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Opto-mechanical design and analysis of a refractive multi element lens assembly for space applications

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Abstract: The objective of this work is to design and analyse the multi element lens assembly for space borne application, in which refractive optical systems are used in remote sensing applications with high resolution optical imaging performance at satellite orbital height of about 600km from earth surface. To achieve such high optical performance it is essential to design highly stiff, thermally and mechanically stable optical mounts for geometrical positioning of the Opto-mechanical system so as to withstand dynamic launch loads and thermal loads during on-orbit conditions.

Key words: **Micro Yield Stress (MYS), Peak To Valley (PV), Optical Elements, Mechanical Mount, Opto-Mechanical Design.**

I. INTRODUCTION

Opto-mechanical design involves many disciplines such as Material Science, Mechanical design, Optics design, Fabrication and Thermal design aspects. The Opto-Mechanical design deals with Design, Analysis, Fabrication, Assembly and Qualification of the Optical systems incorporating optical components mounted in mechanical housing. In order to ensure consistent optical performance of mounted optical components having surface figure accuracy better than $\lambda/6$ (PV), where λ is the reference wavelength. Strain free mounting of optical elements and positioning the components of an optical system relative to each other are the major design considerations in Opto-mechanical design. Both micro-level strain and stress are the major design criteria for Opto-mechanical designs. The space borne optical systems should have sufficient stiffness to withstand rocket launching loads, minimum weight for better agility and requisite thermal properties to ensure minimum displacements, thermal stresses and thermal gradients for thermal loads. Hence, the selection of material and geometry optimization of design is based on strength to weight ratio (E/ρ) & moment to area ratio (I/A) and thermal conductivity to thermal coefficient of expansion ratio (K/α).The performance of optical assembly requires stringent control of dimensional stability, geometrical positioning, alignment accuracies and optical surface deformations against static, dynamic and thermal loads. While designing such optical systems, the designer has to take into account various factors such as manufacturing limitations of the lens and mount, assembly and interface effects, static, dynamic, gravity release, on-orbit thermal and other environmental loads such as vibration, shock etc. Analytical relationships are given for estimating selected important attributes of design such as contact stress due to forces imposed during assembly and temperature change or acceleration. This paper gives the details of Finite element analysis requirements, FEA of lens assembly, performance of lens assembly.

II. LENS MOUNTING REQUIREMENTS

The following critical requirements are summarized for Lens Mounting.

- The Gravity effects must be removed / minimized by the support system for a given size and geometry of the lens.
- The reaction forces generated by the support system must exactly balance out the weight of the supported lens acting along gravity vector i.e. this ΣF_z = weight of the lens (if gravity vector along Z axis)
- All other reaction forces in other degrees of freedom & bending moments must balance out to Zero, i.e. ΣF_x, ΣF_y, ΣR_X, ΣR_Y, ΣR_z, $\Sigma M = 0$
- The support system must be semi-kinematic in nature so that lens can be supported on the support system for repetitive testing.

- The support system must be highly sensitive to detect even minute changes in the load acting on the support points.
- The support system must be stiffer than the lens stiffness so that deflections in the support system are minimum.
- The support locations shall not change laterally with reference to the lens position for repetitive testing.

III. GEOMETRIC MODEL OF THE MULTI ELEMENT LENS ASSEMBLY

The basic structure of the multi element lens assembly is consists of four lenses and its respective mountings, spacers in between the housings to maintain the air space between the lenses, lock nut, main housing and a stand. Figure 3.1 shows Geometric model of multi element lens assembly and figure 3.2 shows Geometric model of multi element lens assembly (sectional view).

