a spacecraft environment. Instead of directly constraining the rack surfaces, a reference node was created at an offset distance of 15 mm from the mounting region. This approach avoids artificial stiffness and allows more realistic structural behaviour Shown in Figure 11.

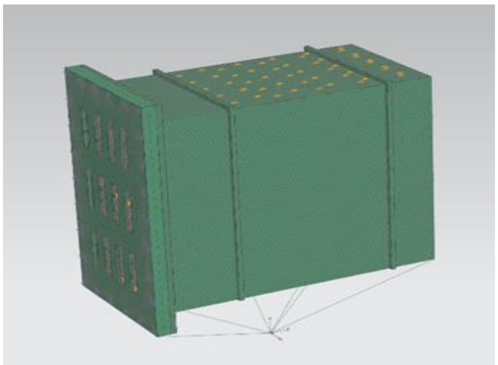

Figure 11 **Mounted Rack**

Six nodes from the mounting interface were connected to the reference node. This configuration represents the actual load transfer path through fasteners and mounting brackets. It simplifies the model while maintaining physical accuracy. At the reference node, translational degrees of freedom (X, Y, Z) were fully constrained. Rotational degrees of freedom were left (free), allowing slight rotational flexibility. This ensures the structure is fixed in position but not over-constrained. Additionally, fixed constraints were applied at critical mounting locations. These constraints restrict all six degrees of freedom, representing rigid attachment to the spacecraft frame. For dynamic loading, a Power Spectral Density (PSD)-based excitation was used. This method represents realistic launch vibrations, which are random and broadband in nature. A vibration level of 21 g RMS was applied to simulate launch conditions. This loading approach captures the effect of distributed vibration energy across frequencies. It enables accurate prediction of displacement, stress, and dynamic response under real operational conditions.

6. Structural Analysis Results

The structural behavior of the avionics rack was evaluated using finite element analysis under modal, random vibration, and static loading conditions.

6.1. Free-Free Analysis

A free-free analysis was first performed to validate the model. The first six natural frequencies were close to zero, confirming proper connectivity and absence of unwanted constraints. This ensures the model is physically correct and ready for further analysis Shown in Table 1

Table 1 **Free Analysis Results**

Modal	Frequency
1	0.4 Hz
2	0.4 Hz
3	0.4 HZ
4	0.4 Hz
5	0.4 Hz
6	0.0017 Hz
7	109.37 Hz
8	175.09 Hz

In these results we understood that there are no loose connections or any unconnected connection every connection is connected properly so we will proceed to the modal analysis.

6.2. Modal analysis

Modal analysis was conducted to determine natural frequencies and mode shapes. From the above table modal results, it is observed that the first mode is occurring at 192Hz at low frequency due to its lesser stiffness Shown in Figure 12 & 13. In order to overcome this, stiffeners are added to the motherboard and the outer Rack Shown in Table 2 & 3.

Table 2 **Modal Analysis**

Mode	Frequency	Mass Participation		
		X	Y	Z
1	192	63.93858	0.00016	0.09045
2	263	0.02102	37.67275	39.00180
3	396	14.81323	0.04343	0.07415
4	535	0.85841	27.79748	53.25748

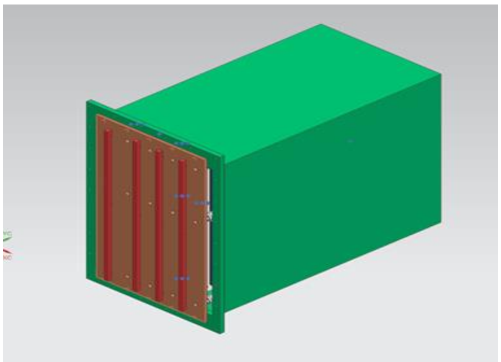

Figure 12 **Stiffeners to the Motherboard**

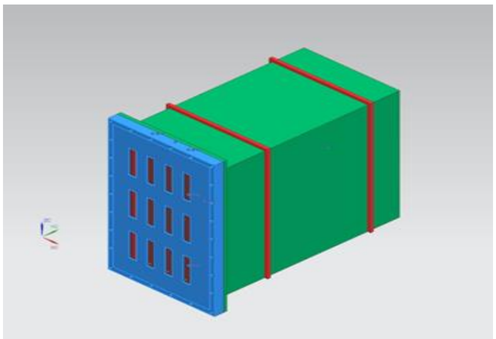

Figure 13 **Stiffeners to the outer Rack**

Table 3 **Modal Characteristics of the Avionics Rack Structure**

Mode	Frequency	Mass Participation		
		X	Y	Z
1	233	63.17879	0.06840	0.35928
2	405	0.27135	53.13511	2.99480
4	683	0.44312	0.69702	44.06788

7	03	0.17246	0.19792	18.83258

In the above table we can see the results where we improved the stiffens by adding the stiffeners to the rack and the motherboard the frequency was increased, we will proceed with these modified results Shown in Figure 14 & 15.

6.2.1. Contour Plots

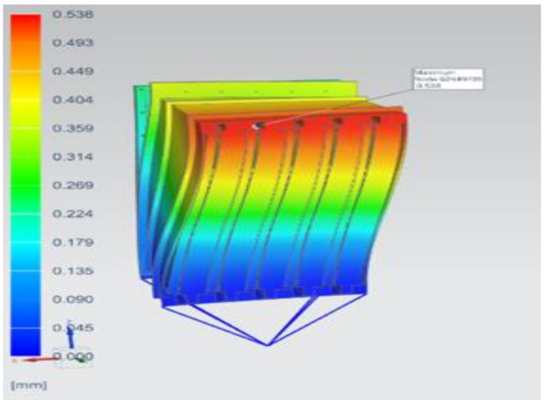

Figure 14 **Mode 1**

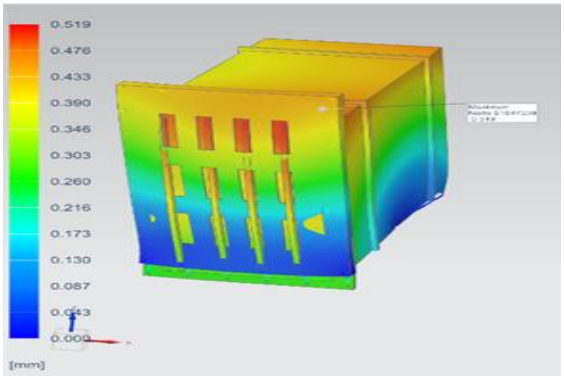

Figure 15 **Mode 2**

6.3. Random Analysis

Random vibration analysis was performed using PSD input of 21 g RMS to simulate launch conditions.

