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STRUCTURAL OPTIMIZATION OF SPACE MIRROR ASSEMBLY TO MINIMIZE MASS AND TO CONSTRAIN OPTICAL ABERRATIONS

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***Abstract**: As key components of the optical system of the space telescope and optical remote sensor, space mirrors' surface accuracy has a direct impact that cannot be ignored of the imaging quality of the space telescope. In the future, large diameter mirror would become an important trend in development of space optical technology. Objective of this study is to design a reasonable lightweight structure to ensure the optical performance of system to meet the requirements. By adopting Finite Element Analysis software, the space mirror assembly can be analyzed and its structure can be optimized. A flexible support structure of the space mirror is being designed and is being optimized to keep higher surface figure accuracy of the space mirrors under gravity and temperature loads encountered in space release.*

***Keywords**: Space mirror, MFD (Bipod Flexure), FEA,Optimization, Zernike coefficients, Optical aberrations.*

I. INTRODUCTION

Ever since the first time Bendsøe [1], Suzuki and Kikuchi [2] used homogenization based approach to solve structural topology optimization problems, many scholars had focused their attention on this appealing filed of structure optimization. Elementaryprerequisite of any aerial payload is low mass and high stiffness. In the case of airborne mirrors, the necessities are more critical. Rather than constraining the stiffness of the structure, constraining surface errors that cause optical aberrations due to gravity release is needed while conforming to a maximum allowable mass limit. There are many studies in available literature on optimization of space mirrors, and in most cases, the objective is to minimize the total or RMS deformation of the active mirror surfaceand the optimization variables are rib thickness and unit-cell dimension [4].

However, these are limited by a particular light weight pattern (triangular/hexagonal) or mirror configuration (sandwich/open back). The stress distribution plots on these mirrors under load cases studied indicate that not all ribs contribute in the load distribution, thereby only adding to the mass of the structure and not stiffness. The following work is not limited to any such restraintsand assumptions. Topology optimization is used to scoop out unnecessary material out of a solid Zerodur blank [3].A typical mirror assembly consists of a mirror, resting on 3 Mirror Fixations Devices (MFDs) to simulate semi-kinematic design and a mounting ring. A semi-kinematic design ensures the mirror structure behaves as close to a rigid body as possible under inertial loads. This helps to minimize stresses on the mirror, while majority of the loads are taken by the MFD.

II. OPTIMIZATION

"An act, process, or methodology of making something (as a design, system, or decision) as fully perfect, functional, or as effective as possible."

Optimization is the act of obtaining the best result under given circumstances. In design, construction, and maintenance of any engineering system, engineers have to take many scientific and administrative decisions at several stages [21]. The ultimate goal of all such decisions is either to minimize the effort required or to maximize the desired benefit. Since the determination required or the profitanticipated in any concrete situation can be articulated as a function of certain decision variables, optimization can be defined as the process of finding the conditions that give the maximum or minimum value of a function [26].

2.1 Topology Optimization:

It is a scientific approach within a given design space, for a given set of loads and boundary conditions that optimizes material layout such that the resulting layout meets a prescribed set of performance targets. Using topology optimization, engineers can find the best concept design that meets the design requirements. It has been implemented through the use of finite element methods for the analysis. It is used at the concept level of the design process to arrive at a conceptual design proposal that is then fine-tuned for performance and manufacturability. This substitutes time consuming and costly design iterations and hence decreases design improvement time and overall cost while improving design enactment. It is used to find the best material distribution or power transmission path within the design space, thus getting the lightest design under various conditions meets the requirements [5].

Topology optimization has three elements: design variables, objective function and constraint conditions. Design variables are changed so as to improve the performance of a set of parameters. Objective function respect to the optimal design performance is a function of design variables. Constraint conditions are restrictions of the design and requirements of design variables and other properties [20].

2.2 Zernike Polynomials and Optical aberrations:

Zernike polynomials are widely used for representing measured and simulated data for optical systems, because mirror is one smooth and continuous surface which can be expressed with radius and polar coordinate defined by azimuth. Zernike Polynomials were formed by F. Zernike in 1934. Zernike Polynomials are orthogonal and linear independence [18]. They have a close relation with Seidel aberrations, so it is an effective method to predict the aberration coefficient and evaluate system's performance. Mirror surface errors causing optical aberrations are effectivelyquantified by Zernike terms. Theyform a complete orthogonal basis on a circle of unit radius.The first 9 items of Fringe Zernike Polynomials Zernike are listed in Table 1.