Fig 3.1: Geometric model of multi element lens assembly

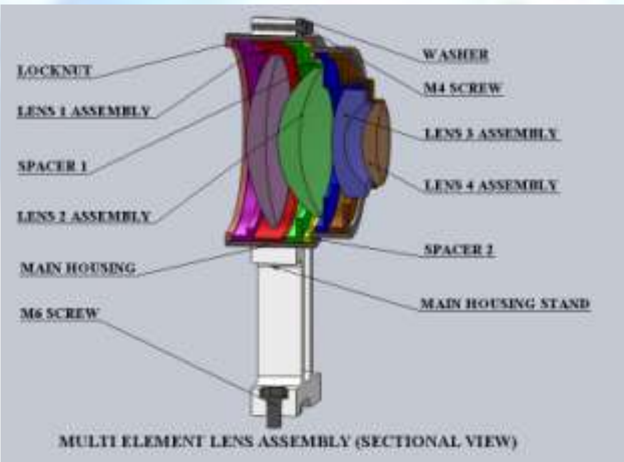

Fig 3.2: Geometric model of multi element lens assembly (sectional view)

IV. FINITE ELEMENT ANALYSIS OF LENS ASSEMBLY

4.1 FEM ANALYSIS REQUIREMENTS: Typically the lens mount designs are based on three stage approach, where in:

1. In the first stage, a preliminary configuration of a lens mount is obtained based on available closed form solutions and literature studies. Iterative analysis is carried out to arrive at a preliminary configuration that is feasible for fabrication.
2. In the second stage, the preliminary model is used to obtain the pitch circle diameter of the lens at which the mounts should be placed.

3. In the third stage the model is modified and each configuration is subjected to detailed FEM analysis for stiffness (stability) requirements. Final geometrical models are then evolved. The final model is studied for actual performance and compared against specific requirements.

4.2 FE Model Assumptions:

1. Lens is assumed to be linearly elastic even though it is brittle, because any brittle material posses elastic property when the deformations are in nano scale.
2. No glue layer is modelled in the FE Models. FE exercises with glue and without glue give near identical results for the front surface deflections and stresses in the lens.

4.3 FEM Analysis Exercises:

Following exercises are very essential (but not limited to) for evaluating the lens mount performance:

- Natural frequency of assembly with both free-free and base rigidly clamped.
- 60g quasi static loading for the assembly along optical axis and normal to Optical axis.
- Temperature excursion for ΔT ± 40°C with reference to reference temperature of 20 °C.

4.4 Mechanical properties:

The following mechanical properties of different material used in the finite element analysis are tabulated in the table 4.1

Table 4.1: Material Properties

PART	MOUNTS	LENS			GLUE	SCREWS
MATERIAL	Titanium	NSF66	NLASF43	NSF57	EC 2216 (3M)	316 L STAINLESS STEEL
YOUNG'S MODULUS E (N/mm2)	1,14,000	93000	1,14,000	96000	689	2,00,000
Shear modulus G=N/mm^3	42,500	36,300	44,186	38,095	241	76,923
POISSON'S RATIO ν	0.34	0.262	0.29	0.26	0.43	0.3
Mass Density N.sec^2/mm^4	4.43X10^{-9}	3.37x10^{-9}	4.26x10^{-9}	3.53 x10^{-9}	1.25	8
CTE-α K^{-1}	8.8 x10^{-6}	9.0 x10^{-9}	5.5 x10^{-9}	8.5 x10^{-9}	102.0 x10^{-6}	17.0x10^{-6}

4.5 Acceptance Criteria:

1. In all the FEM analysis exercises the performance is evaluated in terms of stresses developed in lenses.
2. The co-linearity between optical axis and mechanical axis should be less than 2 microns.
3. The MYS of each of the lenses should not exceed 5 MPA to static load of 60g.

Table 4.2 Criteria for safety margins

Sl. No.	Material	Criteria
1.	NSF66,NLASF43,NSF57 (Schott)	$\sigma_{ys} <$ 5 N / mm2 (Permanent) $\sigma_{ys} <$ 10 N / mm2 (Temporary)
2.	Glue EC 2216 (3M)	$\sigma_{ys} <$ 5 N / mm2 (Stability)
3.	Titanium	$\sigma_{ys} <$ 120 N / mm2

4.6 Finite element model Description

The Final model of lens assembly has been analysed. The results and discussions are shown below in further sections. The Final model of lens assembly is as shown in figure 5.2 of the final model of the lens assembly.

Table 4.3: FE model description

Description	Element Type	Total Mass (Kg)	No. of Elements	No. of Nodes
Lens Assembly	CHEXA	1.33	1,97,240	2,37,049

Fig: 4.2: Finite element model of the lens assembly

4.7 Loads and Boundary conditions:

The base of the Main Housing Stand is fixed with six degrees of freedom and the overall lens assembly is analyzed for the following load conditions.