The response was evaluated in terms of:

- RMS displacement
- RMS acceleration
- Peak response
- Transmissibility

Critical regions with maximum vibration response were identified through contour plots. PSD response curves were used to study frequency-dependent behaviour Shown in Figure 16 - 51.

6.3.1. Random Analysis Results

Rack in Z direction

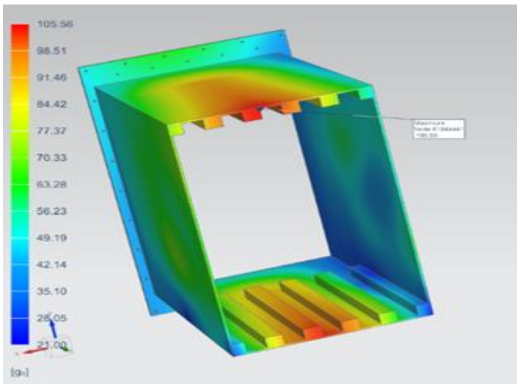

Figure 16 **RMS Acceleration**

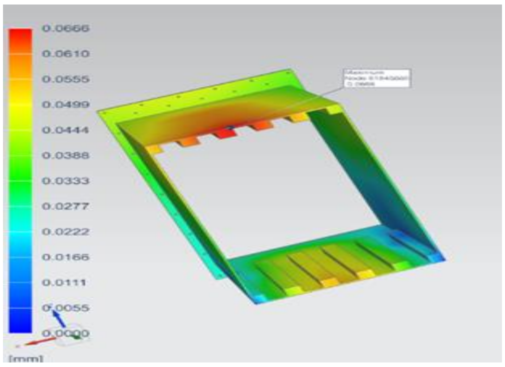

Figure 17 **RMS Displacement**

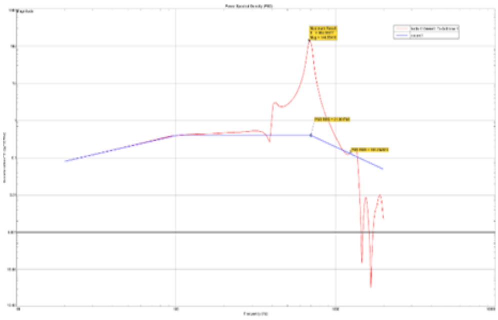

Figure 18 **Peak random Response Curve**

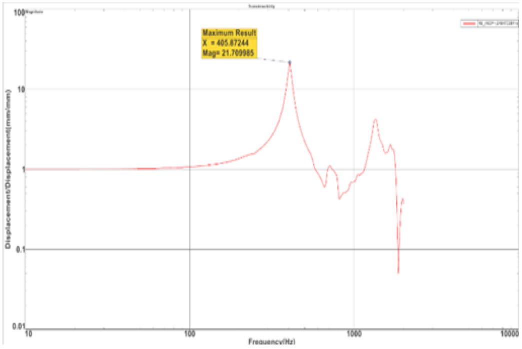

Figure 19 **Transmissibility Curve**

PCB in Z direction

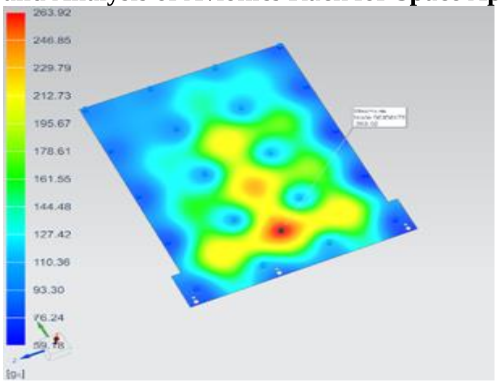

Figure 20 RMS Acceleration

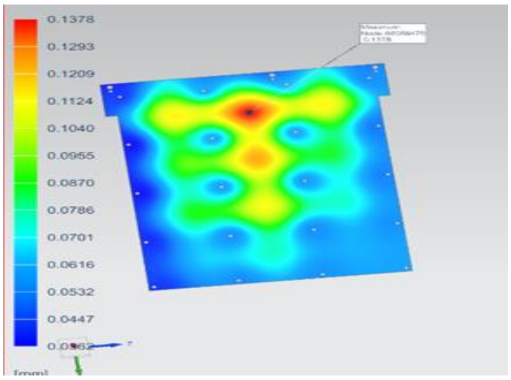

Figure 21 RMS Displacement

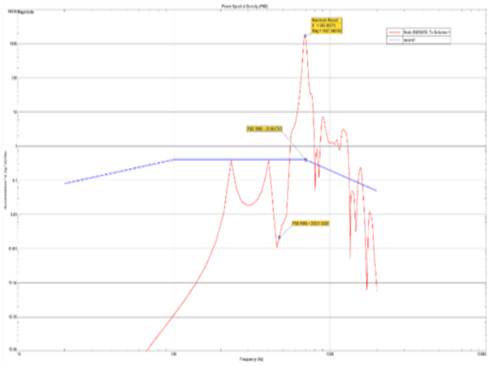

