Design and Analysis of a Typical Payload Having Lightweight Metallic Mirror

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Abstract-The lightweight metallic mirrors are requiring to developed camera with high-resolution imagery using frame imagery technique. The design and analysis of lightweight mirrors is carried out with the consideration of minimum surface abbreviations during fabrication using diamond-turning machine. The configuration design of payload with metallic mirrors is carried out and validity of design is established by detailed analysis under lunch load.

Keywords: Opto-mechanical structure, Material selection, Metal Mirror, Single Point Diamond Turning (SPDT), FEA Analysis, Zernike polynomials.

I. Introduction

Until now, the mirror design is very complication and designs were carried out for only launch load. First time we are attempting innovation in mirror design considering fabrication loads. Simultaneously mirror design should be very light-weight. The well-known example of highly structured lightweight mirror is Hubble Space Telescope's primary mirror. The definition of mirror is that it consists of the reflecting surface and give proper image.. Mirrors can be classified in following three categories:
a) Passive mirrors — self-supporting for minimum deflection and it can be light weighted. It is 100% reliable to give high-resolution image [64].
b) Semi-active mirrors — semi-rigid, usually light-weighted mirrors, usually with multipoint mounts. It is partially reliable.
c) Active mirrors — thin face sheets with fully adjustable, computer-controlled, multipoint mounts. It is also partially reliable.
Fig.1 has Mirror 1 as Primary mirror and Mirror 2 as Secondary mirror. These mirrors are used to multi-fold incoming rays. This multi-fold optical configuration known as Origami optics [60]. What is significant is that the reflective optics is based on metal mirrors, rather than the usual glass based origami lens – first time in ISRO [60]. Metal reflectors camera is potentially much more versatile in terms of spectral coverage [60].

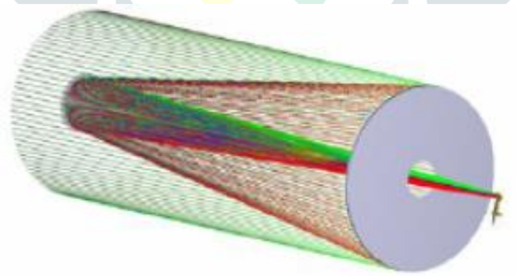

Fig 1. Proposed Optical Ray Diagram [62].

II. Literature Review

1. T. Sugano and K. Takeuchi, T. Go to, Y. Yoshida **"Diamond Turning of an Aluminium Alloy for Mirror"** The life and the wear of single crystal diamond tool. Diamond tools used for mirror finishing of aluminium alloy work pieces. Radius of cutting edge becomes larger, the feed rate becomes smaller, and Surface finish becomes better. The residual stress, the tensile stress arises in the rough cutting and the compressive stress arises in the finish-cutting on mirror surfaces.The magnitude of the res4idual stress depends on the nose radius of cutting tools and the feed rate.The depth of cut is small and depth of a work-affected layer is estimated to be less than 0.5micorn-meter.

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[1]Please note that the LNCS Editorial assumes that all authors have used the western Naming convention, with given names preceding surnames. This determines the Structure of the names in the running heads and the author index.

2.Jizhen Zhang, Xin Zhang, Shuanglong Tan, and XiaolinXie **"Design and Manufacture of an Off-axis Aluminum Mirror for Visible-light Imaging''** Compare of glass to An aluminum mirror in features of light weight, compact design, low cost, and quick manufacturing, Less lead time. To improve the thermal performance of the system [4]. The aperture size of the mirror is 280×100mm and the lightweight provide weight redaction more 40%. Surface deformation caused by centrifugal force during the SPDT, The surface error is reduced to about 1% of the original value. After post-polishing, the form error is 1/30 λ RMS and the surface roughness is better than 5 nm RMS, Specific stiffness(E/ρ) better, coefficient of thermal expansion less, thermal diffusivity high. High thermal distortion, Good mchinability. Robert's Formula, δ=0.021μm.

3.Rikter Horst , Niels Tromp , Menno de Haan , Ramon Navarro , Lars Venema , Johan Pragt **"Directly Polished Lightweight Aluminium Mirror"** Two techniques have been developed: ASTRON [1] Extreme Light weighting [2] improved Polishing Technique for Aluminium Mirrors. Weight reduction up to 95 % improving the Weight-Stiffness ratio. Pockets at the backside of the mirror (see picture below) resulted in a 65 % mass reduction of the mirror. Back mirror with very thin internal ribs and back sheet (1 to 0.3 mm). The CTE tolerance of aluminium grades is extremely small, reliable and predictable. Reduction of mass from 44 kg/m2 to 24 kg/m2 for the deformation and backside reducing global deformation by 29% for a given weight and overall height and improved optical performance using polishing. The extremely light weighted design has a 19% higher Eigen frequency compared to a traditional lightweight design of the same mass.

4. S. Risse, A. Gebhardt , C. Damm , T. Peschel , W. Stöckl , T. Feigl , S. Kirschstein , R. Eberhardt , N. Kaiser , A. Tünnermann **"Novel TMA telescope based on ultra-precise metal mirrors"** Three-Mirror-Anastigmatic (TMA) telescope designed in aluminium with nickel alloy. For brilliant pictures, mirrors with high shape accuracy and very smooth surfaces are required. Mirror thickness smaller than 100μm. Mirrors with roughness down to 1 nm and with a shape quality better than 140 nm. The combination of precise diamond turning and post polishing techniques- classical for the visible and ultra-violet range. One are spherical and two are a spherical mirror. A special new solution for lightweight design was applied. Applications are near infrared (NIR) and infrared (IR) wavelengths.