Table 1 Zernike polynomials relation to optical aberration

No.	Rank	Expression	Meaning
1	0	1	Constant
2	1	$\rho cos\theta$	X Lateral shift
3	1	$\rho sin\theta$	Y Lateral shift
4	2	$2\rho^2 - 1$	Defocus
5	2	$\rho^2 cos2\theta$	0^o or 90^o astigmatism
6	2	$\rho^2 sin2\theta$	45^o astigmatism
7	3	$(3\rho^2 - 2)\rho cos\theta$	X-axis third order coma
8	3	$(3\rho^2 - 2)\rho sin\theta$	Y-axis third order coma
9	4	$6\rho^4 - 6\rho^2 + 1$	Third spherical aberration

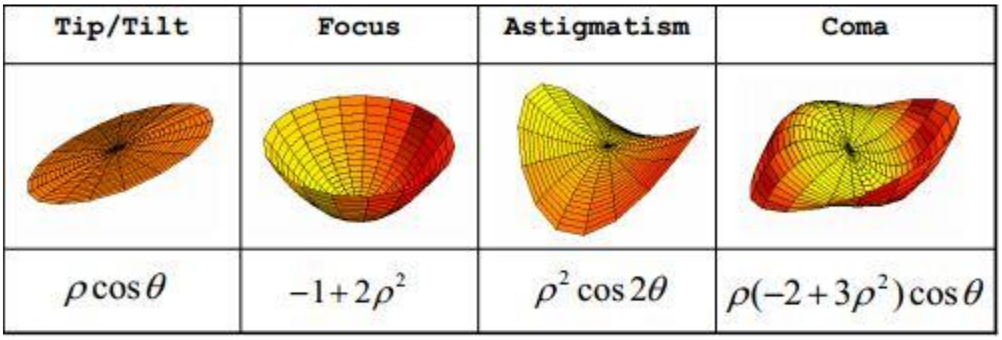


Figure 1(a) Optical aberrations

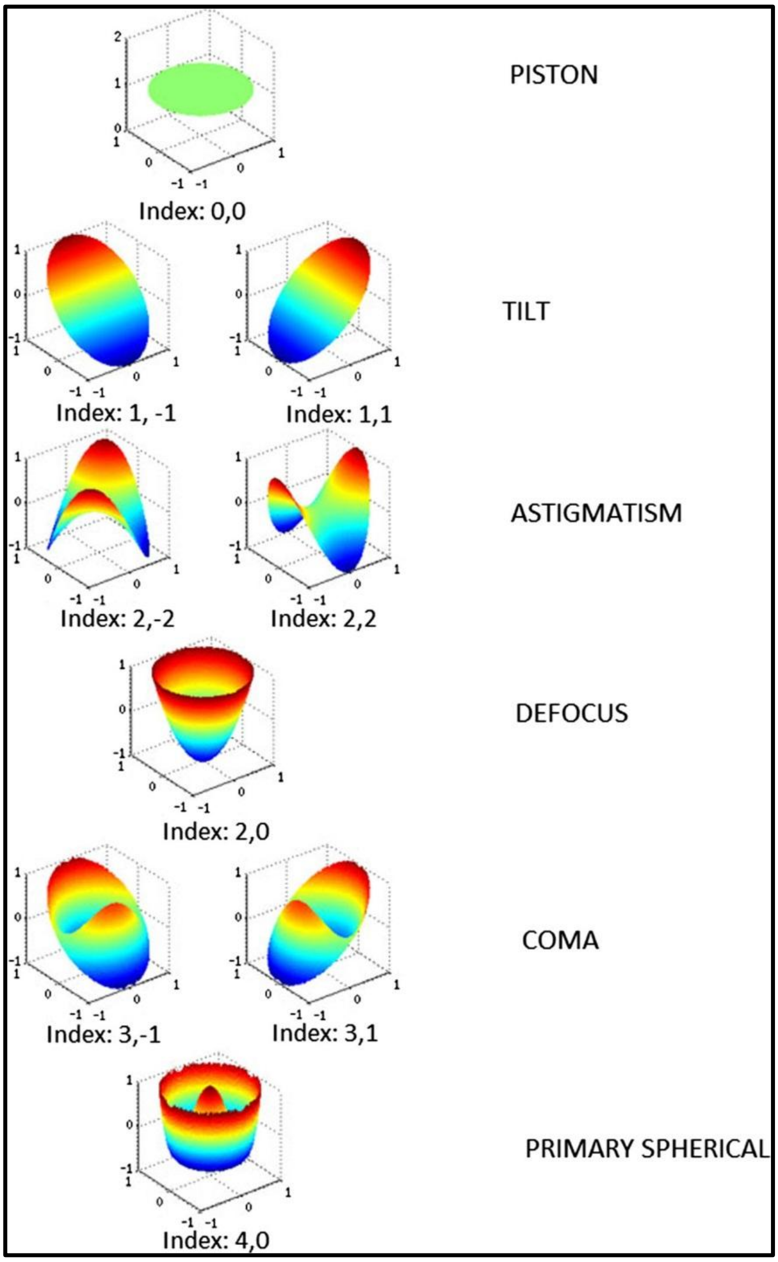


Figure 1(b)Visualization of Zernike surface errors and their corresponding optical aberrations

III. SIMULATION

Topology Optimization is a scientificprocedurewhich produces an optimized shape and material distribution for a structure within a given package space.The OptiStruct algorithm alters the material distribution to optimize the user-defined objective under given constraints. By discretizing the domain into a finite element mesh, OptiStruct calculates material properties for each element[20].

In the case of space mirrors, surface errors occur due to gravity release in orbit. For a multiple mirror system, the first three Zernike surface errors, namely piston and tilt can be compensated by including a mechanism to move the secondary mirror so as to nullify these effects. Even though defocus can be compensated by adjusting the distance between mirrors, magnification and field of view of the optical system are affected. Hence, it helps if defocus is controlled by mirror design and can be avoided altogether [12]. This leaves us with only three surface errors, namely defocus, coma and astigmatism that correspond to distortions of order 3 or lower and can be controlled by Mirror-MFD design [8]. So the optimization problem can be summarized as:

"Minimize mass under lateral and axial gravitational load while constraining defocus, coma and astigmatism."

