Lens mounting method to survive Lunar cryogenic temperature

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Abstract:

Imaging Cameras placed on Lunar missions must survive the cryogenic temperature in the order of -180°C during Lunar nights. Though the cameras won't be used for imaging during nights, they must retain the good health through and be ready for imaging while day light arrives. A new concept of mounting the lens into its barrel was designed to survive cryogenic temperature. The thickness and the distribution of the bonding material used to hold the lens in the barrel has been optimized to absorb the loads due to the contraction of metal barrel and the lens elements are maintained stress free through the Lunar night. It was a challenging task to play between size and performance. The five element optical system was designed within 25gm weight and has provision for initial focusing. In addition to cryogenic temperature survival, the lens has been designed to survive the launch and landing vibrations. The design was validated by FEM analysis and subsequently through experimental methods. The image quality was tested pre and post low temperature storage tests. The full paper consists of the brief design and results of both analysis and experimental tests.

1. Introduction:

Past and recent studies reveal that the temperature on the Lunar South pole during its long nights (max. 14 earth days) goes below -200°C. Instruments fitted to Robotic missions deployed on Moon soil must survive the cryogenic temperature prevails there. Though some instruments get thermal protection by RHUs (Radio-active heating unit) and other means of heat sources, a lens assembly fitted to a camera that images and records the activities on Moon cannot get thermal protection as it is constantly looking at the Moon soil and there by exposed to the cryogenic cold temperature. Though the cameras won't be used for imaging during nights, they must retain the good health through the night and be ready for imaging while day light arrives. A new concept of mounting the lens into its barrel was designed to survive cryogenic temperature. The thickness and the distribution of the bonding material used to hold the lens in the barrel has been optimized to absorb the loads due to the contraction of metal barrel and the lens elements are maintained stress free through the Lunar night. It was a challenging task to play between size and performance. The five element optical system was designed within 25gm weight and has provision for initial focusing. In addition to cryogenic temperature survival, the lens has been designed to survive the launch and landing vibrations. The design was validated by FEM analysis and subsequently through experimental methods. The image quality is compared pre and post low temperature storage tests. This paper presents the brief design and results of analysis.

2. Conventional lens mounting methods:

2.1. Drop-in mount:

As it was briefed in earlier part, the lens elements must be mounted and aligned properly to serve the purpose of proper imaging. Many options are available to mount the element with radial and axial constraints. [1] However maintaining the centering or position through the environment is challenging task. One among the conventional methods is drop-in mount where the element is just dropped in to a cavity on the metal part and axial position control is achieved through a threaded lock

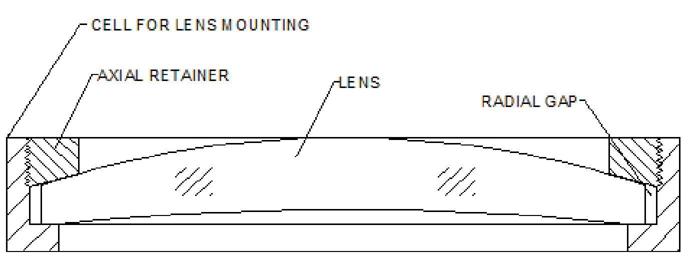


fig.1: Drop -in Mount

ring.(fig.1). The radial gap maintained between the glass and the metal provides room for the variable expansion and contraction during temperature variations. As the axial retaining provides metal to glass contact there would be increased stress on the lens element. Also maintaining co-linearity between the optical and mechanical axis would be difficult in this case.

2.2. Elastomer mount:

The other method is the elastomer mount [2] where an elastomer material is used in between the glass and metal whose viscous structure absorb the differential shape changes of the glass and the metal (fig .2), which results in near stress free status for the lens element. Though the elastomer thickness is carefully estimated to avoid stress build up on glass, the behavior of elastomer during wide temperature range may cause stress build up on the lens. Also if the elastomer selected is not strong enough to absorb loads due to dynamic conditions like shock and vibration, it may transfer the loads to lens element.