Figure 22 Peak Random Response Curve

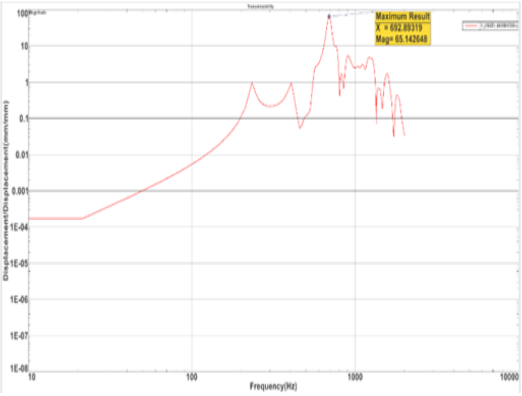

Figure 23 Transmissibility Curve

Motherboard in Z direction

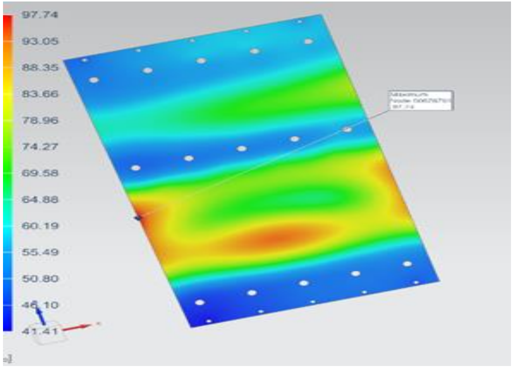

Figure 24 RMS Acceleration

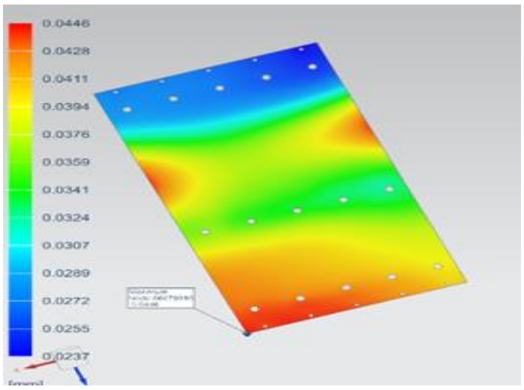

Figure 25 RMS Displacement

Figure 26 Peak Random Response Curve

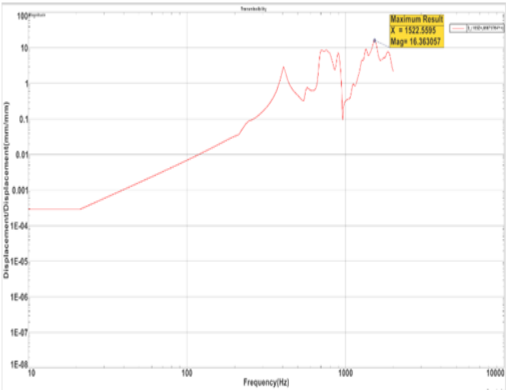

Figure 27 Transmissibility Curve

PCB Module in Z direction

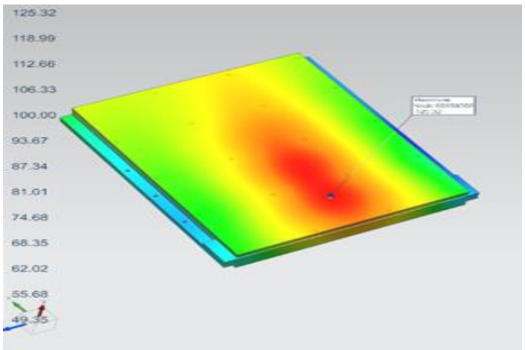

Figure 28 RMS Acceleration

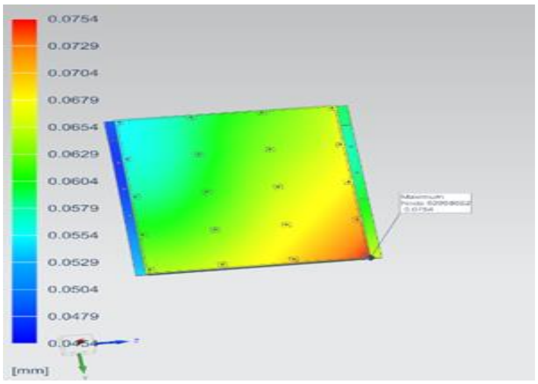

Figure 29 RMS Displacement

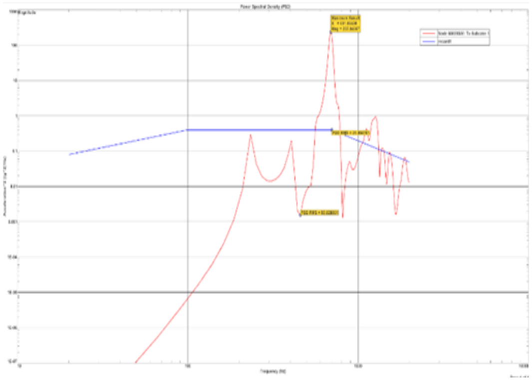

Figure 30 Peak Random Response Curve

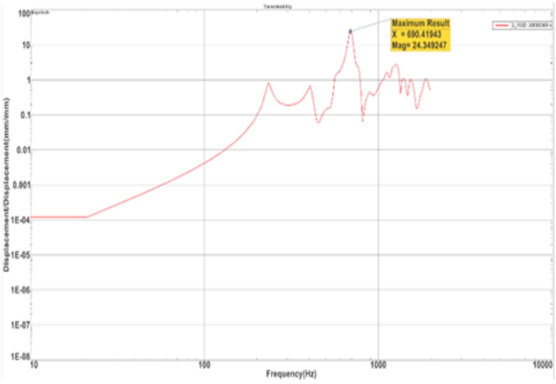

Figure 31 Transmissibility Curve

PCB in Y direction

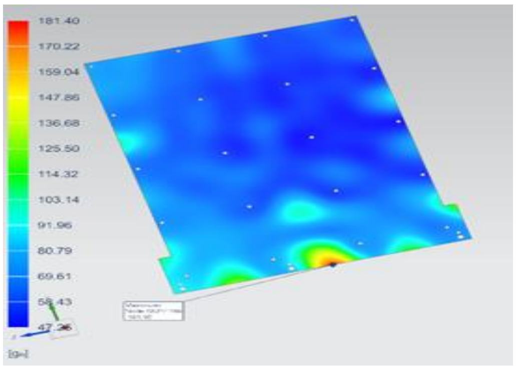

Figure 32 RMS Acceleration

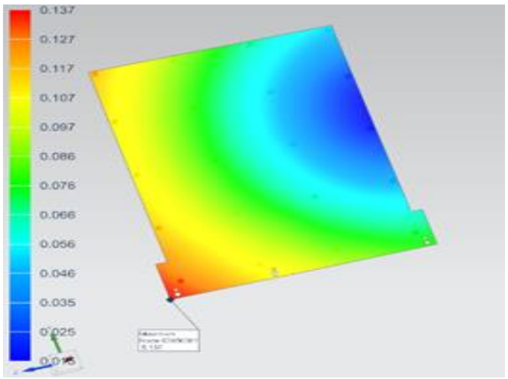

