MECHANICAL DESIGN AND ANALYSIS OF STAR SENSOR

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Abstract - *Star tracker/Star Sensor is an aerospace navigation instrument used to provide absolute 3-axis attitude information to the spacecraft. Attitude determination is a key component in positioning and pointing accuracy. A satellite's attitude is defined as the orientation of its fixed body frame with respect to an external reference frame which is an inertial frame. A "Lost–in-space" case may develop if there is no accurate attitude determination. Hence there is a requirement of attitude determination device of maximized accuracy, reliability, life time and minimized mass, size and cost. Present Study involves mechanical design and analysis of star sensor structural elements and the baffle in line with inputs from optics and electronics design.*

Key Words: **Star Sensor, Attitude, Unigraphics, Accuracy, Reliability.**

1. INTRODUCTION

Star Sensors measures star coordinates in the spacecraft frame and provide attitude information when these observed coordinates are compared with known star directions obtained from a star catalogue. In general, star sensors are the most accurate of attitude sensors, achieving accuracies to the arc-second range.

1.1 Working Principle of Star Sensor

Figure 1 shows the basic working principle of Star Sensor. Stray light is a major problem with star sensors. Carefully designed light baffles are usually employed to minimize exposure of the optical system to sunlight and light scattered by dust particles, jet exhaust, and portions of the spacecraft itself.
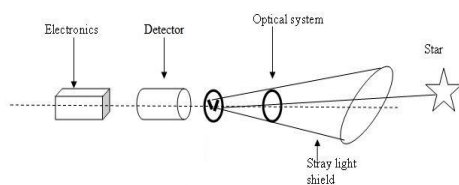

Fig - 1: Basic Working Principle of Star Sensor

The star sensor optical system consists of a lens assembly which projects the image of the star field onto the focal plane i.e. the location of the detector. The detector transforms the optical signal into an electrical signal. Frequently used detectors include photomultiplier and solid-state detector.

Finally, the electronics assembly filters the amplified signal received from the detector and performs many functions specific to the particular star sensor.

The requirements to be met by the Star Sensor Assembly are:

- The Star Sensor Assembly should be robust to take up the static and dynamic loading during launch.
- It should be light weight to meet the mass requirements.
- It should meet the performance requirements under static and dynamic loading condition.

The entire star sensor assembly is modeled and then Modal, Static and Dynamic Analysis were carried out to determine the response of the Star sensor assembly to the various loading conditions. The results are compared with the safe limits of the material.
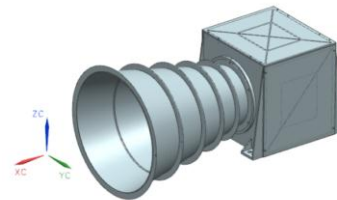
2. CAD MODEL OF THE STAR SENSOR

Fig - 2: Star Sensor Assembly

Figure 2 shows the CAD Model of the Star Sensor Assembly modeled using NX 8.5, based on the design specifications for each component. The main condition is to build a Star Sensor with a mass less than 2.4 Kg.

Star sensors are composed of four elements: a baffle which attenuates and reflects stray light preventing them from falling on the detector through the lens assembly. The performance of the star taker is often limited by the stray light level on the detector. These stray lights undergo multiple reflections by the vanes and goes out of the baffle without reaching the detector. An optics system with single or double lens captures the stellar photons and focuses on to the detector. Detector system generally composed of a charge-coupled device (CCD), charge-injection device (CID), or complementary metal oxide semiconductor (CMOS) onto which the star light is focused. Electronics processing unit digitizes and analyzes the stellar data.

Star trackers are responsible for the digital conversion of the photons collected by the lens into electrons that can be read by the processing unit.

2.1 Material Properties

Table 1 shows the Material properties for different components of the Star Sensor Assembly.