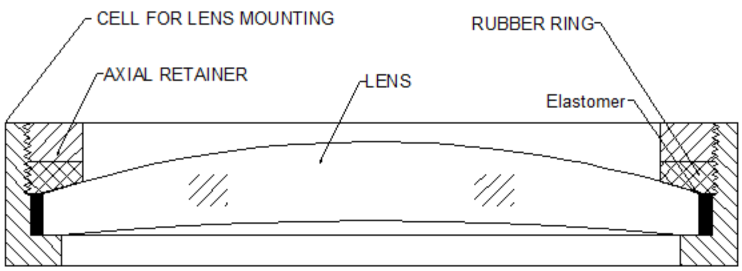


fig.2: Elastomer Mount

2.3. Three blade flexural mount:

To overcome these shortcomings a novel "three blade flexure" method [3] of mounting the lens elements are considered for many space proven lens assemblies. In this method the lens elements are mounted within three extended cantilever blades carved out of a cylindrical cell at 120 degrees apart. The tolerances maintained in the inner diameter of the blades provide radial constraint and the height of the step machined on the blades provides axial constraint to the optical element. A special laser based centering and machining method ensures the centering accuracy of the optical elements with respect to the mechanical axis of the metal cell within 2 arc seconds. As the metal cell is made out of a material whose CTE is very much close to that of glass, there won't be stress build up within the lens element. Even the very small left out difference between CTEs is taken care by the flexural behavior of the three blades on which the lens is mounted. The flexures behave like a cantilever, deflect along with the direction of expansion or contraction of the glass during temperature variations which results in zero stress on glass during

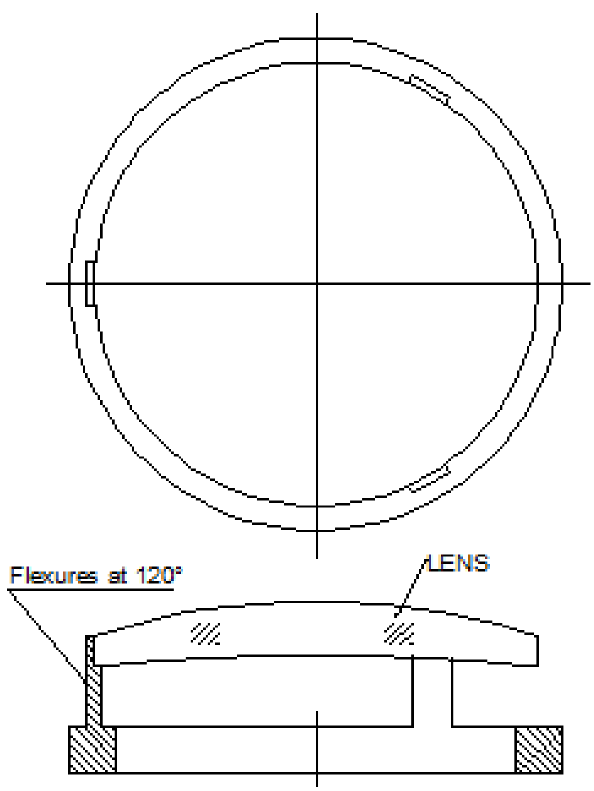


fig.3: Three blade flexure Mount

temperature changes. This method perfectly fits into the requirements of all space optics assemblies. However, the design demands cell-barrel construction for this method which is the negative factor for miniaturization and weight optimization.

3. Lunar Imaging Lens design:

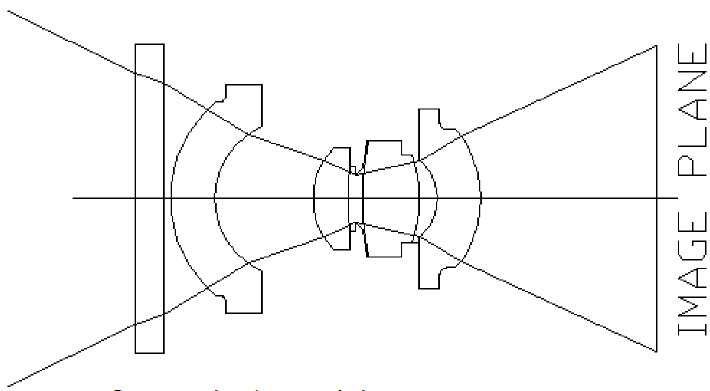


fig.4: Lunar imaging Lens design

The main and foremost requirement of present imaging optics for Lunar imaging system is minimum weight in the order of few grams. The challenge lies in selecting the right materials for this lens. The multi element optics, the lens housing and the special bonding material are selected to accommodate the expansion and contraction of the metal and glass due to temperature excursions. Considering all above requirements, the lens focal length is designed as 21.3 mm giving a square field of view of 37x37 degrees and 52.7 degrees on the diagonal. The lens operates at f/7, images objects whose distances range from infinity to 432 mm, and are fixed-focused at 1000 mm.