4.7.1 Quasi static load:

a) Load Case 1 = 60'g'-Perpendicular to optical axis (X-axis)
b) Load Case 2 = 60'g'-Perpendicular to optical axis (Y-axis)
c) Load Case 3 = 60'g'-Along optical axis (Z-axis)

4.7.2 Thermo static load:

Ambient temperature T= +20˚C

a) Load Case 4 = T+ΔT (ΔT =+40˚C)
b) Load Case 5 = T+ΔT (ΔT =-40˚C)

V. ANALYSIS AND RESULTS

In this section the complete lens assembly is analyzed for the boundary and loading conditions as stated in the previous section.

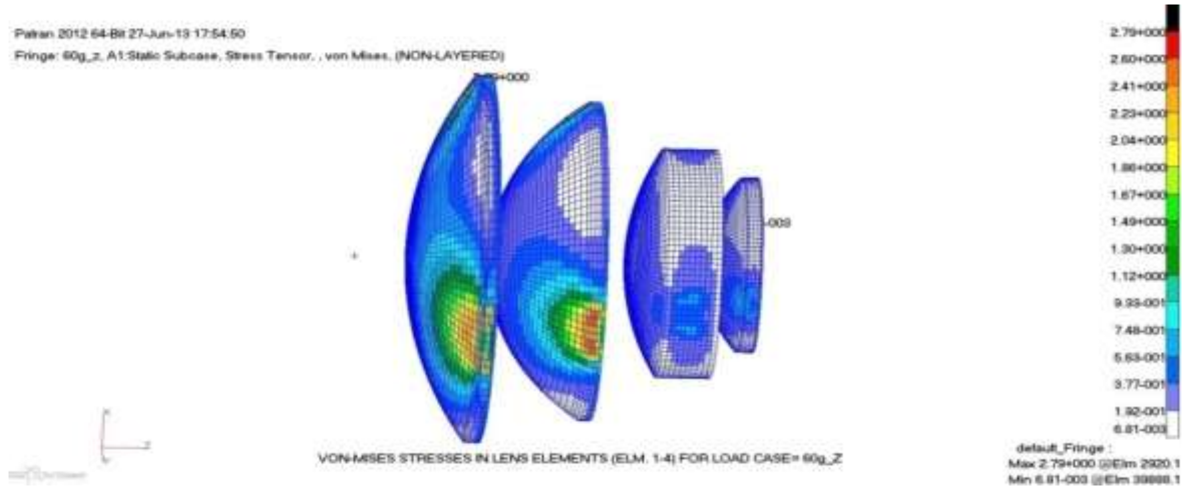

Fig: 5.1: Von-mises stress in lenses for 60g-Z load

The above figure shows the stresses (Von mises stress) in the overall lens assembly for 60g (gravity) load applied in Z-direction and the maximum von mises stress obtained is 2.79 MPa.