Table -1: Material Properties

Sl. No	Component	Material	Density (kg/m³)	Young's Modulus (GPa)	Tensile strength (MPa)	Yield Strength (MPa)	Poisson's ratio
1.	Structure	Al 6061-T6	2700	70	315	290	0.33
2 a.	Optics-Barrel	Ti-6Al-4V	4430	117	1170	1100	0.31
2 b.	Lens	Borosilicate Glass	2200	64	200	165	0.167
3.	Electronics	FR4-C	1800	24.13	75	65	0.136
4.	Detector	Quartz	3700	280	98	48	0.167
5.	Detector plate	Al 6061-T6	2700	70	315	290	0.33
6.	Baffle	Al 6061-T6	2700	70	315	290	0.33
7.	Cover plates	Al 6061-T6	2700	70	315	290	0.33

3. FE MODEL OF STAR SENSOR ASSEMBLY

Figure 3 shows the meshed model of the Star Sensor Assembly. The total no. of elements and nodes used to create the meshed model of the assembly are 295846 and 101914 respectively.
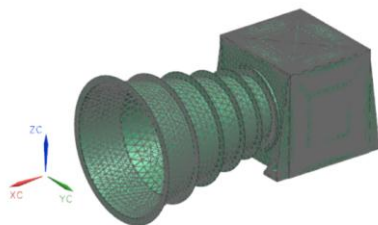
Fig - 3: FE Model of Star Sensor Assembly

Table 2 shows the masses of individual components of the star sensor assembly.

Table - 2: Mass of Individual Components of the Star Sensor Assembly

Components	Mass (Kg)
Baffle	0.695
Optics	0.273
Electronics	0.141
Detector	0.099
Structure	0.662
Covers	0.217
Detector Plate	0.091
Lens	0.100
Total Mass	**2.278**

3.1 Boundary Conditions

3.1.1 Modal Analysis – Free condition:

Modal analysis under free condition is carried out to understand how the Star Sensor assembly behaves when it is unconstrained. Also it gives idea about where to constrain the Star Sensor Assembly in order to get minimum vibration. Here, the first six modes are rigid modes and hence equal to zero.

3.1.2 Modal Analysis – Constrained Condition:

In Constrained Modal analysis, there should be no zero-frequency modes. If any 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 the Star Sensor Assembly are not constrained properly. For performing Constrained Modal analysis, the assembly is fixed at the 8 nodes representing the 8 M6 screws as shown in Figure 4.
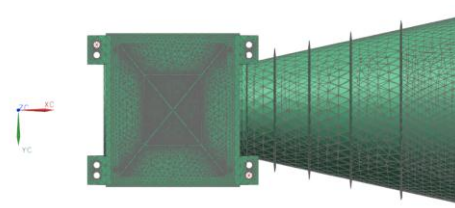

Fig - 4: Boundary Conditions for Modal and Static Analysis

3.1.3 Dynamic Analysis

Static Analysis does not take into account variation of load with respect to time. Output in the form of stress, displacement etc., with respect to time could be predicted by dynamic analysis. In static analysis, velocity and acceleration (due to deformation of the component) are always zero. Dynamic analysis can predict these variables with respect to time/frequency.

For this analysis, all the 8 Bolted locations of the structure are connected to a common node at the center of the base. Same node is provided with base excitation during the dynamic analysis as shown in the figure 5.
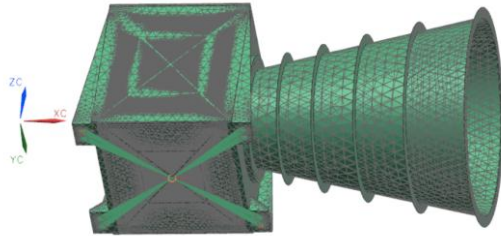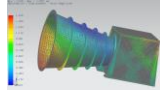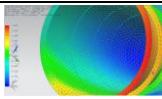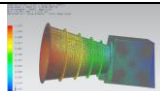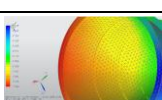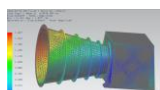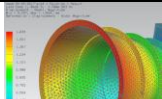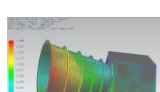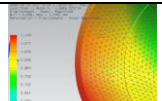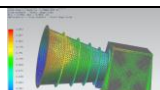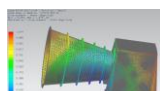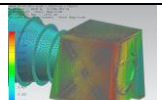