5.Vasudevan Lakshminarayanan and Andre Fleck **"Zernike polynomials: a guide"**The Zernike polynomials are very well suited for mathematically describing wave fronts or the optical path differences of systems with circular pupils. The Zernike polynomials form a complete basis set of functions that are orthogonal over a circle of unit radius. In this paper, the most important properties of the Zernike polynomials have been reviewed including the generating functions of the Zernike polynomials, relationships to other polynomial sets, the orthonormality conditions as well as transformations. It is meant to constitute a reasonable introduction into this exceptionally useful polynomial set with figures that have been combined from multiple sources to provide a useful resource. No detailed comparisons with alternative methods of describing wave fronts have been included nor has any discussion of various methods of wave front measurement. Tyson provides a comprehensive introduction to these topics

III. Design of Primary mirror

The configuration design of barrel is carried out to achieve fundamental mode of mirror greater than 2000 Hz. It is shown in Fig 2. The mirror is bonded to barrel at locations as shown in figure 4. With this boundary conditions, the rib structure of mirror is proposed in configuration 1 considering holding pattern of vacuum chuck. The initial proposed configuration-I is shown in fig 3.

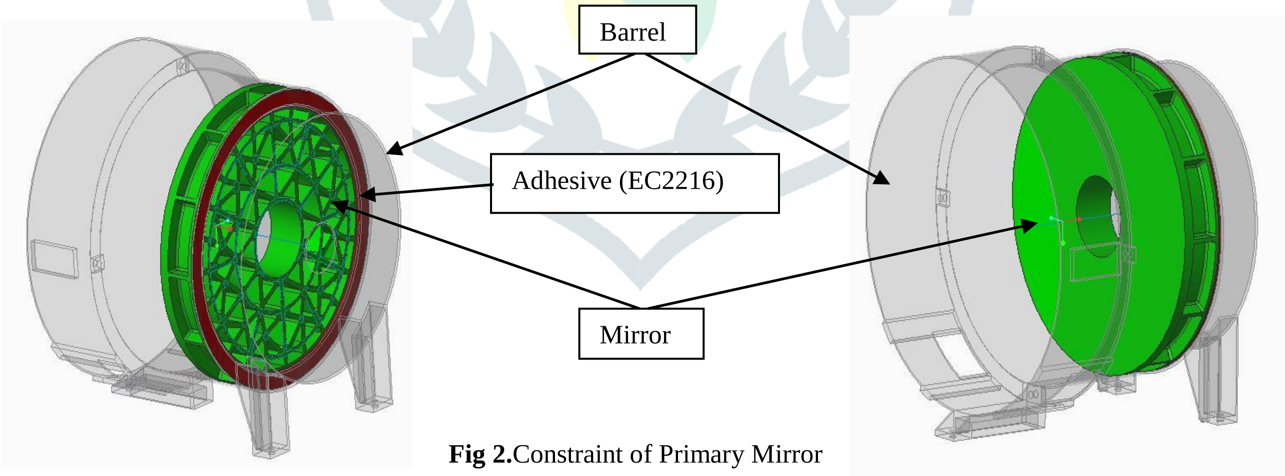


Fig 2. Constraint of Primary Mirror

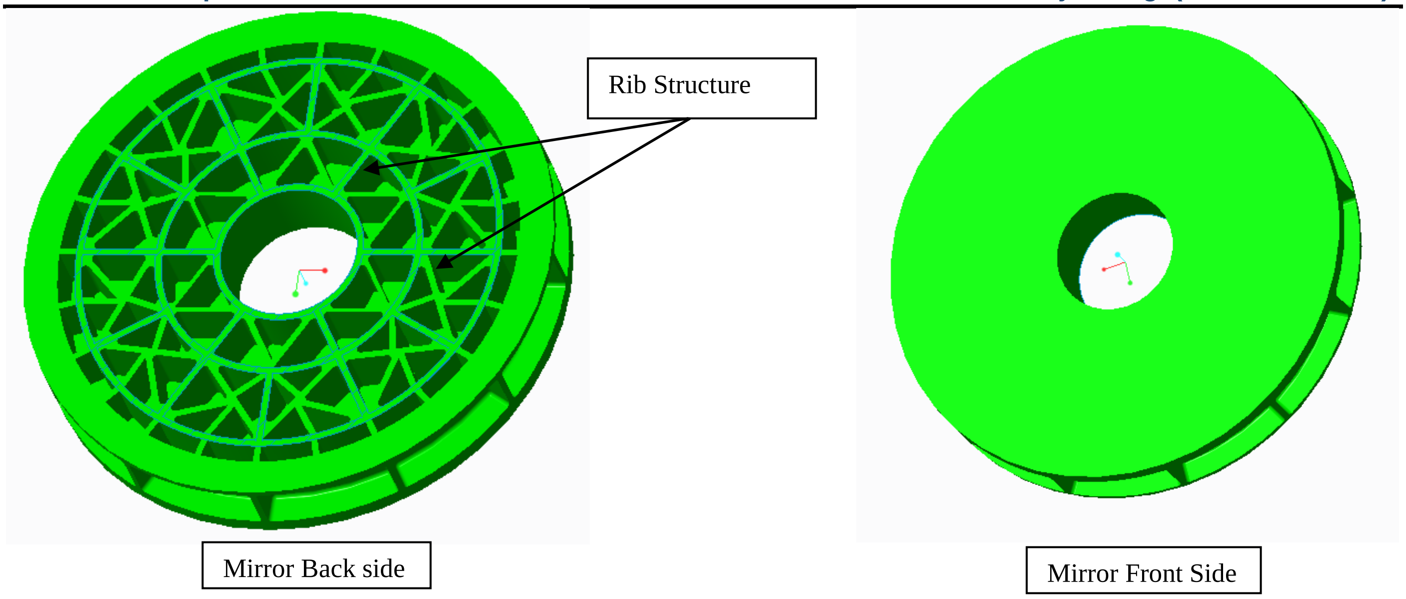


Fig 3. Design of mirror.