Figure 33 RMS Displacement

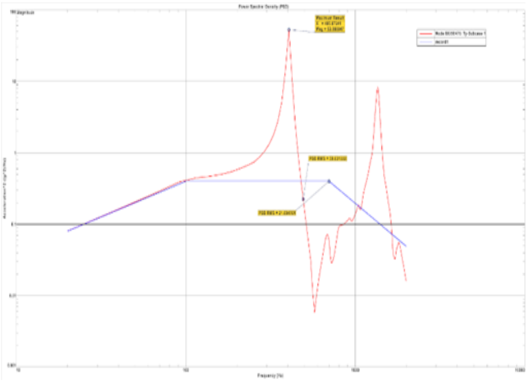

Figure 34 Peak random Response Curve

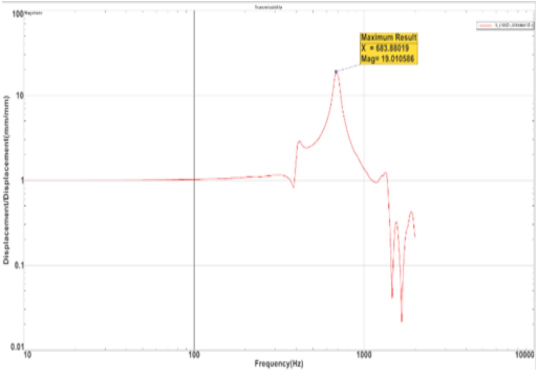

Figure 35 Transmissibility Curve

Motherboard in Y direction

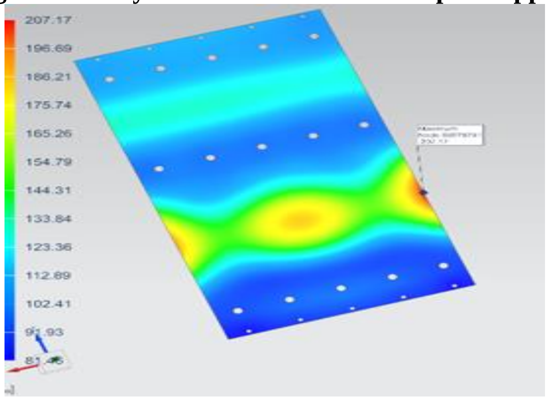

Figure 36 **RMS Acceleration**

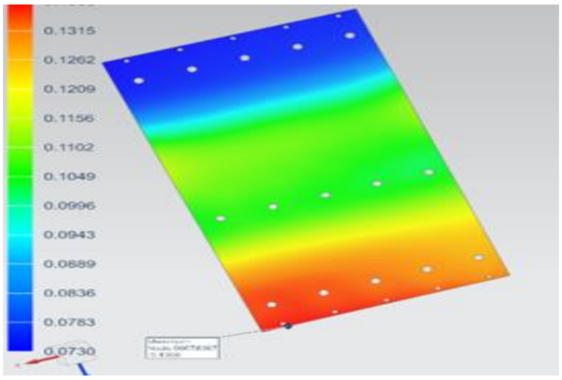

Figure 37 **RMS Displacement**

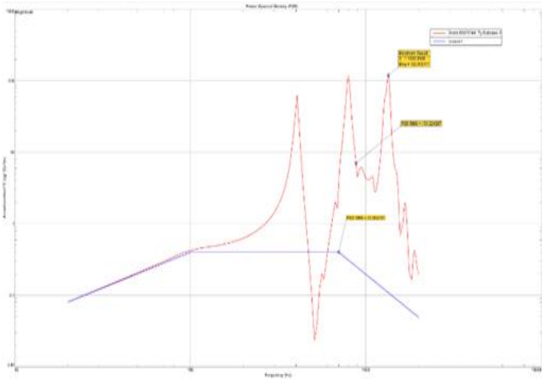

Figure 38 **Peak Random Response Curve**

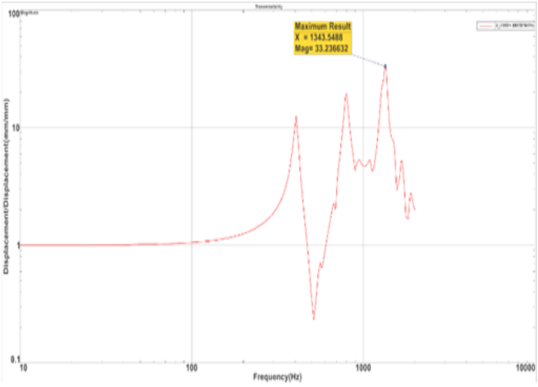

Figure 39 **Transmissibility Curve**

PCB Module in Y direction

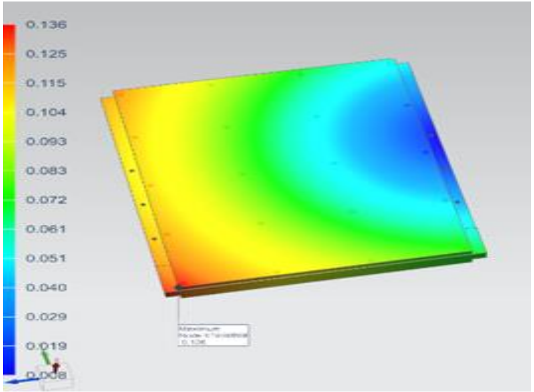

Figure 40 **RMS Acceleration**

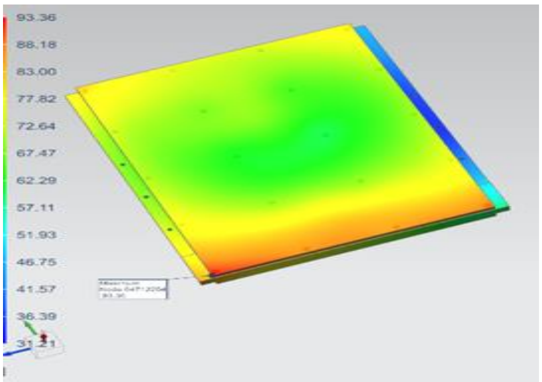

Figure 41 **RMS Displacement**

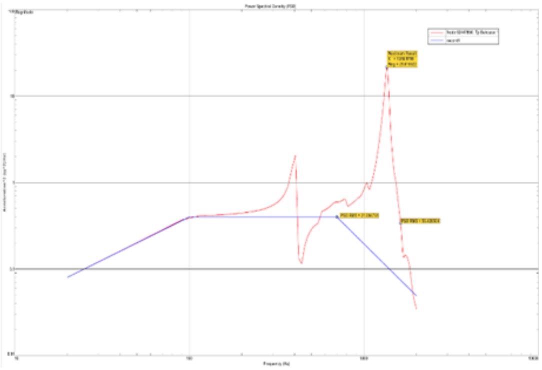

Figure 42 **Peak Random Response Curve**

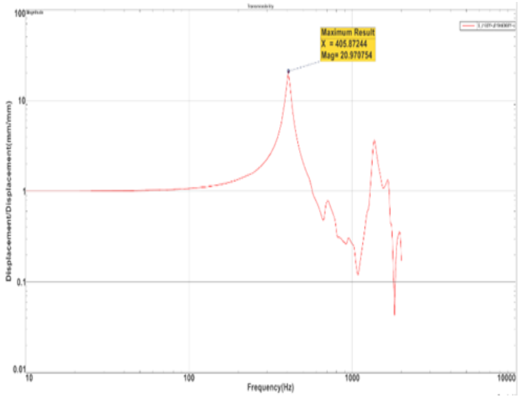

Figure 43 **Transmissibility Curve**