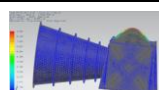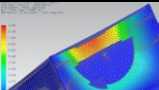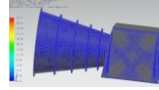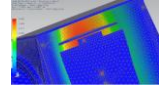**Fig - 5:** Boundary Condition for Dynamic Analysis
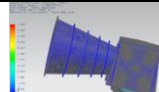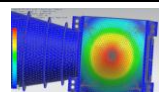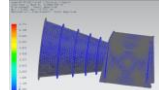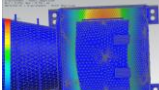
4. Analysis and Results

4.1 Modal analysis – Free Condition:

Table 3 shows the modal frequencies and the corresponding modes obtained from the modal analysis under free condition for the Star Sensor.

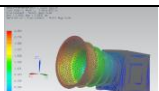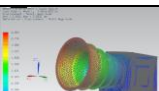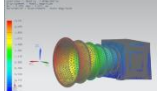**Table 3:** Eigen Values of the Star Sensor for Free Condition
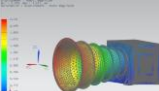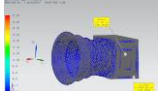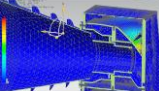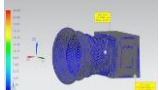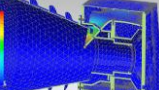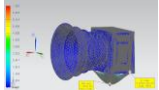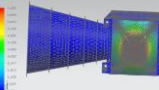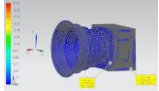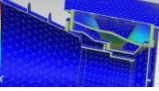
Mode number	Frequency (Hz)	Mode Shapes	Critical Region
1	3.702e-3		
2	1.973e-3		
3	4.841e-4		
4	6.329e-4		
5	1.596e-3		
6	4.017e-3		
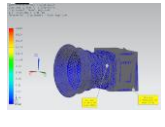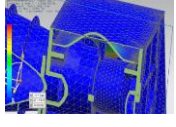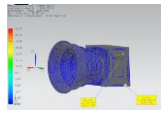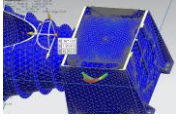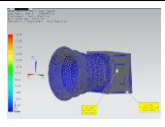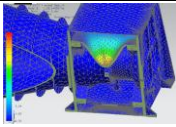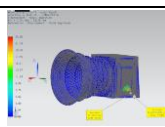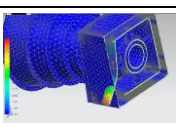
7	736.6		
8	829.9		
9	1002		
10	1029		

4.2 Modal analysis – Clamped Condition

Table 4 shows the modal frequencies and mode shapes for the Star Sensor Assembly while carrying out Modal analysis under Clamped Condition.

Table - 4: Modal Frequencies and Mode Shapes for Clamped Condition

Mode number	Frequency (Hz)	Mode Shapes	Critical Region
1	785.1		
2	797.9		
3	1078		
4	1114		
5	1208		
6	1262		

7	1279	
8	1322	
9	1331	
10	1340	

4.3 Static Analysis

In linear static analysis, displacement and Von Mises stress under 42g load is calculated. Table 5 gives the displacement and Von Mises stress in all three directions for the Star Sensor Assembly.

Table - 5: Displacement and Von Mises stress for the Star Sensor Assembly for Static Analysis.