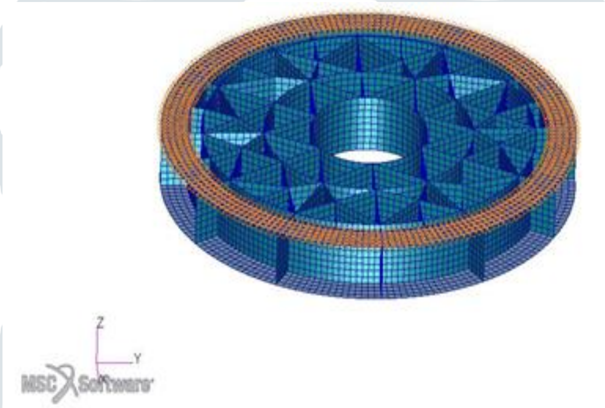


Fig 4. Bonding area of Mirror with respect to Barrel

IV. Selection of Fabrication Process

Based on literature survey, the single-point diamond turning process is selected since it gives minimum tool force on machined surface. Diamond turning is an ultra-precision machining technology for the generation of complex functional surfaces and extremely fine microstructures with the use of geometrically defined diamond cutters. The cutters can be natural diamond or synthetic diamond depending finishing scale of machining and finishing requirements.

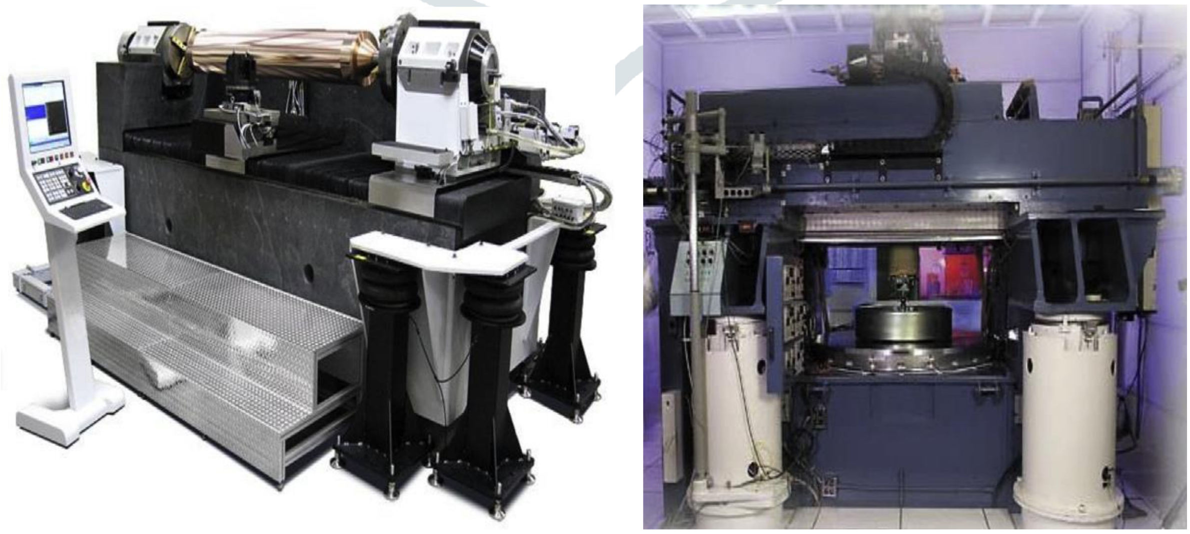


Fig 5. Diamond turning machine.

Fig 6. Diamond machining [59]

Fig 7. Diamond tool [59]

Diamond turning is a multi-stage process. Initial stages of machining are carried out using a series of CNC lathes of increasing accuracy. A diamond-tipped lathe tool is used in the final stages of the manufacturing process to achieve sub nanometer level surface finishes and sub-micrometer form accuracies. The surface finish quality is measured as the peak to- valley distance of the grooves left by the lathe. The form accuracy is measured as a mean deviation from the ideal target form. Quality of surface finish and form accuracy is monitored throughout the manufacturing process using such equipment as contact and laser profile-meters, laser interferometers, optical and electron microscopes. Diamond turning is most often used for making infrared optics, because at longer wavelengths optical performance is less sensitive to surface finish quality, and because many of the materials used are difficult to polish with traditional methods.

V. Fabrication Load and Boundary Condition during diamond turning

The load applied during diamond turning operation on mirror are:

5.1 Vacuum Load:

Vacuum Chuck is used to chuck the work piece by the vacuum pressure. To simulate Vacuum load, the atmospheric pressure of 1.01bars is applied to the mirror top surface.

Fig 8. Vacuum chuck [61]

Vacuum chuck, which are used in diamond turning of aluminum disc because of their high friction coefficient and high damming ratio. The Vacuum chuck holds the mirror at Highlighted area as shown in Fig 9.

5.2Gravity Load:

The gravitation force is applied on mirror during finishing operation through diamond turning. The 1grav load is applied on mirror in in plane direction with respect to Vacuum chuck interface plane

5.3 Centrifugal Load

During finishing operation, the work piece rotates at 1000RPM. It creates Centrifugal Load on the primary mirror during machining.

5.4 Tool Load

A single point diamond is used as the tool. In this study. Since curved surface machining is intended, tools, which have comparatively large nose radii and consequently have little burnishing effect on the work-piece, are adopted. 'The basic geometry of the tools was as follows:

Rake angle:$\alpha =$ 0'
Front. Clearance angle: 5'
Nose radius (R):2mm. 6-mm. and l0 mm
Outer diameter: about **200mm**
Thickness: about **30mm**
Feed rate: 1.5µm/rev
Depth of cut: 2µm
Spindle Speed=300rpm

$$t_1 = depthofcut = fcos\psi = 1.5\,cos(15°) = 1.448\mu m/rev$$

Ultimate Shear Stress (τ_s) = 207MPa

Shear Force:-

$$\text{Shear Force}(F_s) = \frac{\omega \times t_1 \times \tau_s}{\sin\emptyset} = \frac{2.0705 \times 10^{-6} \times 1.448 \times 10^{-6} \times 20710^6}{\sin(16.69°)} = 0.00216N$$