PCB in X direction

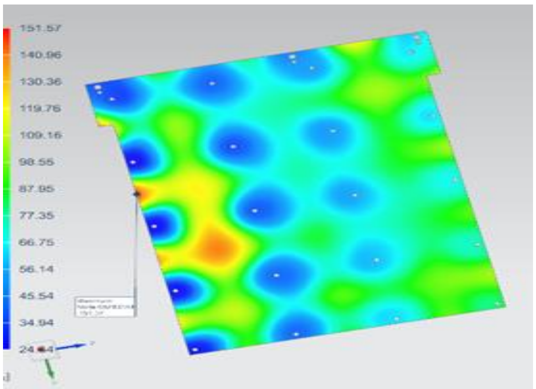

Figure 44 RMS Acceleration

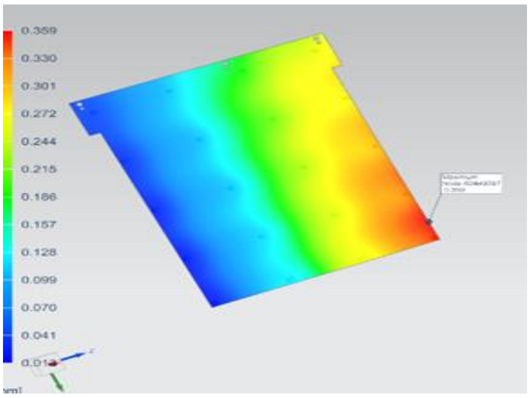

Figure 45 RMS Displacement

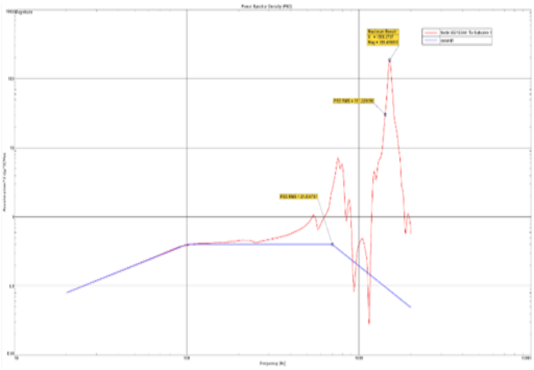

Figure 46 Peak Random Response Curve

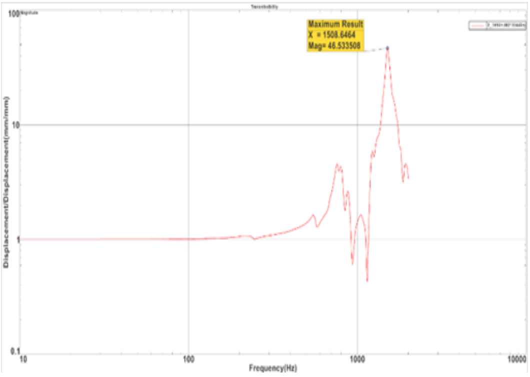

Figure 47 Transmissibility Curve

Motherboard in X direction

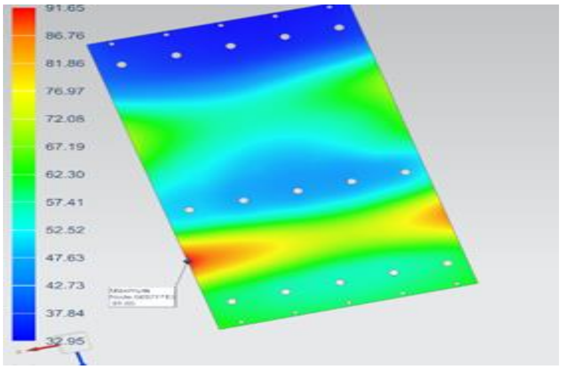

Figure 48 RMS Acceleration

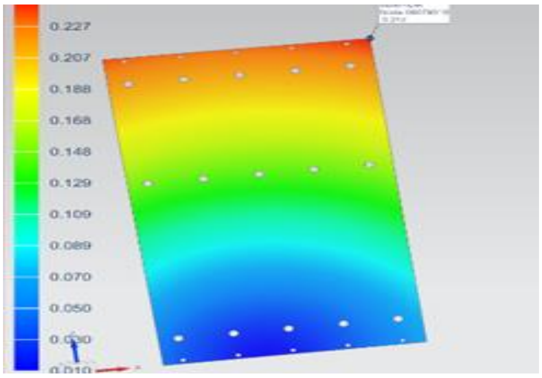

Figure 49 RMS Displacement

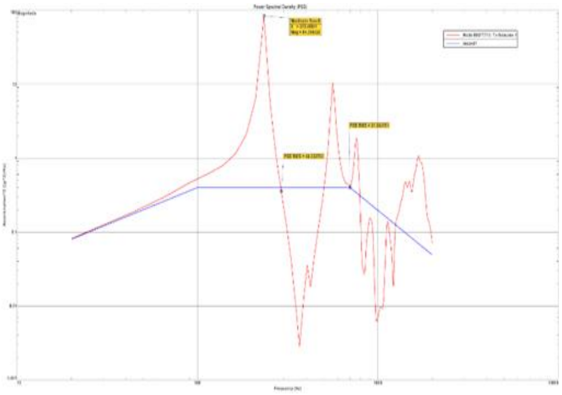

Figure 50 Peak Random Response Curve

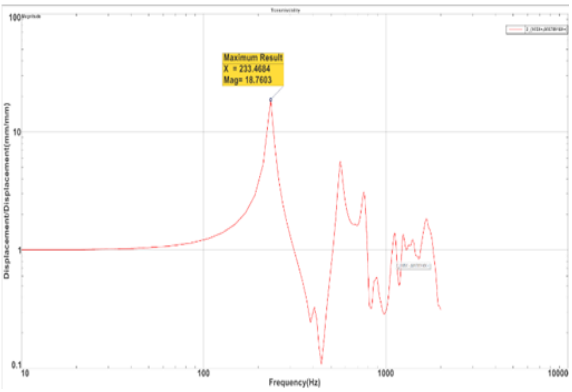

Figure 51 Transmissibility Curve

Table 4 Random Response Results

Location	Transmissibility	Grms Output
Rack	26.8147 @ 1244.11Hz	118.05g
PCB	28.85 @ 233.4Hz	263.92g
PCB Module	28.85 @ 233.46Hz	125.32g
Motherboard	33.23 @1343Hz	207.17g

