Design and Analysis of Space Borne Camera

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Abstract -*Docking and berthing are two techniques for making contact of two space vehicles in space environment. Docking specifically refers to capture of free-flying space vehicles by another. Docking camera and navigation systems will make docking and undocking of Space Station and another spacecraft easier and safer. This is the first time INDIA is going to achieve the docking of space craft's. This paper deals with the "Design and Analysis of Space Borne Camera" which has to sustain the launch vibrations and work in stringent space environment. The docking spacecrafts should move towards another spacecraft, using direction, attitude, angles of target vehicle with high precision for this Space Borne Camera (SBC) system being designed. The static and dynamic characterization of the designed camera has been evaluated and simulated using FEA tools. The target identification range of camera is 20m. The several test conditions such as Modal Analysis, Quasi static analysis, Thermostatic Analysis, Random Vibration Analysis and simulation results are adequate. The design is ready to be incorporate in the space mission.*

Key Words*: *Docking, Space borne camera, Berthing, Dynamic characterization. Modal Analysis.

1.INTRODUCTION

Space borne camera (SBC) is designed to capture the image of illuminated pattern in space. The camera and pattern are carried by different space craft's separated by fixed distance; camera images of the pattern are determining the position of illuminated pattern and relative alignments of crafts [1-2]. Similar camera design are studies from NASA mars science laboratory (MSL) designed a camera for the curiosity mission that is known as Mast camera (mast cam). Curiosity consists of pair of focusable digital CCD camera (detector, optics, filter wheels). Curiosity was launched in November 2011and landed in gale on 6 august 2012. Focal length is 34mm and 100mm respectively [3]. Mangalyaan or Mars orbit mission: It was launched on November 5, 2013 on board a polar rocket from shriharikot, for this mission Mars Colour Camera (MCC) was used. It's Instantaneous Geometric Field of View [IGFOV] varies from 19.5m to 4Km. Detector 2000pxx2000px array detector with RGB buyer filter is used in the Mangalyaan mission [4]. Chandrayann-1, It was launched on October 22, 2008 in this mission Terrain Mapping Camera was used. A complete topographic map of the moon with 5m spatial resolution. The swath coverage will be 20km.The weight of the instrument is about 6 kg [5]. Selection of the number of detectors and number of Optics module lenses usage and the material selection for the mission of cameras is purely depend on the function it going to perform in the space and purely a requirement to the space application on the bases of the application mass and size of the of the camera package will be varies. Mast Camera, Mars colour camera and Terrain Mapping Camera are used for the imaging purpose so for. This SBC is mainly used for the docking in India first time [3-5].

1.1 Working principle

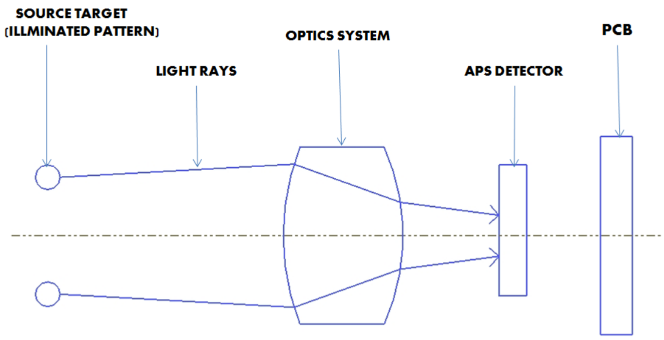
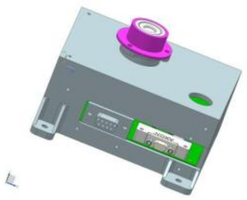


Fig. 1. Working principle SBC

This working principal of the SBC is similar to the normal camera. The camera system with basic components is shown in figure 1. The energy from the target source is collected by a set of optics and brought to the focal point where the APS detector is located for electronic scanning or modulation. The source target crafts consist of the illuminated patterns (LEDs) which are visual spectrum lights [1, 6]. Patterns from the source target is identified and allows the rays to moves towards APS detector through optics lens system. Filter in the optics system which filters out the unwanted light rays coming from the space. APS detector which was mounted on the PCB senses the patterns and send the data information to the to the electronic processing module which determines the location and orientation of target source [7]. Using this information, the craft is made to move towards the target source.