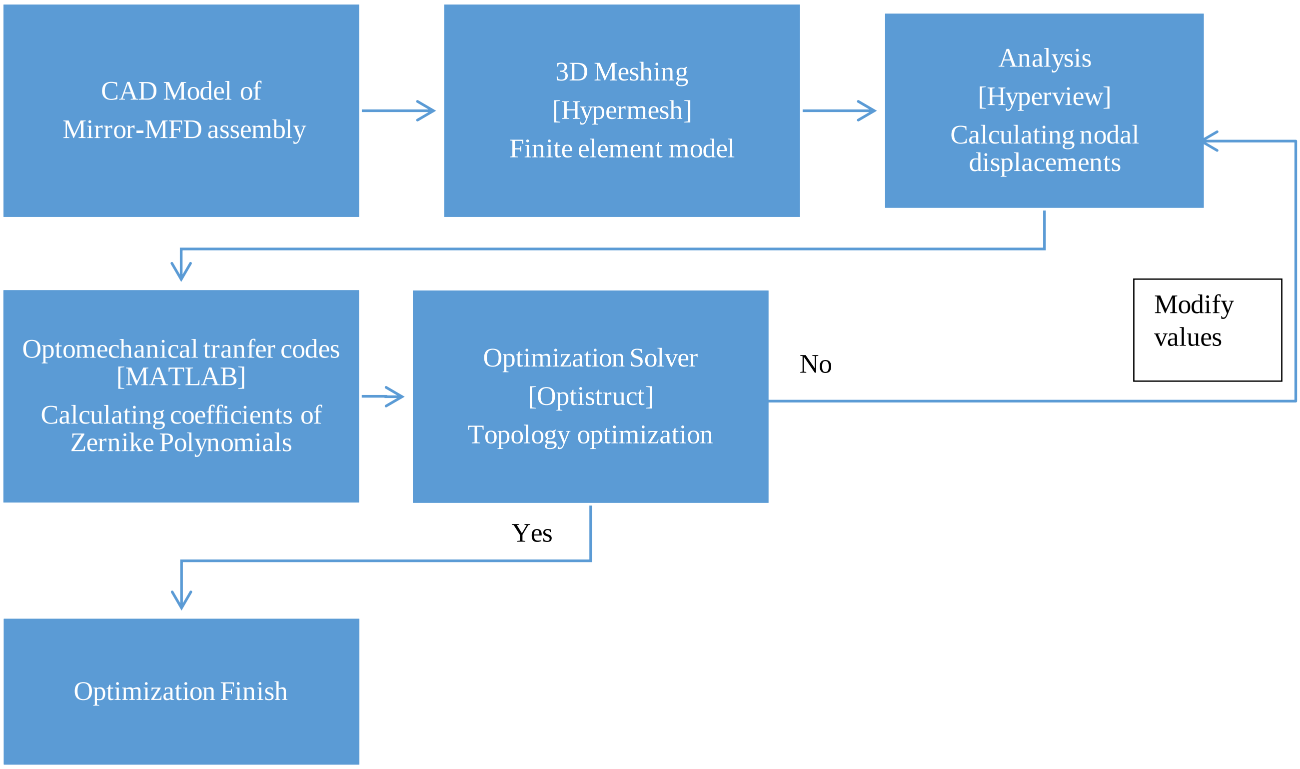


Figure 2.Optimization process flow-chart for the integrated opto-mechanical design.

3.1 Analysis:

For this optimization problem, a solid blank of Zerodur of 1.236 m radius and 0.216 m height is used. Young's modulus is taken as 90.6 N/mm^2, Poisson's ratio 0.15, and density 2.2E-9 Tonne/mm^3. The optical center coincides with the origin of the co-ordinate system used for analysis [16]. Mirror axis is along Z axis. A consistent unit system of mm-Tonne-s is used.

Table 2 Properties of Material

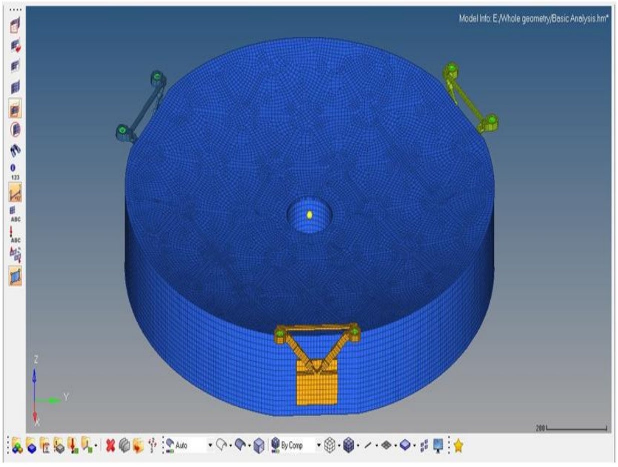
Property	Zerodur	Invar
Elastic Modulus (in GPA)	91	141
Density (G/cu.cm)	2.59	8.1