Normal Force: -

$$F_N = F_S \tan(\emptyset + \lambda - \alpha) = 0.00216 \tan(16.69° + 18.41° - 0) = 0.00152\text{N}$$

Cutting Force: -

$$F_C = F_S COS\emptyset + F_N SIN\emptyset = 0.00216 \cos(16.69°) + 0.00152 \sin(16.69°) = 0.00251\text{N}$$

Tangential Force: -

$$F_T = F_N \cos(\emptyset) - F_S \sin(\emptyset) = 0.00152 \cos(16.69°) - 0.00216 \sin(16.69\,°) = 0.0008356\text{N}$$

Feed Rate Force: -

$$F_R = F_T \sin\varphi = 0.0008356 \sin(15°) = 0.000216\text{N}$$

Depth of Cut Force: -

$$F_F = F_T \cos(\varphi) = F_T \cos(15°) = 0.0008356 \cos(15°) = 0.000807\text{N}$$

VI. Design configuration of Mirror

In this design configuration of mirror, there are four different design configurations as under.

6.1 Configuration-I Initial Design of mirror with angular rib

The 3d-modal of mirror is generated considering holding of mirror in Vacuum chuck during final mirror finish operation. This 3d-modal made in Creo software. The mirror is hold in vacuum chuck as shown in figure 10.

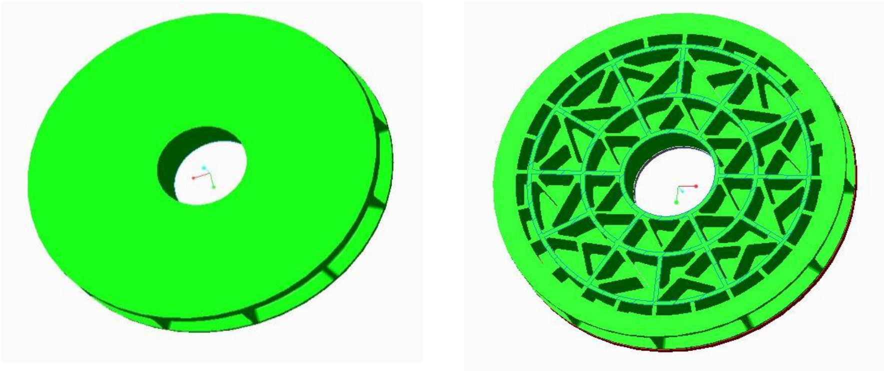


Fig 10. 3D-modal of mirror with angular ribs.

6.2Configuration-II Initial Design of mirror with two additional ribs.

In this configuration, Initial design (Configuration-I) is modified by adding two additional ribs at outer periphery as shown in figure so that we can minimize surface deformation of mirror. Boundary condition to hold mirror during fabrication is same as Configuration-I.

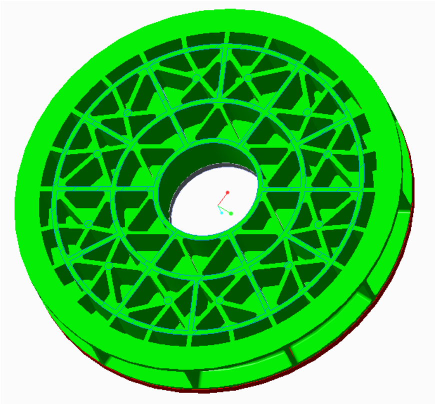


Fig 11.3D-modal of mirror with two additional ribs.

6.3Configuration-III Design of mirror modified as on the base of modified Vacuum Chuck

In this Configuration, The Design of mirror is same as the Configuration-II but in vacuum chuck holding of mirror position is increase as shown in figure.

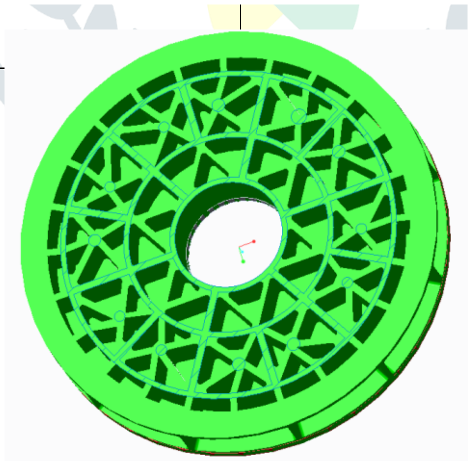
6.4 Configuration-IV Design of mirror modified with thickness and ribs.

In this Configuration, the mirror top surface thickness is modified to 6mm and internal ribs thickness increase to 4mm so that PV errors on mirror surface can be minimized.

Table 1: Change of mirror thickness and rib

Sr No.	Segment of Mirror	Configuration-I, II, III	Configuration-IV
1.	Mirror Surface thickness	5mm	6mm
2.	Ribs	3mm	4mm

Fig 12.3D-modal of mirror modified Vacuum Chuck.



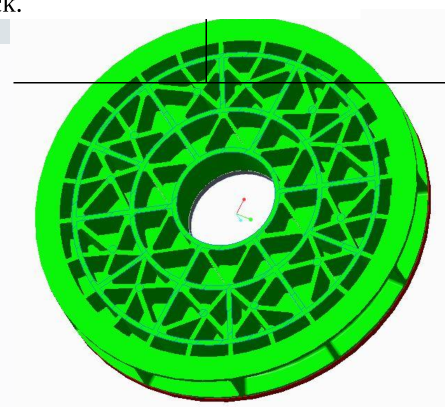


Fig 13.3D-modal of mirror with increase thickness and ribs.