Direction	Deflection (e-2) (mm)	Von Mises Stress (MPa)
X	1.104	9.77
Y	2.81	23.21
Z	2.14	20.12
XYZ	2.96	42.34

Yield strength for Al 6061-T6 is 290 MPa, for Ti6-Al-4V is 1100 MPa, for FR4 it is 65 MPa. Static analysis results showed that different components possess different stress values.

By these results, maximum amount of Von Mises stress acting on Star Sensor Assembly was less than the yield strength of material. Hence, it can be concluded that Star Sensor Assembly is safe for 42g gravity load in terms of yield strength.

4.4 Dynamic Analysis

4.4.1 Frequency Response Analysis

Frequency/Sine response analysis is used to compute structural response to steady-state oscillatory excitation. In frequency response analysis the excitation is explicitly defined in the frequency domain. Excitations can be in the form of applied forces and enforced motions (displacements, velocities, or accelerations).

4.4.2 Input Excitation for Sine Response along X and Y Directions:

Table 6 shows the input excitation for various frequencies to carry out the Sine Response test for the Star Sensor Assembly in X and Y Directions. The corresponding curve for this is shown next to the table and it is a step-input curve with peak amplitude of 15g.

Table - 6: Input Excitation for Sine Response in X and Y Direction

Frequency (Hz)	Amplitude g	
5	1.15	
18	15	
70	8	
100	8	
2000	1	
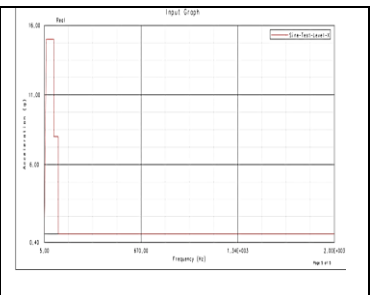
Sine response is a steady state response of the Star Sensor Assembly due to the base excitation. The acceleration v/s frequency graph of Star Sensor for an input spectrum given in Table 6 is shown in Figure 6. Here, the first peak of 6.99g is obtained for the baffle at a frequency of 752.6 Hz. The first peak for all the components is observed at a frequency of 752.6 Hz.

Fig - 6: Acceleration v/s Frequency Plot for Sine Response in X Direction

Sine response of Star Sensor in Y direction for the spectrum shown in Table 6 is shown in Figure 7. Here, the first peak of 43.33g is obtained for the baffle at a frequency of 761.4 Hz. The first peak for all the components is observed at a frequency range of 750Hz-765Hz.

Fig - 7: Acceleration v/s Frequency Plot for Sine Response in Y Direction

Table 7 shows the input excitation for various frequencies to carry out the Sine Response test for the Star Sensor Assembly in Z Direction. The corresponding curve for this is shown next to the table and it is a step-input curve with peak amplitude of 25g.