Poisson's ratio	0.24	0.23
Linear coefficient of thermal expansion (at 20^0 c)	-	1.2

A typical opto-mechanical analysis involves these three steps:

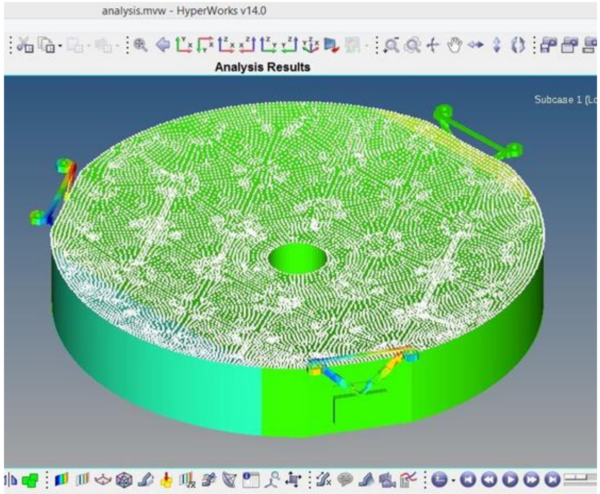
i. FE model generation using Hypermesh 14.0

ii. Extracting nodal displacements in axial direction using HyperView

iii.Calculating Zernike coefficients using Matlab



i. FE Model in Hypermesh



ii. Extracting nodal displacements in axial direction using HyperView

iii. Zernike coefficients are being calculated in MATLAB software with the help of Zernike code and satisfactorily Zernike coefficients of the order of 10−3 or less in the final design are achieved which are shown in table below.