2. CAD Model of the SBC

Modeling is done using NX 8.5 [8], based on the design specifications for each component. Figure 2 and 3 shows Assembled and exploded CAD Model of the SBC system respectively. The main requirement is to have minimum weight and minimum size without compromising for strength. Basically, it consists of an Active Pixel Sensor (APS) detector, 3 lens optic systems, PCB with electronic components and the mechanical housing. The PCBs are fixed to the housing using button system at the four corners. Mechanical housing is the important component of the package which gives the mechanical support. Point contact legs are provided at the bottom and suitable flange to be provided for coupling the lens assembly to camera housing. Focal length of the optics is 20mm. Sufficient margins are available in the mechanical design of SBC Assembly for various loads and sufficient gaps (> 2 mm) are maintained between all the PCBs and mechanical components. Mass of the SBC is 1.14 kg. Material a property of the structural of SBC System is tabulated in table 1.



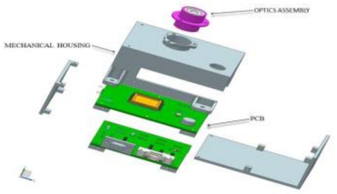


Fig. 2. Assembled isometric view of SBC **Fig. 3.** Exploded view of SBC

Table. 1. Material properties of the structure

Material properties of the structure					
SL. NO	Component	Housing	Optics cells	Optics lens	PCB
1	Material	AL-6061	Ti-6AL4V	SF-6	FR-4
2	Density (kg/mm^3)	2.7xe^{-6}	4.43xe^{-6}	5.52xe^{-6}	1.90xe^{-6}
3	Young's modulus (MPa)	69000	114000	50000	22000
4	Thermal conductivity (W/mK)	167	6.7	0.673	0.25
5	CTE-α (1/^{0}C))	24xe^{-6}	8.80xe^{-6}	8.8xe^{-6}	1.6xe^{-5}
6	Yield strength	210	880	16	70
7	Poisson's ratio	0.33	0.342	0.244	0.136

3. Finite element model of SBC

Finite element modeling of SBC assembly is carried out in UG NX 8.5 CAE software [8]. Hex-8 elements are used for meshing of all components. Node-to-node connectivity is ensured within each part and between two components. Components are rigidly connected using bolted connections. In order to simulate the weight of the components such as detectors, FPGAS, Connectors etc. 6 concentrated masses are put on the PCBs. The meshed model of the camera assembly is shown in figure 4.

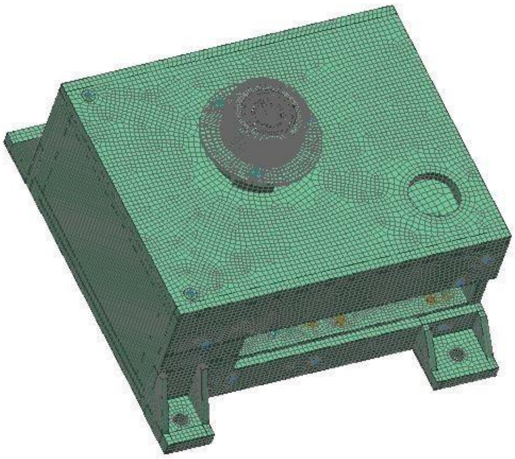


Fig. 4. Finite element model of SBC.