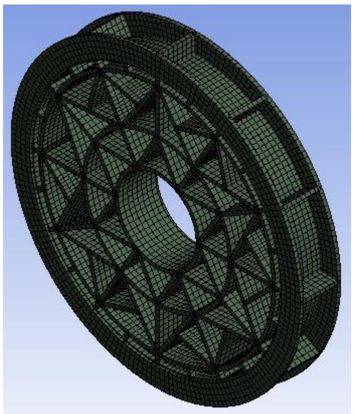
VII. Finite Element Meshing of Mirror

In this mirror, we were done finite meshing by using Ansys 15 software.

Table 2: Number of Nodes and Elements

Number of Nodes	14731
Number of Quadrilateral Element	15294
Number of Triangular Element	30

Fig 14. Finite Element Meshing of Mirror.



VIII. Assessment of Fabrication Load.

Different Load applied to basic Configuration I. The severity of load is assessed based on deformation of mirror surface. The PV error of mirror surface are given in Table 3.

Table 3: Different Load and P-V Errors

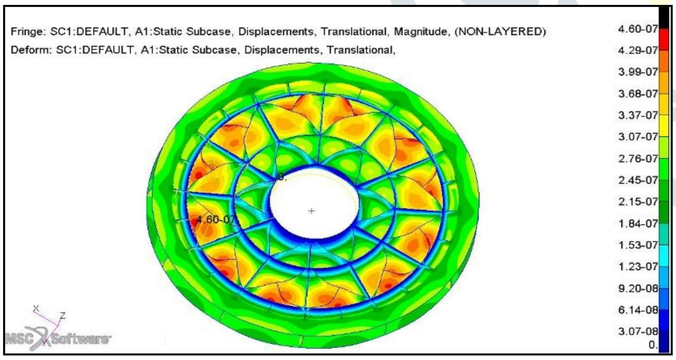
Sr. no.	Load Name	P-V Error(nm)
1	Vacuum Load	298.9
2	Gravity Load	2.36
3	Centrifugal Load	73.7
4	Tool Load	0.0218

8.1 Analysis of Mirror under Fabrication Load

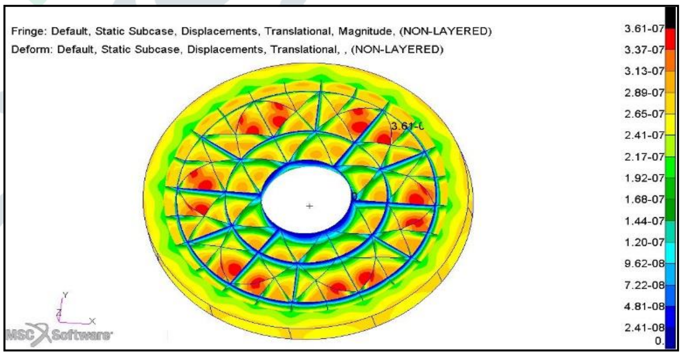
In mirror finishing, all the four load acting together on the mirror. Analysis is carried out by applying all fabrication loads.

8.1.1 Deformation of mirror due to Fabrication Load

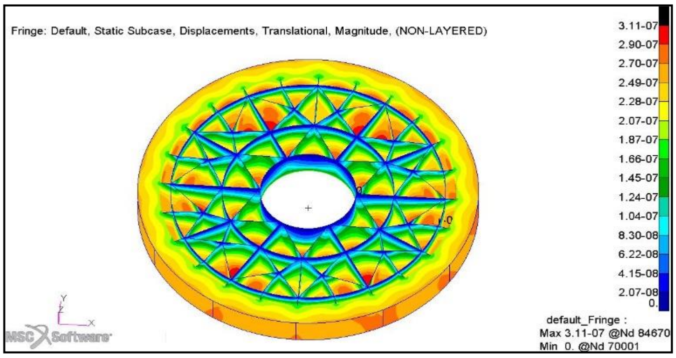
The total Fabrication load is applied on mirror. The Overall Deformation under total Fabrication load is shown below.



