Mechanical Design and Analysis of Detector Head Assembly for Space bone High-Resolution Imaging Sensor

Axat Patel, Maulik Shah

Abstract: The imaging sensors employed in satellites are subjected to a wide range of vibratory loads induced during the launching phase. The effect of temperature change also needs to be looked upon while designing the structure of the imaging sensor as satellite passes through the solar and lunar phase. This project work goes into depth of challenges incurred during launching and in-orbit operation. The research includes development of lightweight structure, incorporating flexure interface to house detector head assembly (DHA) components. The design of flexural mount is a novel approach that not only arrests the deformation of the imaging sensor but also restricts structural stresses to affect the performance of the imaging sensor. This article showcases the assessment of three different mechanical designs of DHA through finite element simulation results computed in ANSYS workbench environment. The survivability of DHA structure has been checked under 55g quasi-static loading to simulate launch vibration along with 10°C thermal gradient corresponded to the in-service orbital motion. In this research work, AL6061-T6 and Kovar has been chosen for various design components of the DHA as they are space qualified materials. Though both material options showed similar performance, due to low density, ready availability and cost effectiveness leads to select Al6061-T6 material for the fabrication of DHA components.

Keywords: Imaging sensor, Flexural mount, Detector head assembly (DHA), Quasi-static loading, Finite element analysis.

I. INTRODUCTION

An object orbiting synchronously around the earth, monitoring diverse parameter through sensing Electro-Magnetic (EM) radiation reflected from the surface of the earth is identified as "Satellite". Satellites are used for various application like for earth observation, weather, aerosol monitoring, examining ferrous/ non-ferrous metals on the earth's surface, geographic location, telecommunication [1],[7].

Revised Manuscript Received on February 28, 2020.
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The major components of an imaging system, includes optics lens assembly, detector head assembly, processing electronics, electrical parts and supporting housing structure [1]-[3]. The imaging sensor is a predominant element employed to produce information in terms of image. Detector Head Assembly is a structure by virtue of which imaging sensor's movement is arrested. It must cease plenty amount of in plane and out of plane vibrations in multiple of ambient gravity induced for small period acting during the launching phase. It should meet all the functional performances required on-orbit operations and retain a friendly interface with some other subsystems. The succeeding section highlights in-depth approach towards the design background of researches related to the proposed technique. Next to that, describes the modeling and analysis procedure incorporated to suit survivability criteria. The further section presents the results obtained under the quasi-static and thermo-elastic load.

II. METHODOLOGY

A imaging sensor is situated right behind to series of imaging optical elements [7]. The imaging sensor has to retain its position with respect to the optical axis and the focal plane of the Front-end optics [2]. The structure which is going to hold the imaging sensor and its associates, well known as "Detector Head Assembly (DHA)" consists, 1) Imaging sensor shown in figure 1, 2) electronics PCB, 3) Detector mount for holding imaging sensor and its electronics PCB, 4) DHA frame for integrating all components with optical filter at front side of imaging sensor. A band pass filter enables the rays of a specified wavelength to pass through and fall on the imaging sensor. A well-restricted positioning all subcomponents results in optical rays to fall right and produces a frame of information [3].

A. Material selection.

The properties of different materials such as stiffness, density, yield strength thermal conductivity, coefficient of thermal expansion etc., play vital role while designing the structure. Components are having divergent thermal expansion leads to induce thermal stresses acted on the structure. With reference to all parameters, material for the imaging sensor, detector mount, band pass filter mount, holding frame, PCB are Ceramic, Kovar, Al6061-T6, Kovar/Al6061-T6 and FR4 respectively. Table I depicts the various properties of materials used in this analysis.