MESH SUMMARY:-
Total number of elements in the part: 120566
Total number of nodes in the part: 163653
Number of concentrated mass elements: 6
Number of bar elements: 27
Number of rigid link elements: 55
Number of Hex8 elements: 120334

4. Boundary Conditions and Analysis Results

4.1. Modal Analysis (Free Condition)

Modal analysis under free condition is carried out to understand how the Space Born Camera assembly behaves when it is unconstrained i.e. without the application of boundary conditions. It gives an idea about where to constrain the Space Born Camera Assembly in order to get minimum vibration. Here, the first six modes are rigid modes and hence equal to zero [9].

4.1.1 Modal Analysis (Constrained Condition)

In Constrained or Clamped Modal analysis, there should be no zero-frequency modes. If any zero frequencies are found, it is an indication that some portion of the assembly is free to move in a rigid body manner and that the components of assembly are not constrained properly. For performing constrained modal analysis, the assembly is fixed at the interface mounting holes and all the translation and rotational displacements of these nodes on the edge mounting holes in X, Y and Z direction are set to zero [9]. Fig

5 shows the Boundary conditions for modal and static analysis.

Fig. 5. Boundary Conditions for Modal and Static analysis

Mode-19 is Significant global mode frequency (1437 Hz) and First 10 modes of the free-free condition and first 20 modes of clamped condition analysis results are shown in figure 6. Individual mode result [14] and critical region also tabulated in the table 2 and table 3. The Mode -7 natural frequency of SBC in free-free condition is 360Hz. TheMode-1 natural frequency of SBC in clamped condition is 354Hz. For any space craft component, the natural frequency should be more than 200Hz the natural frequency of the designed SBC system is 354 Hz there will not be any resonance when it is subjected to launch level vibration [15-16].

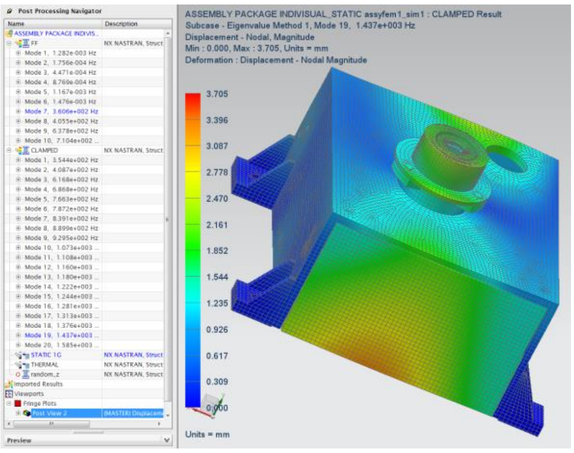


Fig. 6. Modal free-free and clamped condition analysis results (19 mode image).