Table 5 Random Results Table

	Maximum Random Loading Output longitudinal direction 21Grms		
	RMS	**3σ**	**MOS over 3σ**
Max. Stress in rack (MPa)	41.6	124.8	0.92
Max. Stress in PCB (MPa)	27.8	83.4	2.71
Max. Stress in PCB Module (MPa)	30.9	92.7	1.58
Max. Stress in Motherboard (MPa)	8.2	24.6	11.60
Max Displacement in rack(mm)	0.358	1.047	
Max Displacement in PCB (mm)	0.359	1.077	
Max Displacement in PCB module (mm)	0.359	1.077	
Max Displacement in Motherboard (mm)	0.247	0.741	

Results showed

The rack exhibited controlled deformation and acceptable stress levels under random loading. Transmissibility plots confirmed that vibration amplification remained within safe limits.

6.4. Static Analysis

Static structural analysis is used to evaluate the behaviour of a structure when subjected to static loads. It helps determine how the structure responds in terms of deformation, stress distribution, and overall structural integrity The main objective of the static structural analysis was to evaluate whether the avionics rack design can safely withstand the loads experienced during operation and launch conditions. The analysis was conducted to:

- Determine the stresses developed in the structure Shown in Table 4 & 6
- Evaluate the deformation under applied loads
- Identify critical regions with high stress concentration Shown in Figure 52 - 75
- Ensure that stresses remain within allowable material limits

This evaluation helps verify the structural reliability of the avionics racks overall structural integrity.