Table I: Different material and their properties

Materials	Modulus of elasticity E (N/mm^2)	Poisson's ratio μ	Density ρ (Tonne/ mm^3)	Yield strengthσ_y (MPa)	Specific heat C_p (J/kg.°K)	Thermal conductivity K (W/m °K)	Coefficient of Thermal Expansion (x10^{-6}/°K)
Ceramic	3.70E+5	0.22	3.96E-09	276	810	17	7.40
AL6061-T6	0.7E+5	0.33	2.70E-09	275	896	167	23.6
Kovar	1.38E+5	0.317	8.36E-09	345	439	17.3	5.86
EC2216B/A	0.03E+5	0.48	1.25E-09	5	-	0.39461	100
FR4	0.5E+5	0.118	1.88E-09	344	-	0.23	1.5

B. Design criteria.

Spaceflight launch consisting of a series of events leads to the implication of Static and Dynamic loads on the structure of DHA. The statistical quantity which is used to represent random vibration termed as power spectral density (PSD). The PSD is an amount of the amplitude of vibration controlled within specific bandwidth, typically 1 Hz. PSD is an area under a curve and represented in units of area bandwidth [4],[5],[8]. The fundamental frequency can be measured by stiffness-to-weight ratio of the structure. A system's natural frequency depends on the mass of the system and the stiffness of the support structure is derived by (1) [4],[5], in which ω_0 = natural frequency (rad/sec), f_n = the fundamental frequency (Hz), k = Stiffness, and m = mass of the support structure.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (1)$$

Transmissibility (T) is the term used to describe how much of the environmental vibrations are transmitted to the isolated system. The lower the transmissibility, the system will get more isolation [4],[5]. The transmissibility can be expressed by (2) wherein isolation technically begins at the point, where, ω = frequency of external vibrator.

$$T = \frac{1}{1-\frac{\omega^2}{\omega_0^2}} \quad (2)$$

A combination of static and dynamic loads into equivalent static load, known as "Quasi-static" load has to be specified for the design of DHA. The acceptance of design will be based on simulation of quasi-static analysis and thermo-elastic analysis. The qualification criteria for the design would be 18.3g Grms. The common practice for an optomechanical vibration engineering was to assume the structure damage is done by 3-sigma acceleration [3],[5],[6],[11],[12],[14]. Therefore, the proposed configurations have been evaluated under considering the Quasi-Static load of 55g Grms, applied in x, y, z-axis respectively. The results are observed along the z-axis, considered as an optical axis. To ensure optimum yielding of detector frame, flexural mount design concept has been incorporated as shown in figure 2 which resembles kinematic mount. The flexure provide very rigid constraints in certain directions while still maintaining compliance in others. This will perform as spring and reduce the fundamental frequency of vibration of the mounted component subsequently captivate stresses and deformation providing flexural compliancy in radial and stiffness in remaining directions [1],[3],[5],[10],[13] The proposed configurations has a flexural mount with optimum pad area of 5mm x 5mm which is to be interfaced to sway space around the imaging sensor.

In continuation with quasi-static loading, there will be the dominance of thermal in-equilibrium condition caused while functioning in zero gravity environment [2],[3],[7],[8]. The assembly must be analyzed under thermo-elastic simulation i.e. the effect of the thermal gradient of 10°C prone to induce thermal stresses on the structure.

III. MECHANICAL DESIGN AND ANALYSIS

A. Design and Modeling.

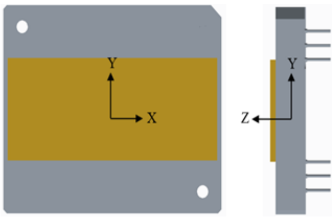


Fig.1. CAD Model of the imaging sensor along with coordinate system.

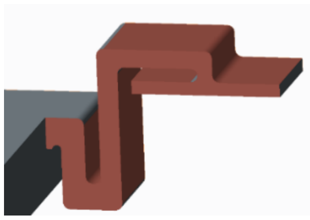


Fig.2. Flexural mount interface between the detector mount and imaging sensor.