Table 2. Eigen values of the SBC for Free-Free Condition

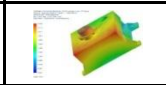
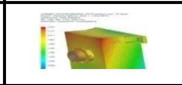
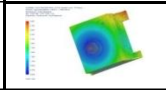
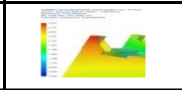
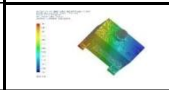
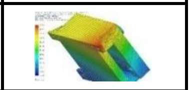
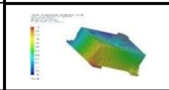
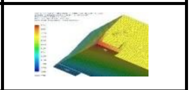
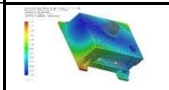
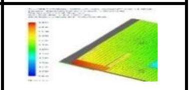
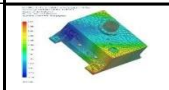
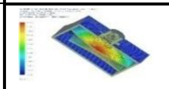
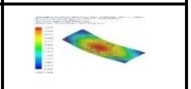
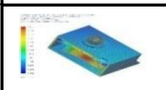
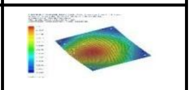
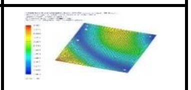
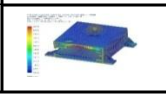
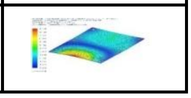
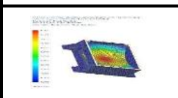
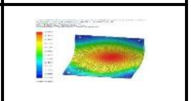
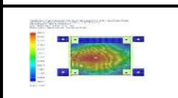
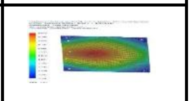
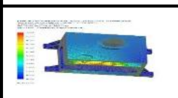
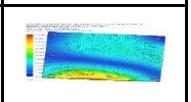
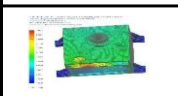
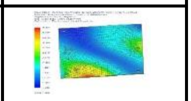
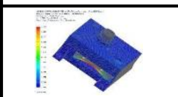
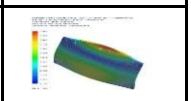
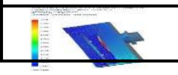
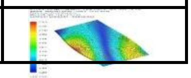
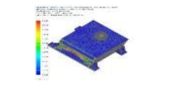
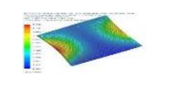
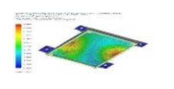
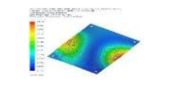
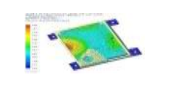
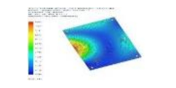
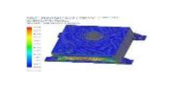
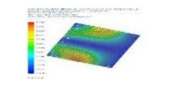
Mode number	Frequency (Hz)	Mode Shapes	Critical Region
Mode 1	$1.28X10^{-3}$		
Mode 2	$1.75\ X10^{-3}$		
Mode 3	$4.47\ X10^{-3}$		
Mode 4	$8.76\ X10^{-3}$		
Mode 5	$1.16\ X10^{-3}$		
Mode 6	$1.47\ X10^{-3}$		
Mode 7	$3.60\ X10^{2}$		
Mode 8	$4.05\ X10^{2}$		
Mode 9	$6.37\ X10^{2}$		
Mode 10	$7.10\ X10^{2}$		

Table 3. Eigen values of the SBC for Constrained Condition

Mode number	Frequency (Hz)	Mode Shapes	Critical Region
Mode 1	$3.54X10^{2}$		
Mode 2	$4.08\ X10^{2}$		
Mode 3	$6.16\ X10^{2}$		
Mode 4	$6.86\ X10^{2}$		
Mode 5	$7.66\ X10^{2}$		
Mode 6	$7.87\ X10^{2}$		

Mode 7	8.39 X10^2		
Mode 8	8.89 X10^2		
Mode 9	9.25 X10^2		
Mode 10	1.07 X10^3		

4.2 Quasi static analysis

In linear static analysis [17], displacement and Von Mises stress under 50g load is calculated. Quasi-Static analysis is done for unit load and results for actual loads are obtained through extrapolation form unit load [9]. The different boundary cases considered for the

analysis they are mentioned below:

a) Load case 1: 50g Perpendicular to optical axis (X-axis).

b) Load case 2: 50g Along the optical axis (Y-axis).

c) Load case 3: 50g Perpendicular to the optical axis (Z-axis).

Static analysis results along Y directions, The Von-mises stresses and displacement found from the static analysis along Y- axis are 0.524 MPa and 0.003 mm respectively. These are shown in the figures 7a, and 7b. Stress experienced by the individual components like lens and PCBs are 0.002 MPa and 0.26 MPa respectively which is shown in the figure 7c and figure 7d.