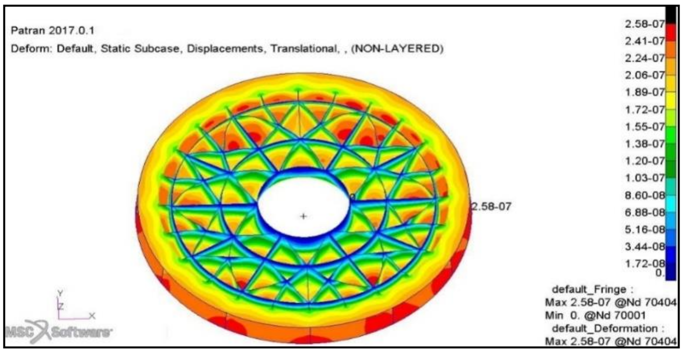
Configuration-I



Configuration-II



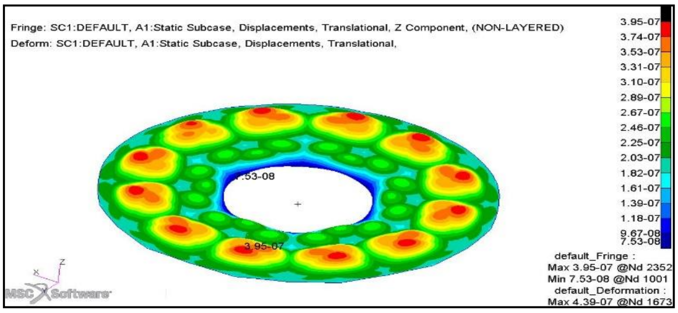
Configuration-III



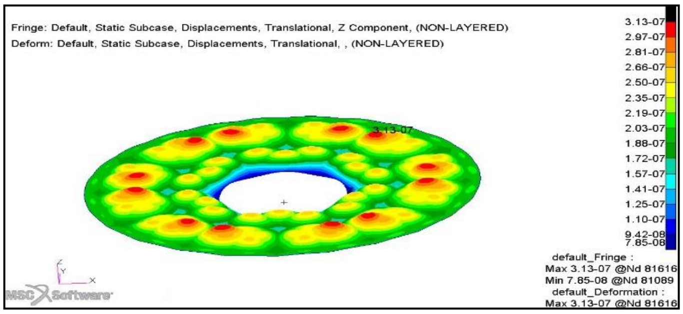
Configuration-IV

Fig 15. Over all Deformation under Total Fabrication Load

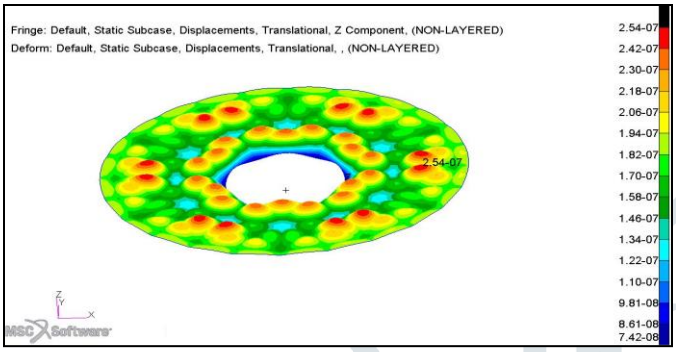
The total Fabrication load is applied on mirror surface. The Mirror Surface Deformation under total Fabrication load is shown below.



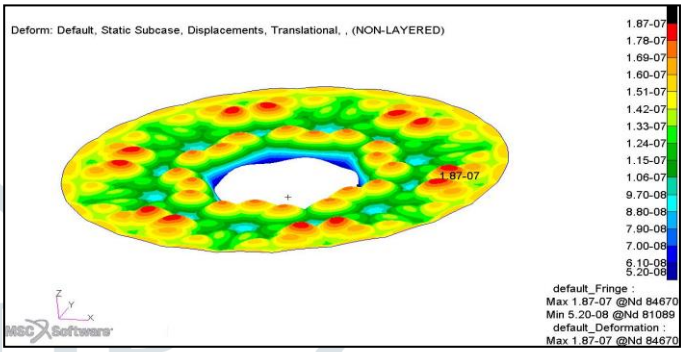
Configuration-I



Configuration-II



Configuration-III



Configuration-IV

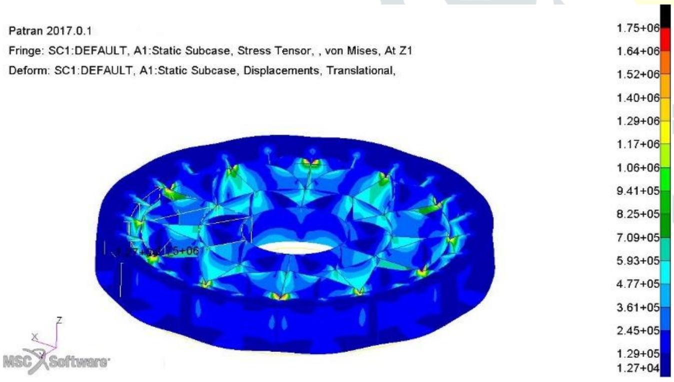
Fig 16. Mirror Surface Deformation (Z-dir.) under Fabrication Load.

8.1.3 Von-misses Stress observed on mirror for all four configuration under fabrication load and Lunch Load

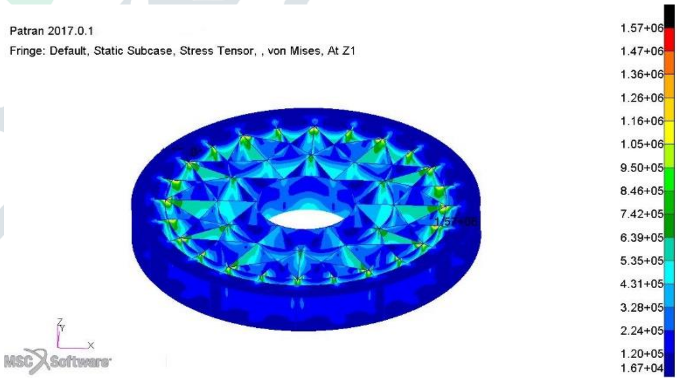
Table 4: For all the Four Configuration PV Error and Von misses Stress

Sr. no.	Configuration Name	P-V Error(nm)	Von-misses Stresses (MPa)
1	Configuration-I	319.7	1.75MPa
2	Configuration-II	234.5	1.57MPa
3	Configuration-III	179.8	1.11MPa
4	Configuration-IV	135	0.897MPa

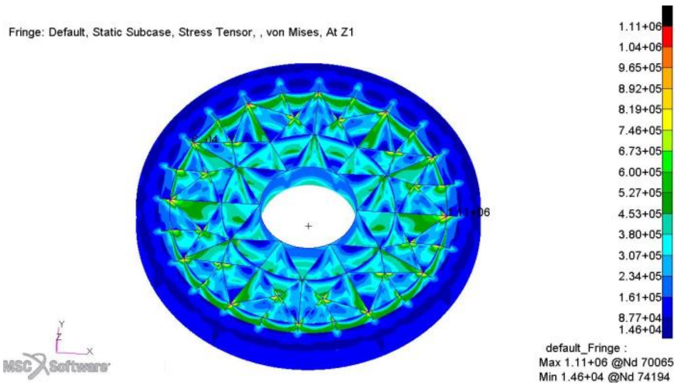
From above table, the stresses are very negligible.



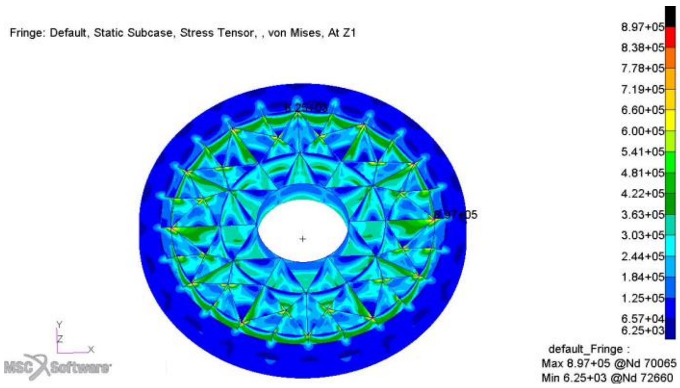
Configuration-I



Configuration-II



Configuration-III



Configuration-IV

Fig. 17. Von misses stress under mirror due to Fabrication Load.