At the outset of the mechanical design, fundamental study of the imaging sensor is carried out. The detector mount has not only enough stiffness to absorb the vibrations occurred during transit from earth to space, but also optimum yield ability not to transfer the structural deformation onto the imaging sensor and should fall below allowable limit to retain the depth of focus limit, which may cause loss of information. The imaging sensor is made of ceramic which is brittle in nature. Integration of ductile frame and imaging sensor is achieved by a thin layer of high strength space qualified glue (EC2216B/A) of 5mm x 5mm area having a thickness of 0.2mm. Mounting of the imaging sensor with detector frame is carried out considering the failure of glue in shear direction with respect to imaging axis. The imaging sensor is coupled with the associative electronics Printed Circuit Board (PCB) on which camera electronics components are placed.

Holding frame is required to accommodate band pass filter assembly integrated from front side of the sensor.

Holding frame must have the arrangement to hold PCB such that any of the components would not interfere with the frame. The PCB, 120mm x 120mm x 1.6mm in size, employed in the current module. A simplified model of electronics card has been modeled in a way that the overall weight of the PCB card is fixed of 150gms. Failure of imaging sensor is observed by Maximum Principal Stress Theory having brittle characteristics subsequently Von Misses theory for detector mount and holding frame having ductile nature [4]-[8].

B. Design Configuration.

Three different approaches have been addressed to hold the components to gather as shown in figure 3, 4 and 5 subsequently. All three design options differentiated from each other in view of holding frame design to hold imaging sensor. The imaging sensor is interfaced with holding structure through flexures. The holding frame has four lugs to hold PCB. Eventually, to aim symmetricity in x and y-axis, the symmetric structure was designed for all three options. Distance between sensor front surfaces to end surface of band pass filter was adjusted by providing lug support to filter frame. The design III enables the imaging sensor, detector PCB and Filter mouth to get housed together being a compact configuration. This compact frame structure ensures the functionality of all components ensuring reduction in overall weight of the DHA qualifies to top of the list of accepted design.

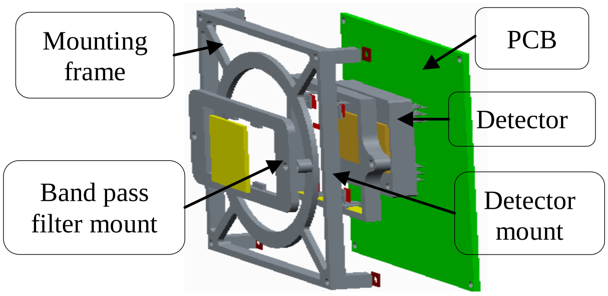


Fig.3. Design- I showing mount frame with circular rim interface.

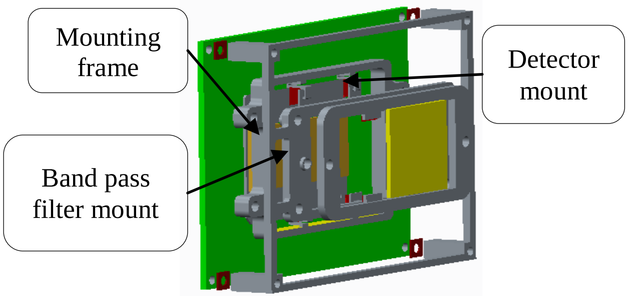


Fig. 4. Design- II showing mount frame with rectangular rim for interface

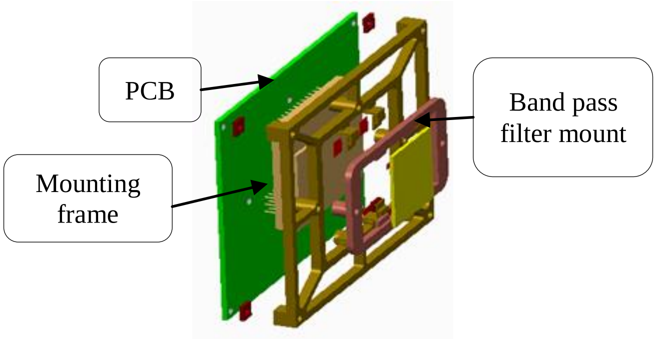


Fig. 5. Design-III Flexural mount interface for detector mount and imaging sensor.