Fig.4 Lunar imaging lens design

The camera is a monochrome (black-and-white) system; an entry filter of dia 32mm (Fused quartz) gives a visual waveband from 0.40 µm to 0.90 µm. The lens design is a cross between a Hologon and a Biogon. The imaging is realized through four elements which are combinations of BK7 and SF 6 and a conventional fixed aperture stop of 3mm diameter is placed between the second and third elements. In addition to be miniature in size, this lens design caters to 1 inch image format to accommodate the space grade image sensor availability.

4. Lens mount method for Lunar imaging lens:

The design of lens mount is a combination of elastomer mount and the flexure mount described earlier. The lens elements are mounted inside the barrel directly to enable weight optimization. The thickness of barrel is designed to behave like a flexure to impart the positive features of flexural mount. The elastomer/bonding material is applied *only at three places over the circumference of the lens at 120° apart*, to impart the positives of elastomer mount. The elastomer selected (EP21CHT) has got the properties of nominal tensile shear strength (16MPa) and survives a wide temperature range of 4° to 400°K. The barrel material selected is Titanium alloy and thickness of it is designed as 1mm, to behave as a flexure. The annular gap between the glass and metal except at three locations where the elastomer is filled provides room for the expansions and contractions of the glass and metal.

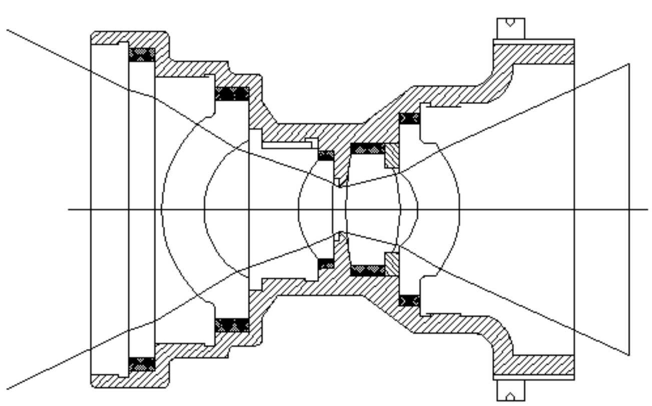


fig.5:Lens assembly for Lunar Imaging system

4.1. Thickness of elastomer:

The thickness of elastomer placed between the glass and metal plays important roll in temperature survival. It absorbs the load due to the expansion and contraction of the metal as well as glass. The Thickness of elastomer is estimated vide the following derived equation, which holds good for all temperatures.

D_m = Diameter of metal
D_g = Diameter of glass
T_e = Thickness of elastomer
α_m = CTE of metal
α_g = CTE of glass
α_e = CTE of elastomer

At any given temperature T_1, Diameter of metal, $D_m = D_g + 2T_e$..............1

At any given temp T2, D_m will change by $D_m' = D_m \times \alpha_m \times \Delta T$

At any given temp T2, D_g will change by $D_g' = D_g \times \alpha_g \times \Delta T$

At any given temp T2, T_e will change by $T_e' = T_e \times \alpha_e \times \Delta T$

To maintain the same stress levels in the glass at T1 and T2, D_m' must be equal to $D_g' + 2\,T_e'$.

$$\text{i.e. } (D_m \times \alpha_m \times \Delta T) = (D_g \times \alpha_g \times \Delta T) + 2(T_e \times \alpha_e \times \Delta T).$$

By cancelling ΔT both sides, we get,

$$(D_m \times \alpha_m) = (D_g \times \alpha_g) + 2(T_e \times \alpha_e)$$

Substituting eqn…1 for D_m,

$$(D_g + 2T_e)\,\alpha_m = (D_g \times \alpha_g) + 2 \times T_e \times \alpha_e$$

$$(D_g.\,\alpha_m + 2T_e.\alpha_m) = (D_g \times \alpha_g) + 2 \times T_e \times \alpha_e$$