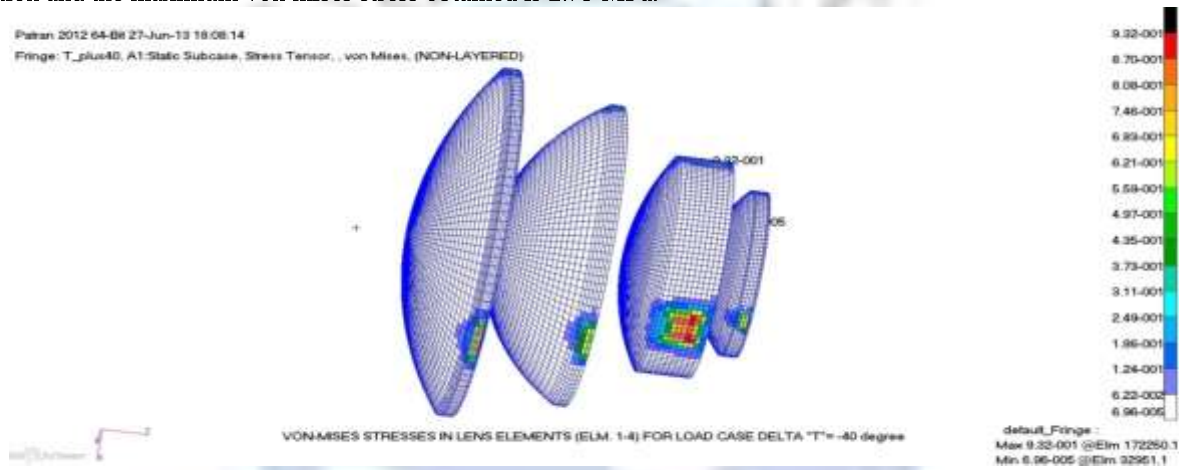

Fig: 5.2: Von-mises stress in Lenses for Delta T=+40^{o}c

The above figure shows the stresses (Von mises stress) in the overall lens assembly for and a temperature load of + 40°C and the maximum von mises stress obtained is 0.932 MPa.

Modal analysis:

To predict the free-free natural frequency and clamped case natural frequency of the assembly, normal modal analysis is carried.

Fig 5.3: Mode shape for first flexible mode (Free-free case)

Main housing stand of the lens assembly is rigidly clamped and natural frequency is simulated.

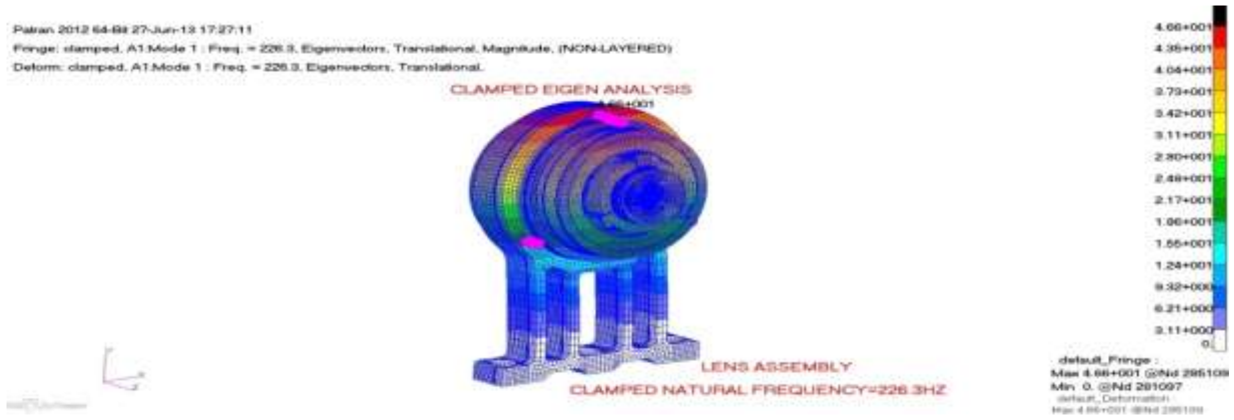

Fig 5.4: Mode Shape for 1st mode (Clamped case)

VI. CONCLUSION

In this project the objective is to design and analyze the Lens assembly. The acceptance criteria are compared with the obtained results in the table below.

Table 6.1 Summarized Lens design performance and acceptance criteria

S. No	Parameter	Goal	Achieved value
1	Lens assembly free-free natural frequency	>1000Hz	1331.9Hz
2	Lens assembly clamped natural frequency	>200Hz	226.3Hz
3	Overall Mass of the Lens assembly	<1.5Kg	1.33Kg
4	Stresses for 60g along Z axis	<5MPa in Lens	2.79MPa
5	Stresses for 60g along Y axis	<5MPa in Lens	4.76MPa
6	Stresses for 60g along X axis	<5MPa in Lens	4.67MPa
7	Stresses for ΔT=40°C	<5MPa in Lens	0.932MPa
8	Stresses for ΔT=-40°C	<5MPa in Lens	0.932MPa

- Design goals of Natural frequency requirements for both free-free Eigen and clamped Eigen conditions are met.
- Stresses in the lenses for 60g static loading and for temperature changes of Δt=±40°C are within MYS criteria.

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