C. Mechanical Analysis.

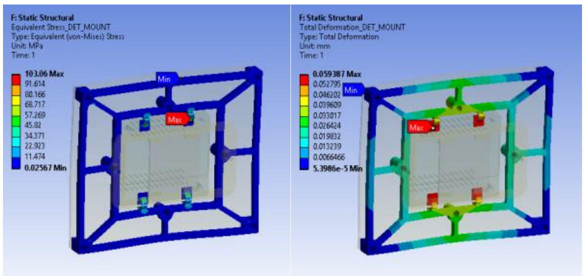
Modeling of each configuration has been carried out in Creo parametric 3.0. The structure has meshed with quad elements of 1mm element size results 3,86,800 nodes and 2,03,343 elements. The separate finite element analysis is carried out in ANSYS workbench environment with changing material Kovar and AL6061-T6 for design III. As the image sensor plays vital role in the design of DHA, the allowable deformation limit is 0.1mm for imaging sensor. The results of the all designs are shown in table II. The results of von misses stress (σ) and deformation (δ) for holding frame and maximum principle stress and deformation for imaging sensor are shown in (6) and (7) respectively.

Table II: Results obtained under quasi-static loading and temperature change for proposed three configurations

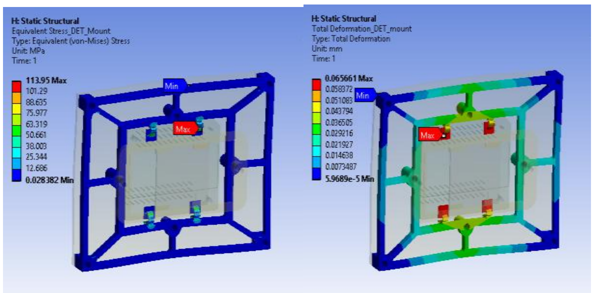
	Part name	Material type	Under quasi-static load		Under 10° C Temperature gradient (ΔT)		Weight (Grams)
			σ (MPa)	δ (mm)	σ (MPa)	δ (mm)	
Design I	Imaging sensor	Ceramic	6.32	0.017	3.048	0.017	242.28
	Detector Mount	Kovar	94.88	0.150	69.34	0.032	
	Holding Frame	Kovar	46.48	0.080	205.74	0.023	
	Bandpass Filter Mount	Al6061-T6	17.92	0.037	20.34	0.058	
	Periphery glue	EC2216A	4.04	0.016	4.07	0.016	
	Filter glue	EC2216A	1.03	0.001	2.37	0.005	
Design II	Imaging sensor	Ceramic	5.93	0.015	4.16	0.037	234.88
	Detector Mount	Kovar	84.72	0.017	97.34	0.048	
	Holding Frame	Kovar	48.46	0.007	180.57	0.053	
	Bandpass Filter Mount	Al6061-T6	10.66	0.004	17.66	0.048	
	Periphery glue	EC2216A	5.137	0.002	7.23	0.018	
	Filter glue	EC2216A	0.624	0.001	20.13	0.02	
Design III	Imaging sensor	Ceramic	6.74	0.058	7.45	0.065	202.57
	Holding Frame	Al6061-T6	103.06	0.059	113.95	0.065	
	Bandpass Filter Mount	Al6061-T6	8.17	0.0273	9.03	0.030	
	Periphery glue	EC2216A	0.88	0.0586	0.976	0.064	
	Filter glue	EC2216A	0.41	0.027	0.453	0.029	

IV. RESULTS AND DISCUSSION

The results obtained depicts the weight reduction in design III in contrast to other designs. The design III resembles optimum design to suit environmental conditions. The performance of holding frame under quasi-static loading for AL6061-T6 and Kovar are shown in (8). Figure 9 shows stresses and deformation under the effect of temperature change in zero gravity environment.