By re arranging,

$$(D_g.\,\alpha_m) - (D_g \times \alpha_g) = 2\,.T_e\,.\alpha_e - 2T_e.\alpha_m$$

$$D_g(\alpha_m - \alpha_g) = 2T_e(\alpha_e - \alpha_m)$$

$$\underline{\mathbf{T_e = Dg(\alpha_m - \alpha_g) / 2(\alpha_e - \alpha_m)}}$$

Using the above equation, the thickness of the elastomer for different combinations of available bonding materials with the designed glass and metal were worked out.

dg	αm	αg	αe	te	elastomer	metal	glass	optics
22	0.00002300	0.00000060	0.00001600	-35.2	bacon	al.6061	silica	filter
22	0.00002300	0.00000060	0.00010200	3.118987	2216	al.6061	silica	filter
22	0.00002300	0.00000060	0.00001900	-61.6	EP21TCHT	al.6061	silica	filter
22	0.00000890	0.00000060	0.00001600	12.85915	bacon	titanium	silica	filter
22	**0.00000890**	**0.00000060**	**0.00010200**	**0.980666**	**2216**	**titanium**	**silica**	**filter**
22	0.00000890	0.00000060	0.00001900	9.039604	EP21TCHT	titanium	silica	filter
22	0.00004700	0.00000060	0.00001600	-16.4645	bacon	peek	silica	filter
22	0.00004700	0.00000060	0.00010200	9.28	2216	peek	silica	filter
22	0.00004700	0.00000060	0.00001900	-18.2286	EP21TCHT	peek	silica	filter
17	0.00002300	0.00000780	0.00001600	-18.4571	bacon	al.6061	SF6G05	Ele- 1
17	0.00002300	0.00000780	0.00010200	1.635443	2216	al.6061	SF6G05	Ele- 1
17	0.00002300	0.00000780	0.00001900	-32.3	EP21TCHT	al.6061	SF6G05	Ele- 1
17	0.00000890	0.00000780	0.00001600	1.316901	bacon	titanium	SF6G05	Ele- 1
17	0.00000890	0.00000780	0.00010200	0.10043	2216	titanium	SF6G05	Ele- 1
17	**0.00000890**	**0.00000780**	**0.00001900**	**0.925743**	**EP21TCHT**	**titanium**	**SF6G05**	Ele- 1
17	0.00047000	0.00000780	0.00001600	-8.65352	bacon	peek	SF6G05	Ele- 1
17	0.00047000	0.00000780	0.00010200	-10.6758	2216	peek	SF6G05	Ele- 1
17	0.00047000	0.00000780	0.00001900	-8.71109	EP21TCHT	peek	SF6G05	Ele- 1
10	0.00002300	0.00000700	0.00001600	-10.8571	bacon	al.6061	bk7g18	Ele- 2
10	0.00002300	0.00000700	0.00010200	0.962025	2216	al.6061	bk7g18	Ele- 2
10	0.00002300	0.00000700	0.00001900	-19	EP21TCHT	al.6061	bk7g18	Ele- 2
10	0.00000890	0.00000700	0.00001600	1.271127	bacon	titanium	bk7g18	Ele- 2
10	0.00000890	0.00000700	0.00010200	0.096939	2216	titanium	bk7g18	Ele- 2
10	**0.00000890**	**0.00000700**	**0.00001900**	**0.893564**	**EP21TCHT**	**titanium**	**bk7g18**	Ele- 2
10	0.00047000	0.00000700	0.00001600	-4.84416	bacon	peek	bk7g18	Ele- 2
10	0.00047000	0.00000700	0.00010200	-5.97622	2216	peek	bk7g18	Ele- 2
10	0.00047000	0.00000700	0.00001900	-4.87639	EP21TCHT	peek	bk7g18	Ele- 2
10	0.00002300	0.00000700	0.00001600	-10.8571	bacon	al.6061	bk7g18	Ele-3
10	0.00002300	0.00000700	0.00010200	0.962025	2216	al.6061	bk7g18	Ele-3
10	0.00002300	0.00000700	0.00001900	-19	EP21TCHT	al.6061	bk7g18	Ele-3
10	0.00000890	0.00000700	0.00001600	1.271127	bacon	titanium	bk7g18	Ele-3
10	0.00000890	0.00000700	0.00010200	0.096939	2216	titanium	bk7g18	Ele-3
10	**0.00000890**	**0.00000700**	**0.00001900**	**0.893564**	**EP21TCHT**	**titanium**	**bk7g18**	Ele-3
10	0.00047000	0.00000700	0.00001600	-4.84416	bacon	peek	bk7g18	Ele-3
10	0.00047000	0.00000700	0.00010200	-5.97622	2216	peek	bk7g18	Ele-3
10	0.00047000	0.00000700	0.00001900	-4.87639	EP21TCHT	peek	bk7g18	Ele-3
13	0.00002300	0.00000780	0.00001600	-14.1143	bacon	al.6061	SF6G05	Ele- 4
13	0.00002300	0.00000780	0.00010200	1.250633	2216	al.6061	SF6G05	Ele- 4
13	0.00002300	0.00000780	0.00001900	-24.7	EP21TCHT	al.6061	SF6G05	Ele- 4
13	0.00000890	0.00000780	0.00001600	1.007042	bacon	titanium	SF6G05	Ele- 4
13	0.00000890	0.00000780	0.00010200	0.076799	2216	titanium	SF6G05	Ele- 4
13	**0.00000890**	**0.00000780**	**0.00001900**	**0.707921**	**EP21TCHT**	**titanium**	**SF6G05**	Ele- 4
13	0.00047000	0.00000780	0.00001600	-6.6174	bacon	peek	SF6G05	Ele- 4
13	0.00047000	0.00000780	0.00010200	-8.16386	2216	peek	SF6G05	Ele- 4
13	0.00047000	0.00000780	0.00001900	-6.66142	EP21TCHT	peek	SF6G05	Ele- 4