6.4.1. Static Analysis results

Rack in Z direction

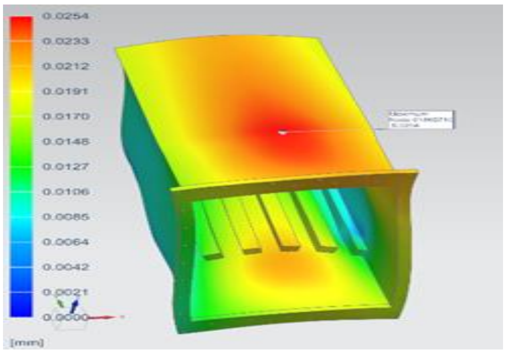

Figure 52 Displacement Contour

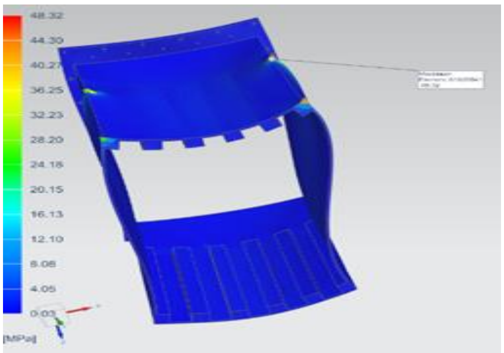

Figure 53 Stress Contour

PCB in Z direction

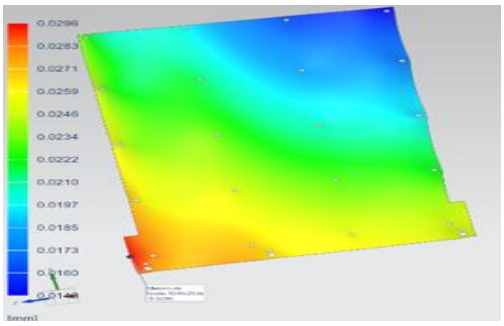

Figure 54 Displacement Contour

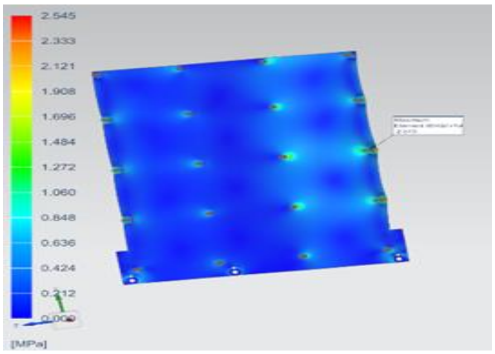

Figure 55 Stress Contour

Motherboard in Z direction

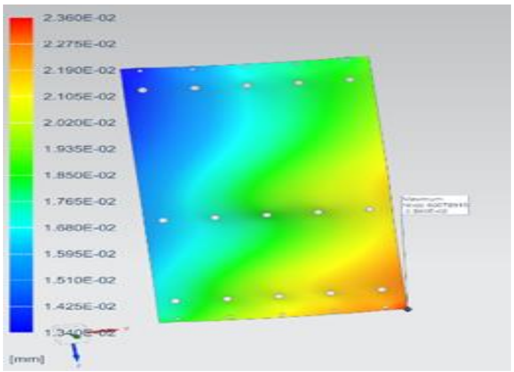

Figure 56 Displacement Contour

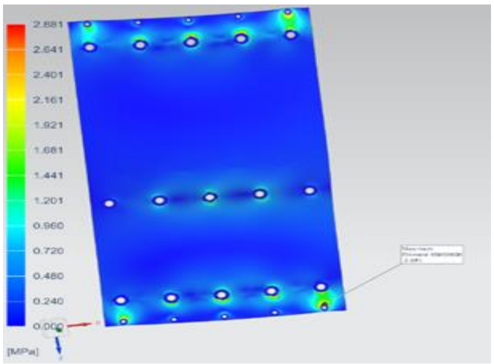

Figure 57 Stress Contour

Rack in Y direction

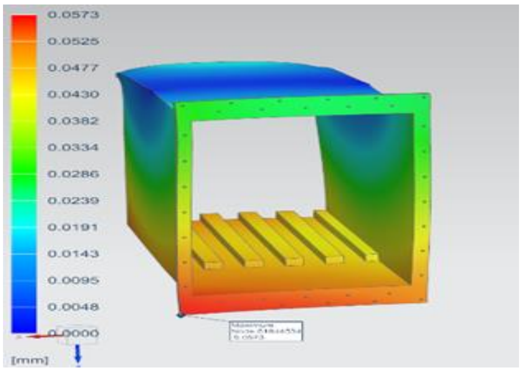

Figure 58 Displacement Contour

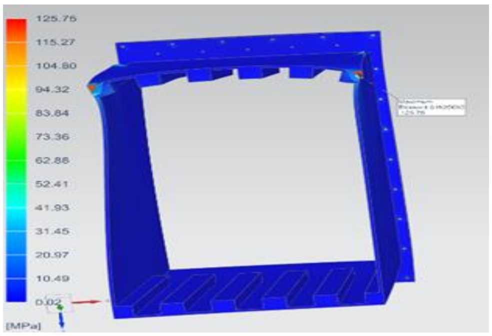

Figure 59 Stress Contour

PCB in Y direction

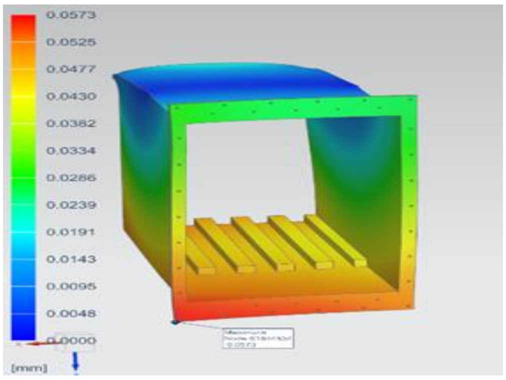

Figure 60 Displacement Contour

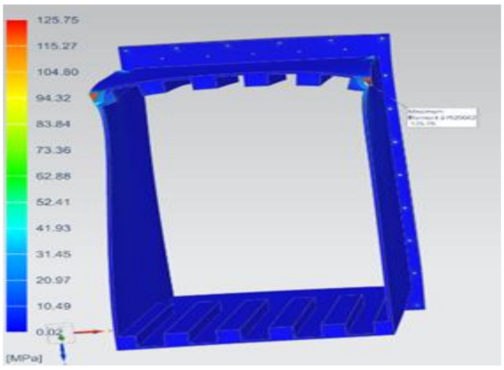

Figure 61 Stress Contour

Motherboard in Y direction

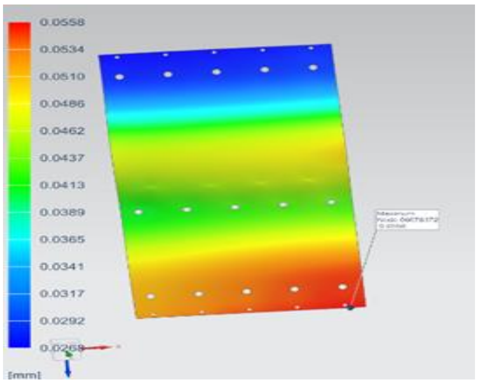

Figure 62 Displacement Contour

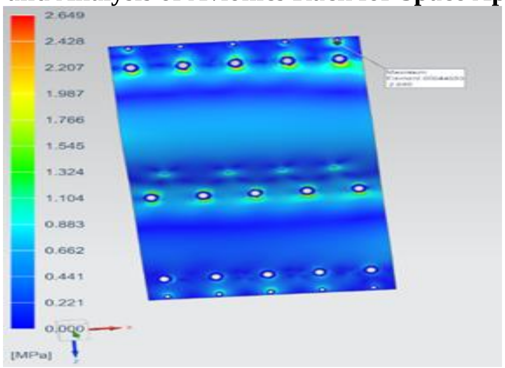

Figure 63 Stress Contour

PCB Module in Y direction

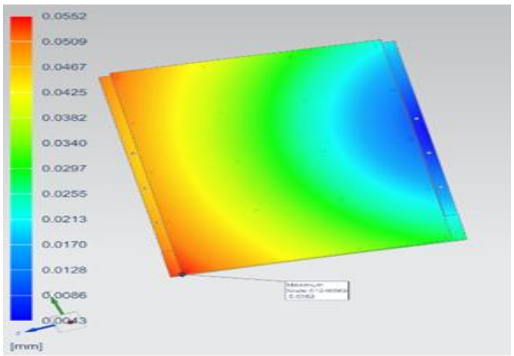

Figure 64 Displacement Contour

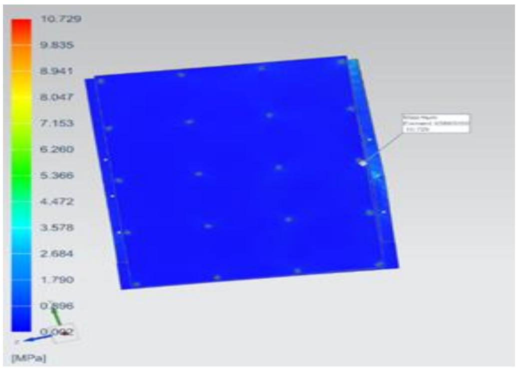

Figure 65 Stress Contour

PCB Module in Y direction

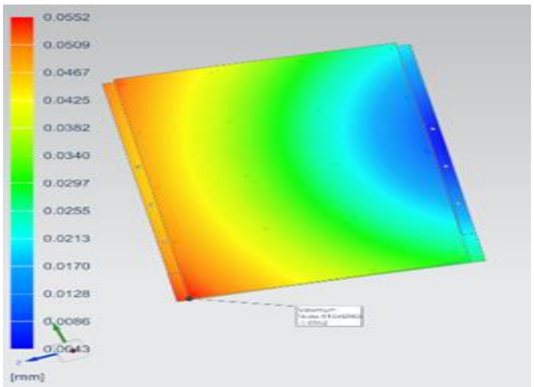

Figure 66 Displacement Contour

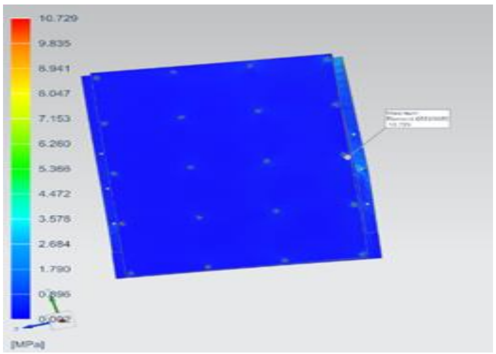

Figure 67 Stress Contour

Rack in X direction

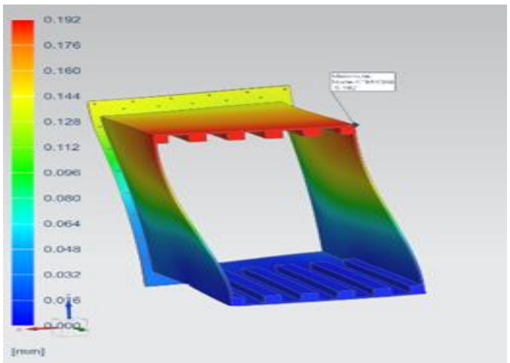

Figure 68 Displacement Contour