IX. Computation of Zernike Coefficient and Surface Roughness (RMS)

Zernike polynomials are computed for Mirror surface deformation of final configuration (i.e. conf. IV).

Table 5: Zernike Modes

Coefficient. No.	Zernike Mode Value (nanometer)	Name
1	135.442328	Piston
2	0.171132	tilt
3	0.000048	
4	13.129028	Defocus
5	-0.000147	Astigmatism
6	0.000096	
7	0.178585	Primary coma
8	0.000281	
9	-5.627142	Primary spherical
10	0.000147	Primary coma
11	0.000133	
12	0.000028	Secondary Astigmatism
13	-0.000051	
14	0.026125	Secondary Coma
15	-0.000205	
16	4.724666	Secondary spherical
17	0.000042	Secondary Astigmatism
18	0.000047	
19	-0.000038	Secondary Coma
20	-0.000126	
21	0.00002	
22	-0.00001	
23	0.009373	
24	0.000219	
25	-3.880266	Tertiary spherical
26	0.003073	
27	0.000041	
28	0.000167	
29	-0.000052	
30	-0.000043	

X. Comparison of Surface Roughness with Literature

The RMS and PV error of finished surface of mirror for configuration IV is computed and compared with literature having similar size mirror. It is given in Table 6.

Table 6: Zernike Modes

	Theoretical Work	Literature-4
RMS VALUES(nm)	22.62	74.04
PV Error(nm)	135nm	140nm
	1/40 λ RMS	1/30 λ RMS

XI. Analysis of Mirror under Launch loads

The normal modes of Mirror is computed considering boundary condition stated in section III. The first mode occurs at 3402.3 Hz, it is greater than the targeted frequency of 2000Hz. The first two modes are shown in Figure 18 and 19.

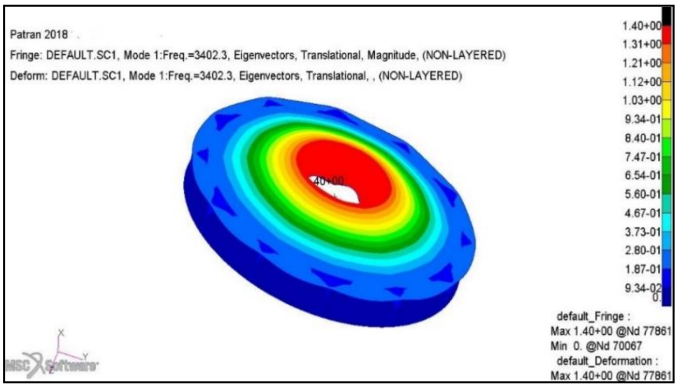


Fig 18. Deformation in mode 1 at frequency 3402.3Hz

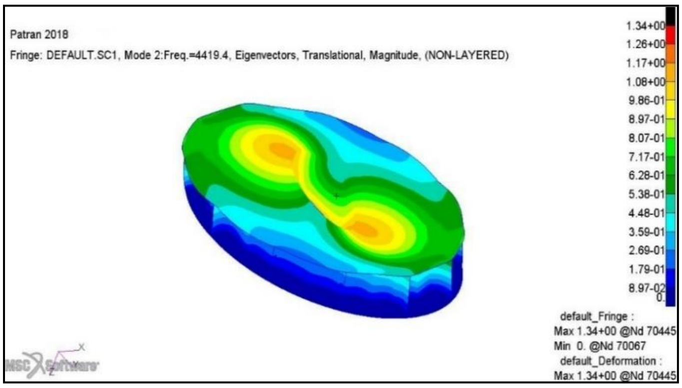


Fig 19. Deformation in mode 1 at frequency 4419.4Hz

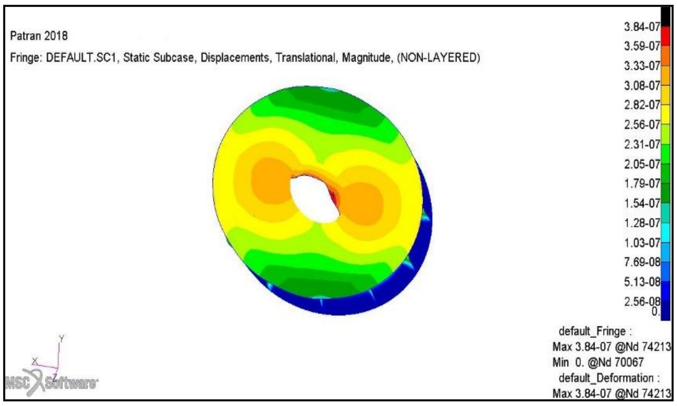


Fig 20. Deformation of mirror in X-direction due to 25g Lunch Load.

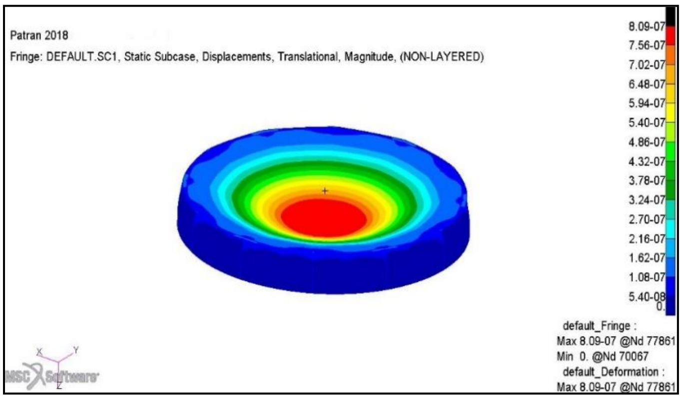


Fig 21. Deformation of mirror in Z-direction due to 25g Lunch Load

The deformation of mirror under Static load of 25g applied individually in in-plane X and out of plane Z direction are shown in figure 20 and 21.. Maximum deflection of 3.84e-7m for in plane X load and 8.09e-7m for out of plane Z load is observed at mirror surface.