Table - 7: Input Excitation for Sine Response in Z Direction

Frequency (Hz)	Amplitude g	
5	1.248	
22	25	
70	20	
100	20	
2000	1	

The sine response of Star Sensor in Z direction for an input spectrum mentioned in Table 7 is shown in Figure 8. Here, the first peak of 15.65g is obtained for the baffle at a frequency of 752.6 Hz. The first peak for all the components is observed at a frequency range of 750Hz-790Hz.
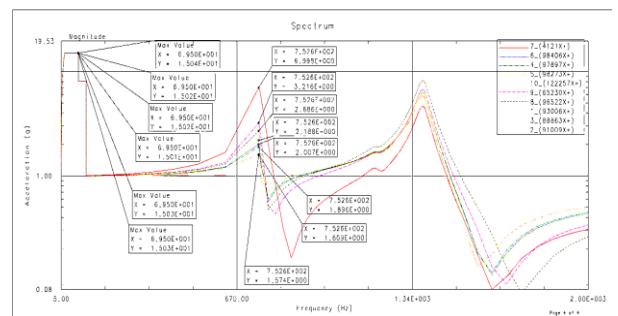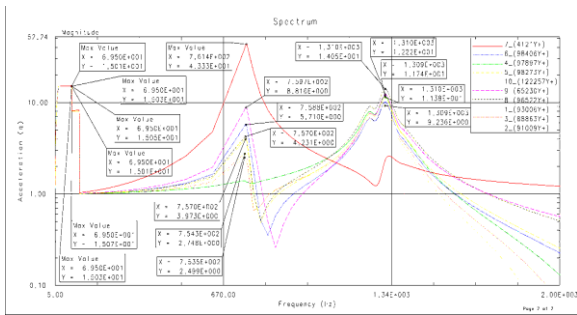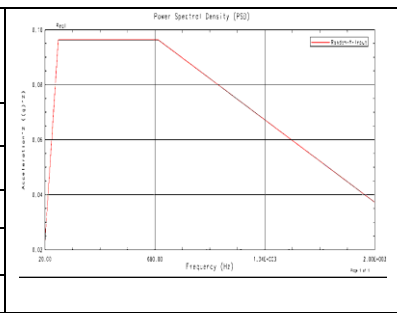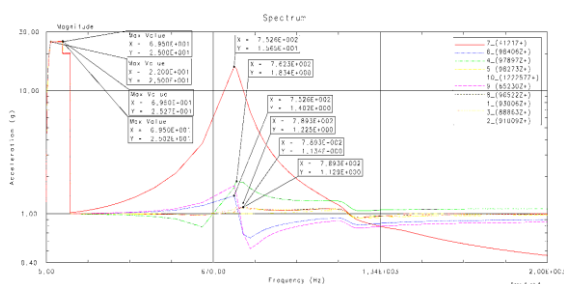

Fig - 8: Acceleration v/s Frequency Plot for Sine Response in Z Direction

From the figures 6,7 and 8, it is observed that the first peak of all the components are similar to that of baffle because the baffle drives all of them simultaneously at frequencies nearer to baffle natural frequency.

4.4.3 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 (such as mean value, Standard deviation and probability of exceeding a certain value). 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.

4.4.4 Power Spectral Density

It 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 at which it is less.

Figure 9 shows the input excitation to carry out the Random Vibration Test for the Star Sensor Assembly in X and Y Directions. The corresponding input data for this is shown in Table 8.

Frequency (Hz)	Acceleration PSD (g^2/Hz)	
20	0.02	
100	0.1	
700	0.1	
2000	0.035	

Fig - 9: Input Excitation for Random Response in X and Y Direction

Table - 8: Input data for Random Response in X and Y Direction

Frequency (Hz)	PSD (g^2/Hz) Qualification Level
20-100	+3 dB/ octave
100-700	0.1
700-2000	-3 dB/octave
Overall g_{RMS}	11.8 g
Duration	120 secs

Figure 10 shows the acceleration v/s frequency plot for Random Response of the Star Sensor Assembly in X Direction. Here, the first peak of 4.709 g2/Hz is obtained for the baffle at a frequency of 752.6 Hz. There are 2 peaks in the graph which indicate the frequencies at which the response of the Star Sensor Assembly is maximum.

Fig - 10: Acceleration v/s Frequency Plot for Random Response in X Direction

Figure 11 shows the maximum Von Mises Stress plot for Random Response of the Star Sensor Assembly in X Direction. The Maximum value of the Von Mises stress is 111.5 MPa at a frequency of 753.5 Hz. There are two peaks which indicate that the maximum stress points at the corresponding frequencies.

Fig - 11: Maximum Von Mises Stress Plot for Random Response in X Direction

Figure 12 shows the acceleration v/s frequency plot for Random Response of the Star Sensor Assembly in Y Direction. Here, the first peak of 179.2 g2/Hz is obtained for the baffle at a frequency of 761.4 Hz. There are 2 peaks in the graph that indicate the frequencies at which the response on the Star Sensor Assembly is maximum.

Fig - 12: Acceleration v/s Frequency Plot for Random Response in Y Direction

Figure 13 shows the maximum Von Mises Stress plot for Random Response of the Star Sensor Assembly in Y

Direction. The Maximum value of the Von Mises stress is 121.3 MPa at a frequency of 762.3 Hz. There are two peaks which indicate that the maximum stress points at the corresponding frequencies.