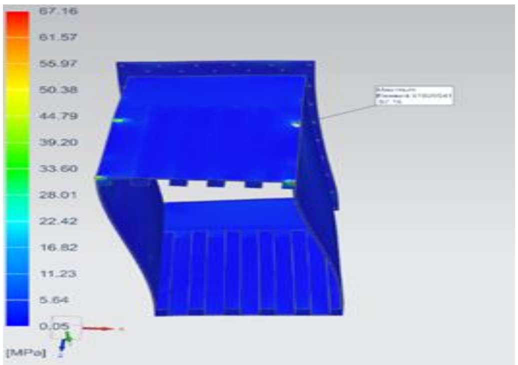

Figure 69 Stress Contour

PCB in X direction

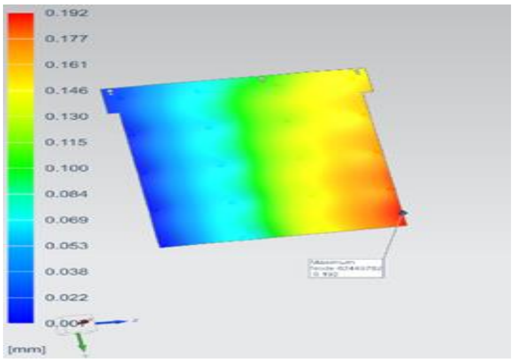

Figure 70 Displacement Contour

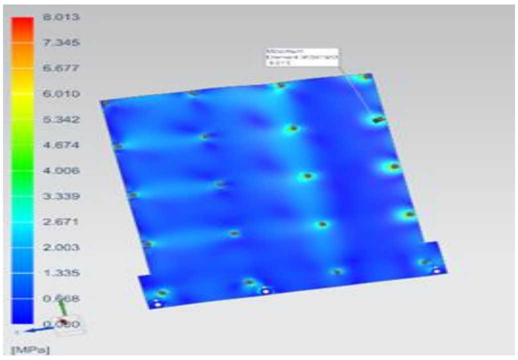

Figure 71 Stress Contour

PCB Module in X direction

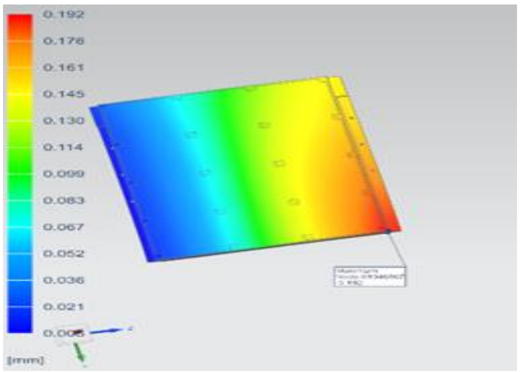

Figure 72 Displacement Contour

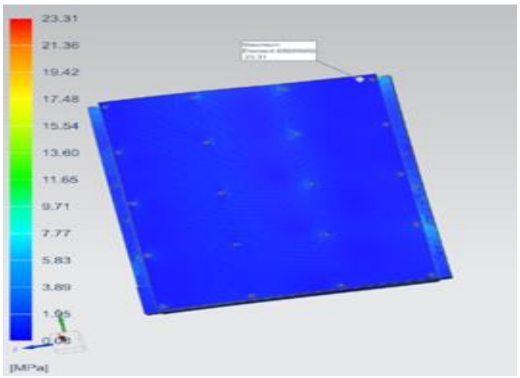

Figure 73 Stress Contour

Motherboard in X direction

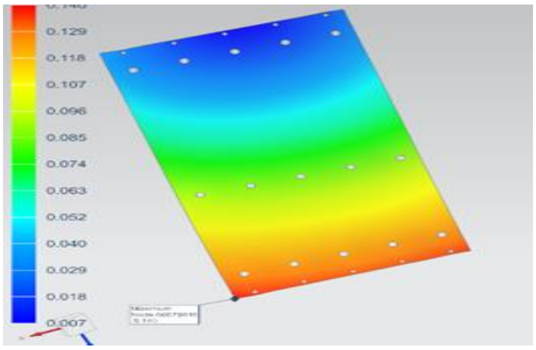

Figure 74 Displacement Contour

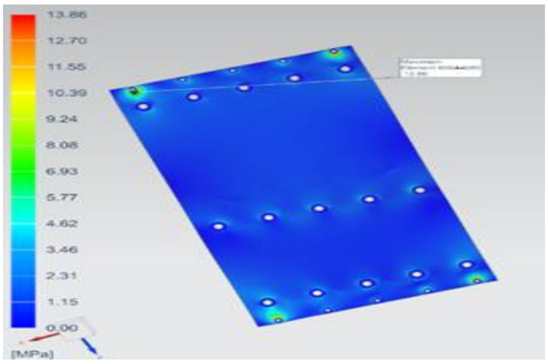

Figure 75 Stress Contour

Table 6 Static Result Summary

	30g Longitudinal (Z)	**30g Lateral (Y)**	**30g Lateral (X)**
Max. Stress in Rack (MPa)	48.32	125.75	67.16
Max. Stress in PCB(MPa)	2.545	3.300	8.013
Max. Stress in PCB Module (MPa)	13.58	10.729	23.31
Max. Stress in Motherboard (MPa)	2.881	2.649	13.86
Max. Displacement in Rack	0.0254	0.0573	0.192
Max. Displacement in PCB	0.0296	0.0557	0.192
Max. Displacement in PCB Module	0.0301	0.0552	0.192
Max. Displacement in Motherboard	2.360E-0.2	0.0558	0.140

Conclusion

The structural analysis showed that the rack can safely withstand the forces experienced during launch and operation. The stress levels and deformation remained within safe limits, ensuring that the structure will not fail under expected conditions. The vibration study also confirmed that the design avoids resonance, which is important for maintaining stability during launch

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