The Overall von misses stress due to Lunch Load is shown below. Maximum stresses in plane direction of 0.0967MPa are observed on circular rib of mirror.

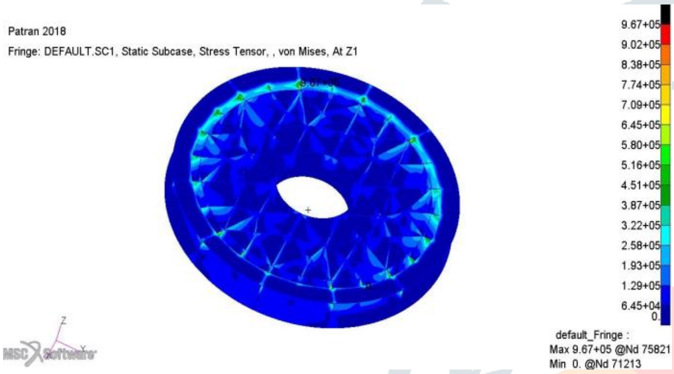


Fig 22. Von-misses Stresses due to Lunch Load in-plane X-direction.

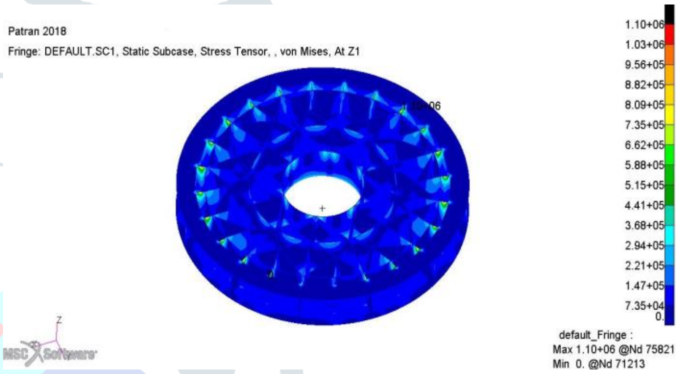


Fig 23. Von-misses Stresses due to Lunch Load in-plane Z-direction.

The maximum shear strain occurs on Adhesive between mirror and structure is negligible as compare to shear strength of Adhesive**.**

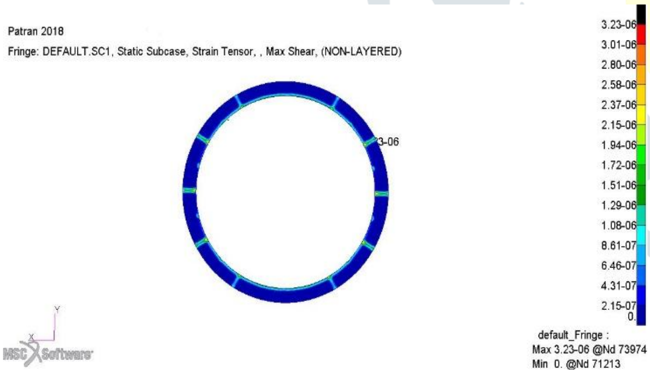


Fig 24. Maximum Shear Strain at Banded area due to Lunch Load in-plane X-direction.

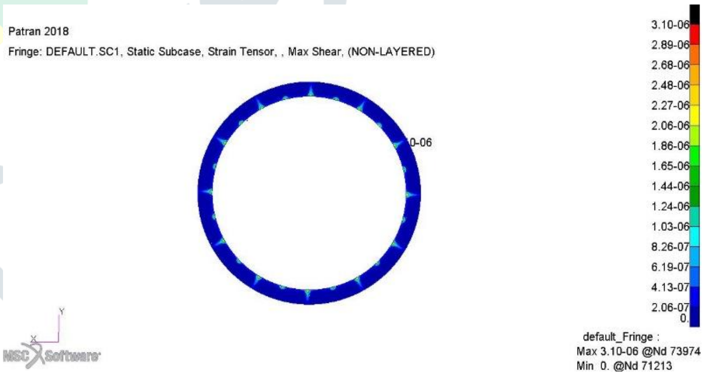


Fig 25. Maximum Shear Strain at Banded area due to Lunch Load in-plane Z-direction.

Table 7: Mirror and Adhesive Stress

Sr.No.	Description	Stress Component	Stress at (MPa) 25g in X-direction	Stress at (MPa) 25g in Z-direction
1.	Adhesive	Max. Shear	0.022	0.021
2.	Mirror	Von-misses	0.967	1.10

XII. Conclusion

In this paper, the design and analysis of optical payload assembly for the remote sensing satellite have been carried out. In the first section, we have found because of literature review that aluminum is most suitable material for mirror fabrication. Different manufacturing process is studied and found that for mirror finish diamond-turning process is more preferred since it gives negligible tool load on mirror surface. In the second section, 3d-modal is generated and FEA analysis is carried out. The deformation of surface of mirror is computed and compared with Literature. The Von-misses stress of Mirror also computed.

From analysis of mirror, it is found that most severe deflection in mirror occurs due to centrifugal load and vacuum load. Deflection due to tool load and gravity load are negligible. The stress observed on mirror during diamond turning operation is negligible. Design modification on baseline configuration was carried out and it is found that there is around 25 % drop in PV error in each configuration with respect to previous configuration. Because of P-V Error ≤ λ/4(158nm) is acceptable, Configuration-IV is acceptable. The configuration IV is found to be safe under launch loads.

XIII. Acknowledgement

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