Table 3 Zernike coefficients from MATLAB

Z=	-0.0000230038433	0.0003573218226	-0.0000009246668
-0.0002589908264	-0.0001144690665	-0.0000061742910	-0.0000009727195
0.0536453628211	-0.0000036278250	0.0000244817869	-0.0000106604949
-0.0012200755560	0.0000043675638	0.0000059227383	0.0000052371671
-0.0000111433934	-0.0000014045744	0.0000004578296	0.0000014364828
-0.0060470490530	0.0000347283160	0.0000729458128	-0.0000614868739

3.2 Optimization:

Intended for this optimization, a volume of the solid extending from the active surface to a depth of 16 mm is identified as non-design region. Two load cases, one for axial and other for lateral inertial force on the mirror are created for each problem [17]. The optimization problem here can be set in two ways:

A).By targeting to minimize the mass of the structure with constraints imposed on the surface deformation, and
B).By targeting to minimize the surface deformation of the mirror active surface with constraints imposed on the mass of the structure.

3.2.1Function Response:

Methodology for creating a function response is described below:

i. Determine a set of nodes that will capture the required phenomena.
ii. Define displacement of each of these nodes along axial direction as a response.
iii. Derive a function that approximates a certain surface error with the responses defined above.
iv. Define the functional response and constrain it.

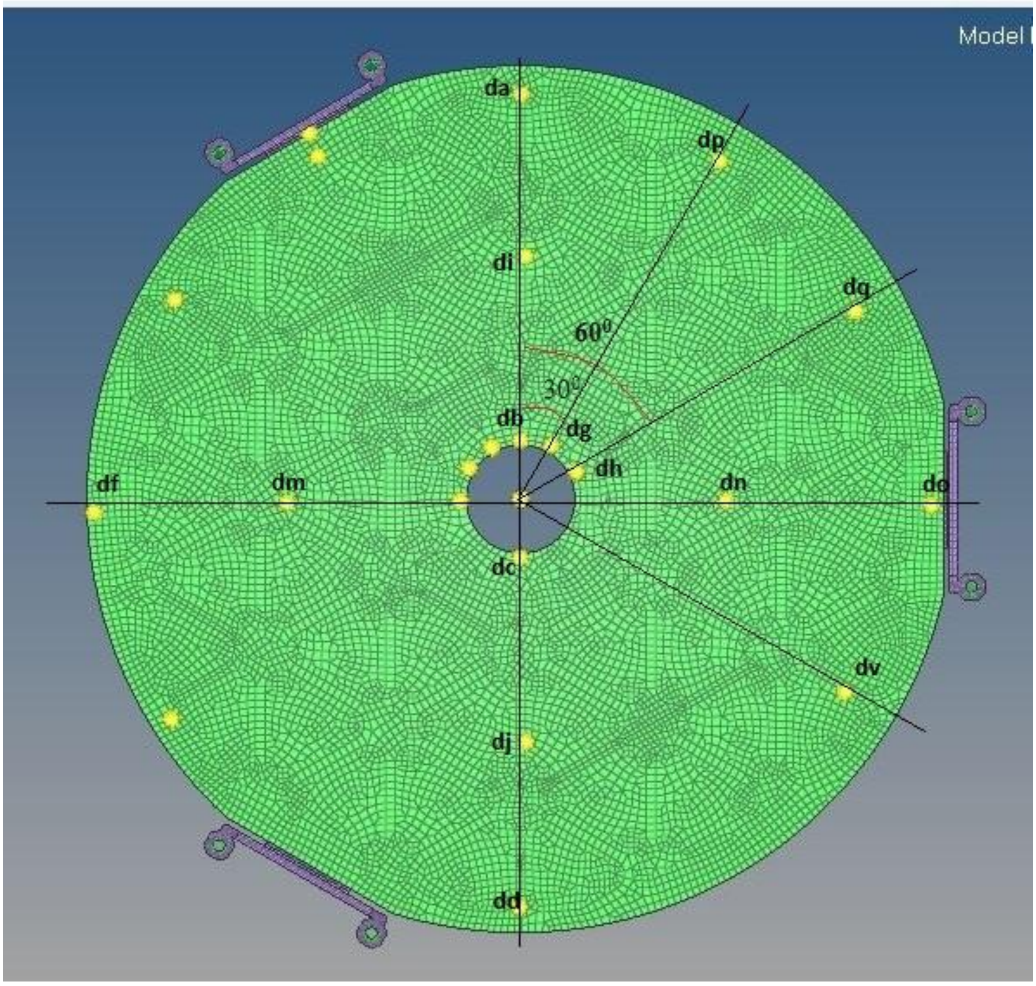


Figure 3 Identification of nodes on active surface of mirror

Here, figure 3identifies the selected set of nodes for this process. The nodes are selected so as to capture the maximum relative displacement due to a particular surface error [19]. It can be seen from Fig. 3that for tilt of the mirror about X axis, maximum relative displacement occurs between nodes do and df.