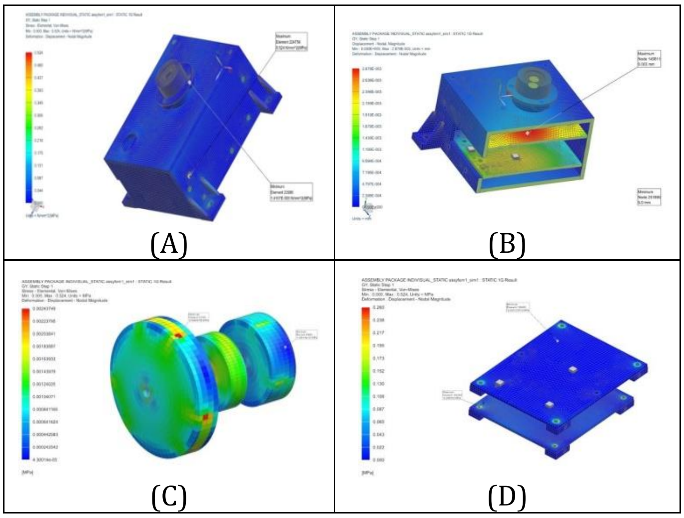


Fig. 7. Static Analysis Results along Y-axis (a) Von-mises stresses in assembly, (b)Displacement in the assembly, (c) Von-mises stresses in lens, (d) Von-mises stresses in PCBs.

Similarly, the Von-mises stresses and displacement found from the static analysis along X- axis are 0.468 MPa and 0.0006 mm. Stress experienced by the individual components like lens and PCBs are 0.0025 MPa and 0.201 MPa respectively. The Vonmises stresses and displacement found from the static analysis along Z-axis are 0.446 MPa and 0.0006 mm respectively. Stress experienced by the individual components like lens and PCBs are 0.0027 MPa and 0.16 MPa. In static analysis for 1g the maximum von-mises stresses in X, Y and Z directions are 0.468, 0.524 and 0.446 MPa and these stresses are noticed in the housing near the bolt connection. Maximum stress, displacement and the factor of safety under 50g quasi static load is tabulated in table 4. Max stresses are experienced by each component are tabulated in the table 5 subjected under quasi static load of 50 g.

FOS = Yield Stress/Allowable Stress

Table 4. Displacement and Von Mises stress for the Assembly for Static Analysis.

Load case	50g (X-axis)	50g (Y-axis)	50g (Z -axis)
Max stress (von mises stress) (MPa)	23.4	26.20	22.3
Max displacement (mm)	0.0324	0.15	0.03
FOS	9.03	8.01	9.14

Table 5. Von Mises stress of Individual Components of Assembly for Static Analysis.

Component	Material	Yield Stress (MPa)	Von mises Stress(MPa)	FOS
LENS	SF-6	16	0.135	106
PCB's	FR-4	70	13	5.38
HOUSING	Al-6061	210	26.2	8.01

4.3. Thermostatic Analysis

The camera system during its operation in space undergoes temperature changes. The specified temperature limits to which the SBC is subjected is -100C to 500C. The analysis is carried out for the temperature limits of +200C to +500C. The maximum displacement of 0.091mm is noticed in the top plate is shown in figure 8a and the maximum stress of 155 MPa is observed at the bottom fixing legs which is shown in figure 8b and the factor of safety is 1.35.

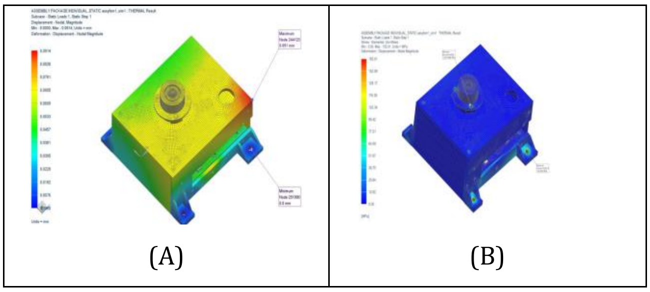


Fig. 8. Thermostatic Stress Analysis of SBC (a) Displacement (b) Von-mises Stress