Fig - 13: Maximum Von Mises Stress plot for Random Response in Y Direction

Figure 14 shows the input excitation to carry out the Random Vibration Test for the Star Sensor Assembly in Z Direction. The corresponding input data for this is shown in Table 9.

Frequency (Hz)	Acceleration PSD (g^2/Hz)	
20	0.039	
100	0.198	
700	0.198	
2000	0.024	

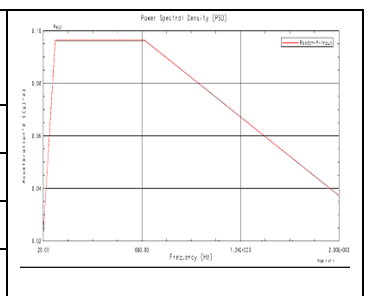**Fig - 14:** Input Excitation for Random Response in Z Direction

Table - 9: Input data for Random Response in Z Direction

Frequency (Hz)	PSD (g^2/Hz) Qualification Level
20-100	+3 dB/ octave
100-700	0.2
700-2000	-6 dB/octave
Overall g_{RMS}	14.8 g
Duration	120 secs

Figure 15 shows the acceleration v/s frequency plot for Random Response of the Star Sensor Assembly in Z Direction. Here, the first peak of 45.69 g2/Hz is obtained for the baffle at a frequency of 752.6 Hz. There are 2 peaks in the graph which indicate the frequencies at which the response of the Star Sensor Assembly is maximum.
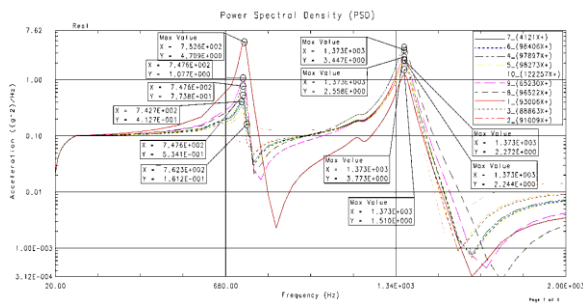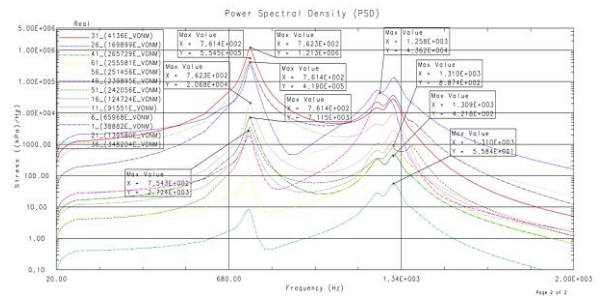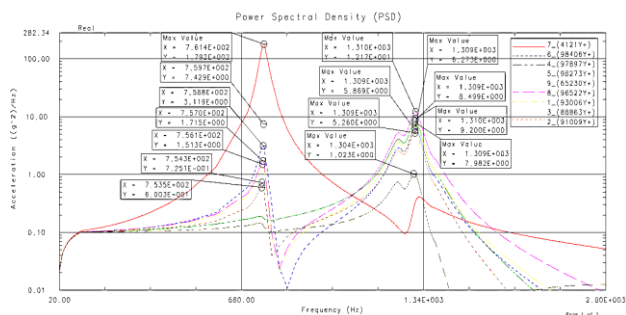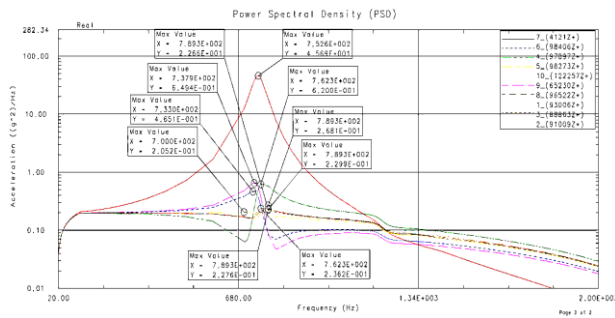
Fig - 15: Acceleration v/s Frequency Plot for Random Response in Z Direction