Table 4 Functional approximation of Zernike surface errors

Sr. No.	Surface error	Function	Function Definition in Hypermesh
1	Piston	Average of responses da-dq	avg(da,db,dc,dd,de,df,dg,dh,di,dj,dm,dn,do,dp,dq)
2	TiltX	|do-df|	abs(do-df)
3	TiltY	|da-dd|	abs(da-dd)
4	Defocus	Maximum(|da-db|,|dp-dg|,|dq-dh|)	maxabs((da-db),(dp-dg),(dq-dh))
5	ComaX	Max(|df-dm|,|dm-dn|,|dn-do|)	maxabs((df-dm),(dm-dn),(dn-do))
6	ComaY	Max(|da-di|,|di-dj|,|dj-dd|)	maxabs((da-di),(di-dj),(dj-dd))
7	AstigmatismX	|da-df|	abs(da-df)
8	AstigmatismY	|dp-dv|	abs(dp-dv)

Hence, constraining the displacement between these two indirectly constrains tilt about X axis. Similarly, constraining the relative axial displacement of nodes marked da and df constraints astigmatism. Similar functional responses based on Fig. 3is given in Table 4.

It should be noted that this approximation of surface errors holds true only for a 120° periodic symmetric circular mirror for which load is applied along X, Yor Z axes as described in Fig. 3. The symmetry constraint is introduced to accommodate inertial loading along any in-plane direction [12].

3.2.2 Design Constraint:

Zernike coefficients are always calculated by condensing it into a circle of unit radius. We target the surface errors to have a Zernike coefficient of the order of 10^{-3} or less in the final design [14]. However, constraints on the surface errors in the optimization problem need to be of at least one order less than that needed in the final design because of the following reasons:

i). Considering the difference in diameter of the condensed mirror used for calculation of Zernike terms and the actual mirror (2m and 1.2 m, respectively)
ii). Inability to reproduce the optimized design as suggested by OptiStruct, as OptiStruct assigns an element density of 0–1 to each element, which is not possible in final design.
iii). Inadequacy of the functional approximation for surface errors.
iv). The need to constraint surface errors of order greater than 3 indirectly by reducing the maximum allowable value of their corresponding lower order surface errors.

Therefore, a factor of 100 was introduced in constraint values, resulting in maximum allowable value of $6.0*10^{-5}$ mm for 10G load along lateral direction. As sag under axial load is higher than in lateral load, a similar maximum allowable value of $6.0*10^{-5}$ mm on displacement responses for load case 1 resulted in infeasible design.Hence, constraints were relaxed by a factor of 10 for load case 1. These values on constraints were further tested by either relaxing or constricting the constraints in multiples of 10.

Table 5 Constraints defined for the optimization problem

Sr. No.	Functional Response	Load case	Lower bound(mm)	Upper bound (mm)
1	Defocus	1	0	6.0e-4
2	Defocus	2	0	6.0e-5
3	ComaX	1	0	6.0e-4
4	ComaX	2	0	6.0e-5
5	ComaY	1	0	6.0e-4
6	ComaY	2	0	6.0e-5
7	AstigmatismX	1	0	6.0e-4
8	AstigmatismX	2	0	6.0e-5
9	AstigmatismY	1	0	6.0e-4
10	AstigmatismY	2	0	6.0e-5

IV. RESULTS

Hence, the optimization problem can be mathematically represented as:

Find	For each element, 0 < element density <1
To	minimize mass
Subject to	Response constraints as defined in table
	Periodicity constraint of cyclic repetition after 120° with mid-plane symmetry