4.4. Random Vibration Analysis

Random Vibration can be described only in a statistical sense. The instantaneous magnitude is not known at any given time; rather, the magnitude is expressed in terms of its statistical properties. Examples include earthquake ground motion, ocean wave heights and frequencies, fluctuating wind pressure on aircraft, and acoustic excitation due to rockets. These random excitations are usually described in terms of a PSD (Power Spectral Density) Function [18-19]. PSD tells us how the power of a random signal is distributed over a certain bandwidth (frequency range). In other words, at which frequencies, Power is more and is less. Table 6 and 7 gives the input excitation to carry out the Random Vibration Test for the space born camera system along the mounting plane (X and Z Directions) and normal to the mounting plane (Y Direction) respectively. Equivalent static acceleration for response of SBC assembly to random vibrations is estimated from Miles equation [20].

G peak :-

$$G = 3.\sqrt{((\pi.Q.F.w)/2)}$$

Where

Transmissibility (Q) = $\sqrt{(outputPSD/inputPSD)}$

F = Eigen frequency

w = spectral value.

Table 6. Input Excitation for Random Vibration Test for X, Z-Axis.

Frequency(Hz)	PSD(g2/Hz) Qualification Level
20–100	+3db/octave
100–700	0.1
700–2000	-3 db/octave
Overall grms	11.80g

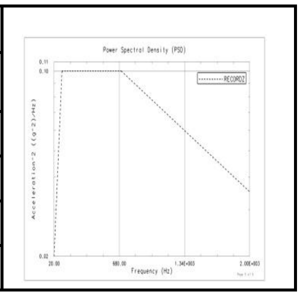
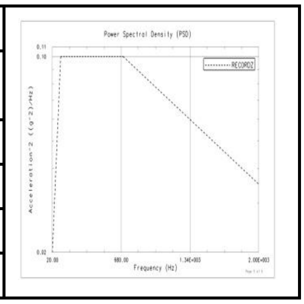


Table 7. Input Excitation for Random Vibration Test for Y-Axis.

Frequency(Hz)	PSD(g2/Hz) Qualification Level
20–100	+3db/octave
100–700	0.2
700–2000	-6db/octave
Overall grms	14.80g



Random analysis result along X-axis: PSD curve response shows that a maximum acceleration of 16.3 g2/Hz occurs at an excitation frequency of 502Hz. The response is shown in figure 9a. Vonmises stress of assembly is 48.66 MPa and is shown in the figure 9b. Stress experienced by the individual components like lens and PCBs are 0.102 MPa and 8.9 MPa which is shown in the figure 9c respectively.

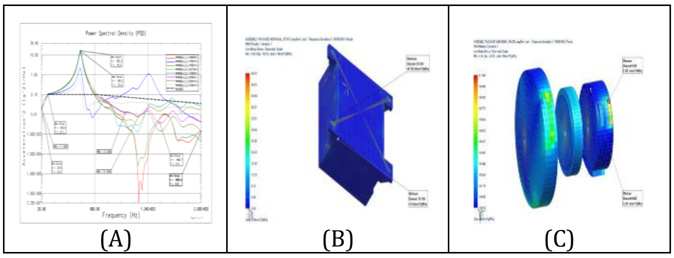


Fig.9. Random response analysis in X-direction (a) Acceleration v/s Frequency plots (PSD Curve) (b) Maximum Von-mises Stress in assembly (c) Von-mises Stress in lens component.

Similarly, along Y-axis, the response shows that a maximum acceleration of 78.38 g2/Hz occurs at the excitation frequency of 353 Hz. The response is shown in the figure 10a. Von- mises stress of assembly is 19.52 Mpa and is shown in the figure 10b. Stress experienced by the individual components like lens and PCBs are 0.091 Mpa and 10.457 Mpa respectively which is shown in the figure 10c.