Table -1: Estimation of elastomer thickness

The options on bold letters finalized for the present lens assembly design. This design of proper elastomer thickness ensures the temperature survival.

5. Design Analysis:

5.1. Analysis for shear load:

Space based instruments would be subjected to dynamic loads during the launch of the spacecraft due to Launch vehicles'dynamics. For any such system a max of 30g sine vibration is considered for estimating the worst case equivalent static loads. Hence, each lens element is subjected to a shear load equivalent to 30 times its mass. The results shows that the maximum stress observed (0.112Mpa) is well within the allowable shear strength of the elastomer selected.(Ref fig.6). Hence this design of the lens mounting only with elastomer bonding is justified. This to a great extent helped to do away with the metal locknut/retainer used to constrain the lens elements axially.

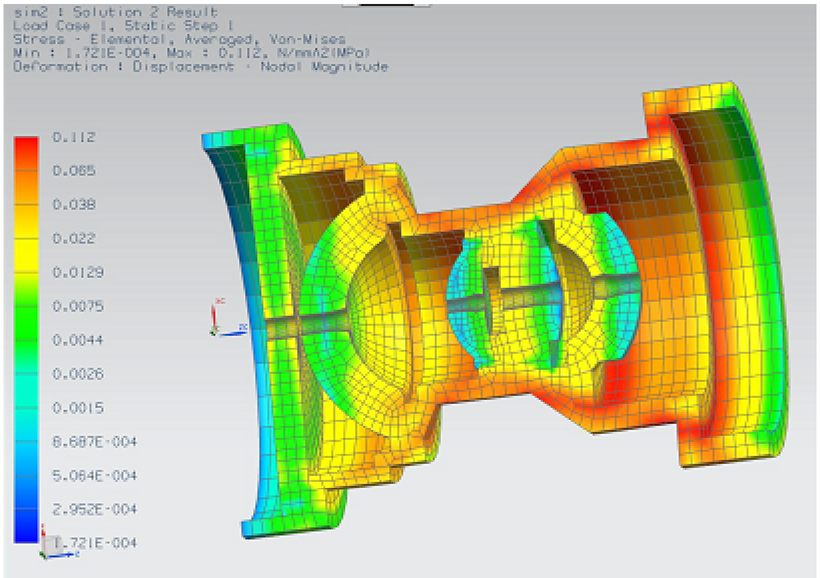


fig.6: FEM model for shear load analysis

5.2. Analysis for temperature survival:

As it was expressed from the beginning, survival of lunar cold temperature is the main target of this lens mount design. To validate this through FEM analysis, the lens assembly model (fig.7) was subjected to thermal loads. Analysis was also carried out to compare the Von-Mises stress results between the **three point** elastomer mounted and the **all round** elastomer mounted lens models.The purpose of designing the three point elastomer model was to reduce the load bearing area on the circumference of the lens on which the load of contraction of the metal housing acts. The results (ref table -2) suggest the three points elastomer mounts is better than the all round elastomer mount in terms of stress values observed on the lens elements.

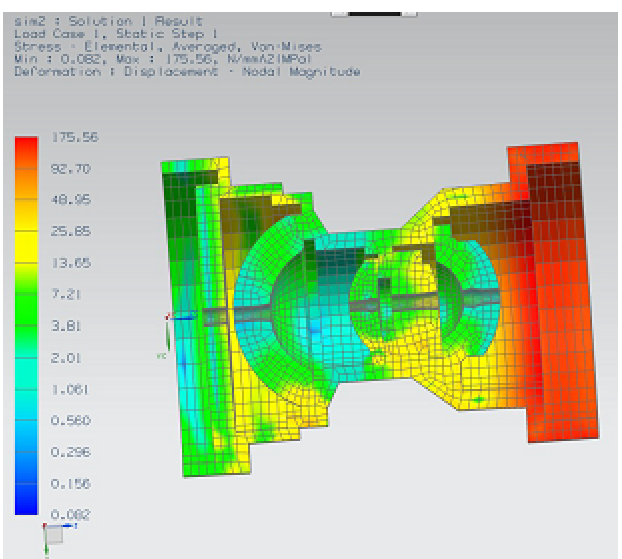


fig.7: FEM model for thermal analysis

table – 2 : stress values observed @ -100°C

Lens element	Max.stress in lenses in all round elastomer MPa	Max.Stress in lenses in three place elastomer mount MPa	