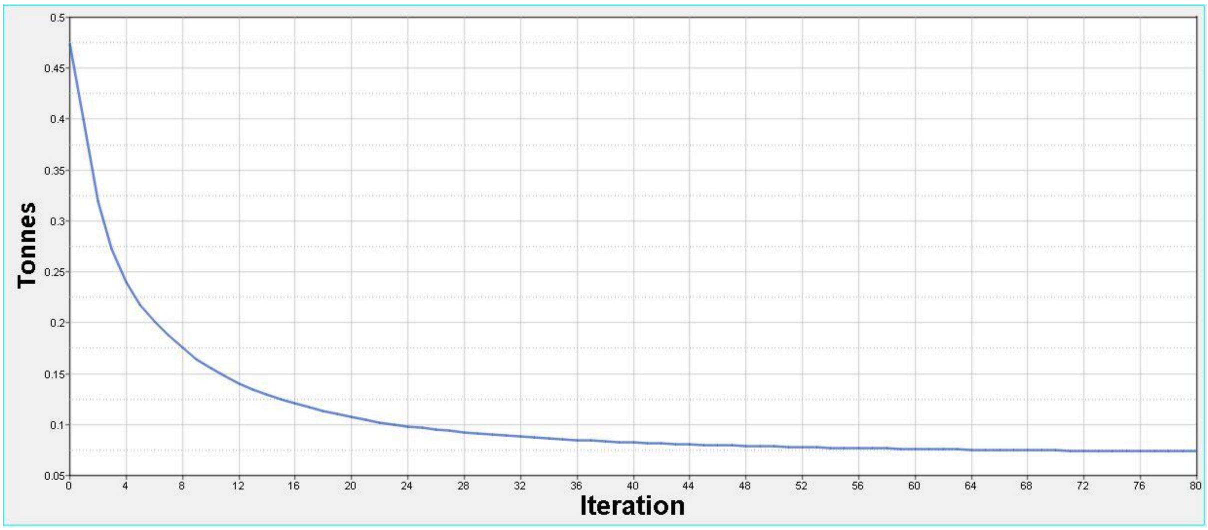


Figure 4(a) Linear graph (Iteration vs mass-in tonnes)

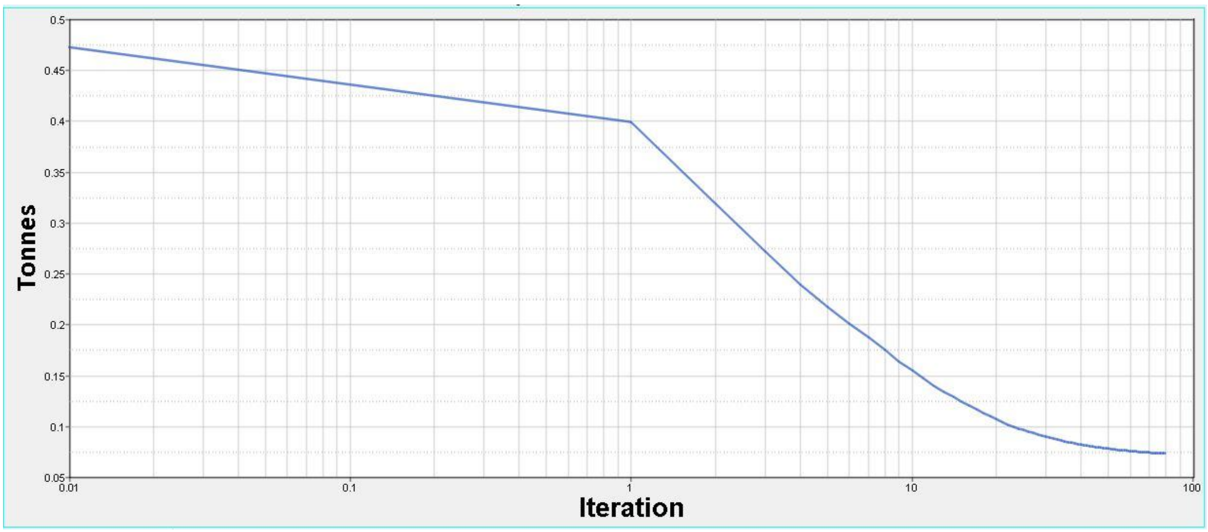


Figure 4(b) Logarithmic graph (Iteration vs mass-in tonnes)

Ever since, response functions are defined to capture only the absolute value of relative displacements, the minimum allowable value is set to zero. 80 iterations were used in each case, which is a default value for Topology Optimization in OptiStruct [7]. However, constraints are satisfied at around 50th iteration, and further iterations only decrease the mass of the design space. The optimization was allowed to run for a maximum of 80 iterations, even though change in mass or design variable was only marginal (~1 %) after around 70th iteration.