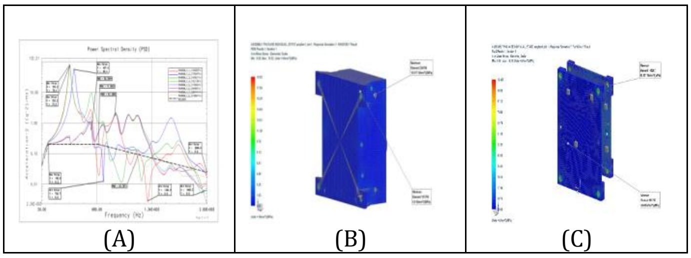
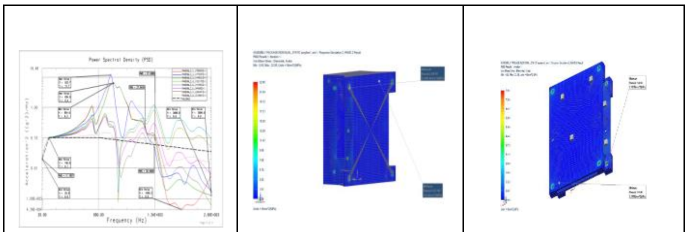


Fig. 10. Random response analysis in Y-direction (a) Acceleration v/s Frequency plots (PSD Curve) (b) Maximum Von-mises Stress in assembly (c) Von-mises Stress in PCBs component.

Similarly, along Z-axis, from the response shown in figure 11 a, Maximum acceleration is 11.7 g2/Hz at occurs at an excitation frequency of 827 Hz. Von- mises stress of assembly is 22.95 MPa and is shown in the figure 11b. Stress experienced by the individual components like PCBs and lens are 7.951 MPa and 0.064 MPa respectively which is shown in the figure 11c.



(A) (B) (C)

Fig. 11. Random response analysis in Z-direction (a) Acceleration v/s Frequency plots (PSD Curve) (b) Maximum Von-mises Stress in assembly (c) Von-mises Stress in PCBs component.

Transmissibility and g peak levels of the components are tabulated in the Table 8. In Random analysis for the whole assembly the maximum RMS von-mises stresses in X, Y and Z axis are 48.66, 19.53 and 22.95 MPa respectively and the "three-sigma"[21] is obtained by multiplying these values with a factor of 3. Table 9 gives the maximum stress and factor of safety levels that are obtained in the assembly when excited in X, Y and Z direction. Table 10 gives the maximum stress in individual component and FOS in individual components of the assembly when excited simultaneously in all the three directions.

Table 8. Transmissibility and g peak levels of SBC

AXIS	Comp onent	Frequ ency (Hz)	Outpu t PSD (g^2/H z)	Input PSD(g 2/Hz)	Q Trans missib ility	g peak
X-AXIS	LENS	502	16.3	0.1	12.76	94
Y-AXIS	PCB 2	353.2	78.4	0.2	19.8	140
Z-AXIS	PCB 1	822.7	11.7	0.1	11.72	107.7

Table 9. Maximum stress and FOS of the assembly along X, Y and Z directions

AXIS	Yield stress (MPa)	Allowable stress (MPa)	FOS
X-AXIS	210	146	1.43
Y-AXIS	210	58.6	3.58
Z-AXIS	210	68.85	3.05

Table 10. Maximum stress among the all axis in individual component of the assembly

Component	Material	Yield stress (MPa)	Von misesstress (MPa)	FOS
LENS	SF-6	16	0.27	59
PCB's	FR-4	70	31.35	2.23
HOUSING	Al-6061	210	146	1.43

5. Conclusion

The Space Borne Camera is mainly designed to determine the position of the target space craft and is to sustain the environmental conditions during launch as well as its function in space. In order to see the designed system with stands the stringent environmental conditions FEM analysis is carried out for Modal, Quasi static, Thermal, Sine and Random vibrations by simulating the specified conditions. The minimum factor of safety 1.35 is obtained in thermostatic analysis. The simulation results are adequate and several test conditions of the design is ready to be incorporate in the space mission design.

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