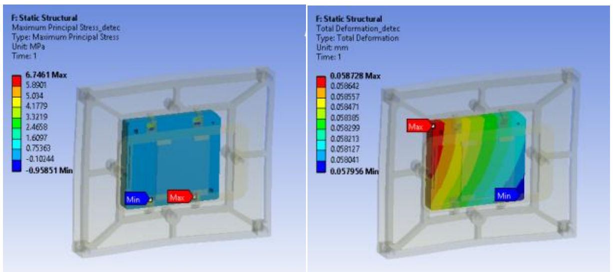


(a) **(b)**

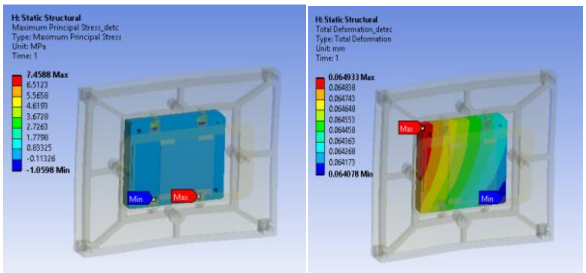


(c) **(d)**

Fig.6. (a) Von-misses stress and (b) Deformation of detector mount under Quasi-Static loading (c) Von-misses stress and (d) Deformation of detector mount under 10 °C temperature gradient.

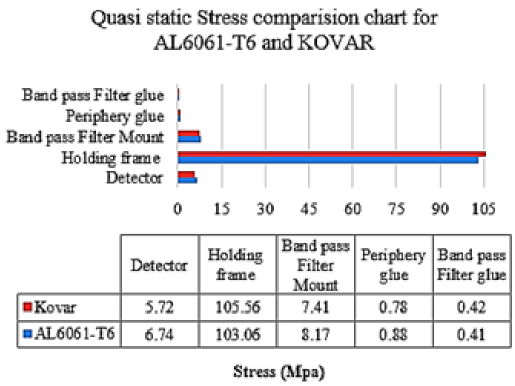


(a) **(b)**

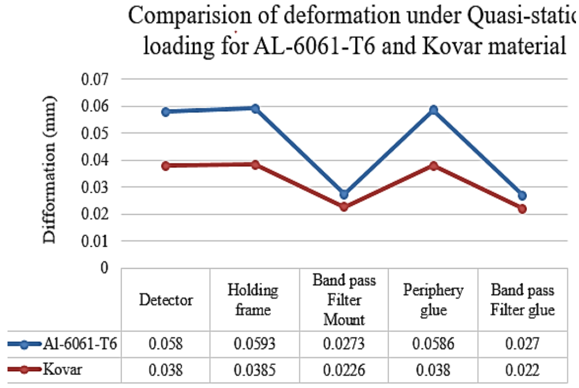


(c) **(d)**

Fig. 7. (a) Maximum Principal stress and (b) Deformation of imaging sensor under quasi-static loading (c) Maximum principal stress and (d) Deformation of Imaging sensor under 10 °C temperature gradient.

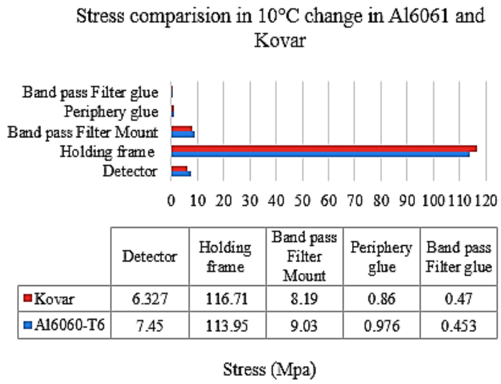


(a)