		At elastomer contact points	Between elastomer contact points
1 – SF6	19.5	17.5	7.6
2 - BK7	37.4	32.2	10.1
3 – BK7	25.4	23.3	8.2
4 - SF6	23.7	19.6	7.9
5- Filter Fused silica	16.2	14.4	6.5

6. Experimental validation:

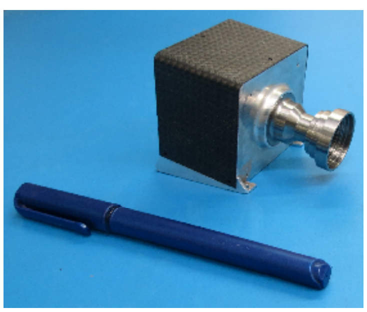
To validate the design through experiments, the lens elements were assembled to a titanium alloy barrel with elastomer (EP21CHT) bonded at three places between glass and the metal. After the elastomer cured, the lens assembly was integrated with its electronics, consists of detector, power and data handling systems in a rigid flex polyamide PCB. The images were recorded after achieving reasonably good focus. The full camera system was kept inside a thermal vacuum chamber whose vacuum level was maintained as 10^{-6} Torr and temperature was slowly brought down to -120°C, with a dwell period of 12 Hours. After reaching the room temperature 25°C, the camera was mounted in the same fixture and image was captured at the same time next day to maintain same illumination. Both the images are comparable and shown below in fig,8 and fig.9.

fig. 8 : Image prior to cold storage

fig. 9 : Image after cold storage

Conclusion:

A new lens mounting method is designed, which is a combination of conventional elastomer mount and flexural mount. The design ensures the survival in Lunar night temperature(-200°C) and the dynamic environment specified for the spacecraft. Also the design meets the weight target specified, 25gm for the lens and 150gm for the full camera. The design is validated through FEM analysis and experimental tests. Images captured pre and post 'low temperature storage' is comparable. Further experiments will be conducted to validate the survival up to -200°C. Tests will be conducted to qualify for launch and landing environments survival. On successful qualification this lens will be part of navigation cameras of Lunar Rover planned via India's second Moon mission, Chandrayaan-2



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