Figure 16 shows the maximum Von Mises Stress plot for Random Response of the Star Sensor Assembly in Z Direction. The Maximum value of the Von Mises stress is 271.2 MPa at a frequency of 752.6 Hz. There are two peaks which indicate that the stress is maximum at the corresponding frequencies.
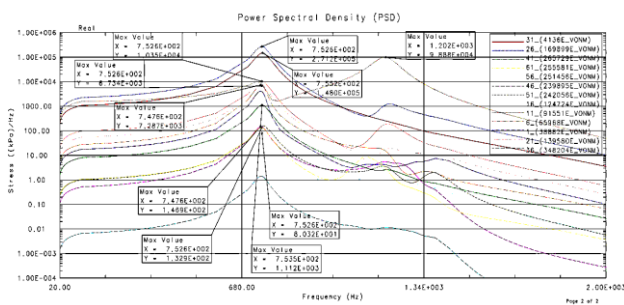

Fig - 16: Maximum Von Mises Stress plot for Random Response in Z Direction

In all the above graphs, 1st peak occurs at the natural frequency of the system. It is observed that the 1st peak of all the components of the Star Sensor Assembly have similar values with little variation because the baffle drives all of them. The 2nd peak is harmonic which is found to be in the range of 1200-1350 Hz.

5. CONCLUSIONS

The results for the Star Sensor assembly for different load cases are tabulated and it is observed that the Von Mises stresses are within limits.

- The first natural frequency of Star Sensor Assembly is 785.1 Hz, which is greater than 100 Hz and hence there is no chance of resonance.

- From Static Analysis, the Maximum Von Mises stress of 42.34MPa is observed at the mounting location, whose yield stress is 290 MPa, which is safe with considerable factor of safety of 6.8.

- The Von Mises stress obtained from Static Analysis in individual components of the Star Sensor Assembly are well below the yield stress of the material used as shown in Table 10.

Table - 10 – Comparison of Yield Stress and Stress Obtained from Static analysis for different components of the Star Sensor Assembly.

Component	Material	Yield Stress (MPa)	Stress Obtained (MPa)
Baffle	Al 6061-T6	290	8.64
Structure	Al 6061-T6	290	42.34
Optics	Ti-6Al-4V	1100	1.15
Detector	Quartz	48	15.11
Detector Plate	Al 6061-T6	290	2.41
Top Card	FR4	65	0.35
Bottom Card	FR4	65	0.57
Right Card	FR4	65	0.91
Left Card	FR4	65	0.48

- In Sine Response Analysis, the peak acceleration obtained is 43.33g in the Baffle Tip when the Star Sensor Assembly is loaded with 42g dynamic load in Y Direction. This is not critical since the natural frequency of Baffle is 785.1 Hz obtained from Modal analysis under constrained condition and the peak acceleration of 43.33g is obtained at 761.4 Hz which is well below the natural frequency of the baffle.

- Table 11 shows the comparison of yield stress and Von Mises stresses obtained from Random Response Analysis in individual components of the Star Sensor Assembly. The stresses in individual components are well below the yield stress of the material used for the component.

Table 11 - Comparison of Yield Stress and Von Mises Stress Obtained from Random Response Analysis

Component	Material	Yield Stress (MPa)	Stress Obtained (MPa)
Baffle	Al 6061	290	148
Structure	Al 6061	290	271
Optics	Ti-6Al-4V	1100	7.115
Detector	Quartz	48	0.056
Detector Plate	Al 6061	290	24.97
Top Card	FR4	65	16.57
Bottom Card	FR4	65	0.422
Right Card	FR4	65	43.62
Left Card	FR4	65	3.532

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