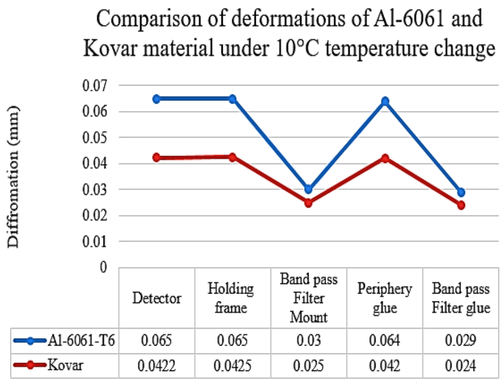


(b)

Fig.8. (a) Stress (b) Deformation comparison chart for DHA parts with AL6061-T6 and Kovar material under Quasi-Static loading.



(a)



(b)

Fig.9. (a) Stress (b) Deformation comparison chart for DHA parts with AL6061-T6 and Kovar material under 10°C change in temperature.

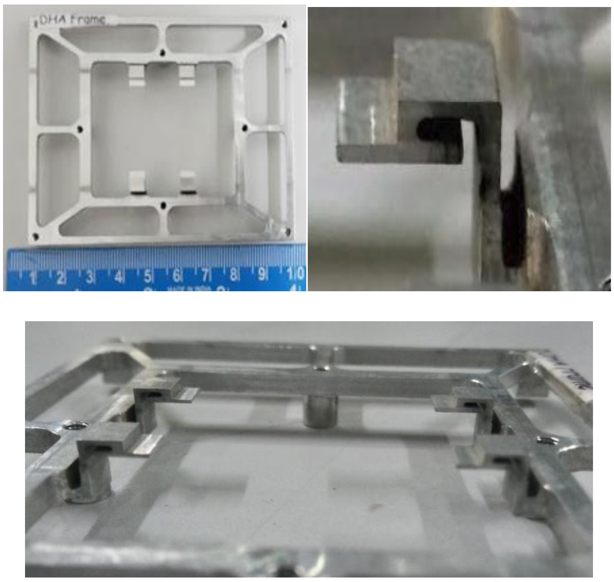


Fig.10. Detector holding frame fabricated from AL6061-T6 material depicting flexure design.

V. CONCLUSION

This article mainly envisaged the mechanical design and analysis of DHA which employed to arrest the movement of high-resolution imaging sensor, having capacity to withstand rigorous vibration load acted during launching and thermally induced deformations while operation. Through this research, following points can be highlighted.

1) Design I and Design II has separate mount for holding the imaging sensor with holding frame. These designs concludes increasing number of parts to handle DHA components along with their weights. Therefore, structural integrity cannot achieved.
2) While design III enables direct integration of imaging sensor to holding frame through flexure mount, stands best suitable solution for the application amongst rest two design options providing reduction in overall weight of the DHA.
3) Along with the reduction in the weight, design III also satisfies the yield and deformation criteria of ceramic made imaging sensor under quasi static and 10 °C temperature gradient situation.
4) Further, both material options for holding frame in design III broadcast the equal capability to survive during the vibration and thermal induced load because of the least change in state by being functionally stable in 55g vibration and 10 °C change in temperature conditions.
5) Kovar is being not only costly also requires specialized tolling for fabrication. In contrast to this, the availability of AL6061-T6 material is handy/inexpensive that decision was made to pursue verification model fabrication from this. Figure 10 shows the actual fabricated DHA Holding frame.

ACKNOWLEDGEMENT

The authors would like to thank CHARUSAT Space Research and Technology Center for giving opportunity to carry out this research work. The authors would also like to express cavernous sense of obligation and gratitude to Mr. Chirag Dewan, SAC, ISRO, Ahmedabad for his genuine guidance and constant encouragement throughout this project work through his knowledge expertise. The authors also would like to thank CHARUSAT University management for their endless support.

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