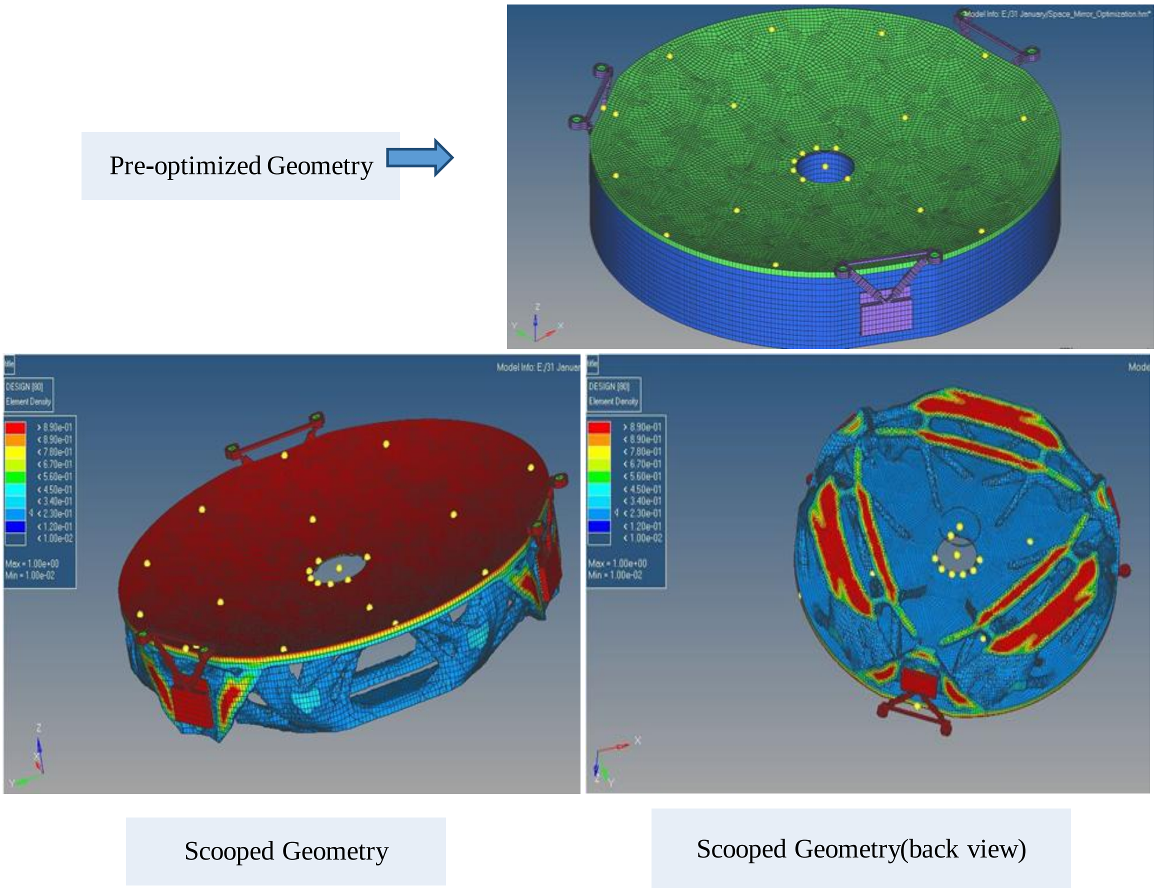


Figure 5.Mirror-MFD Optimized geometry

Table 6 Optimization Output results

Sr.No.	Response type	Response label	Subcase	Response Value	Objective Reference/Constraint Bound
1	Mass	Mass	-	7.356e-02	-
2	Equation	Defocus	1	8.811e-04	6.000e-04
3	Equation	Defocus	2	1.276e-02	6.000e-05
4	Equation	Coma X	1	5.966e-04	6.000e-04
5	Equation	Coma X	2	9.332e-03	6.000e-05
6	Equation	Astigmatism X	1	5.944e-04	6.000e-04
7	Equation	Astigmatism X	2	5.464e-05	6.000e-05
8	Equation	Coma Y	1	5.779e-04	6.000e-04
9	Equation	Coma Y	2	6.902e-02	6.000e-05
10	Equation	Astigmatism Y	1	5.961e-04	6.000e-04
11	Equation	Astigmatism Y	2	1.438e-03	6.000e-05

From the scooped geometry, CAD model was developed in Hypermesh 14. A tetra-mesh is generated on the CAD model, which is then reflected and rotated appropriately to obtain a FE model of the complete mirror. The complete model has a mass of 88 kg, which is close to value mentioned in table 6. FE model of the optimized mirror configuration is shown in Figure 6 and its respective Optimization results are shown in table 7.

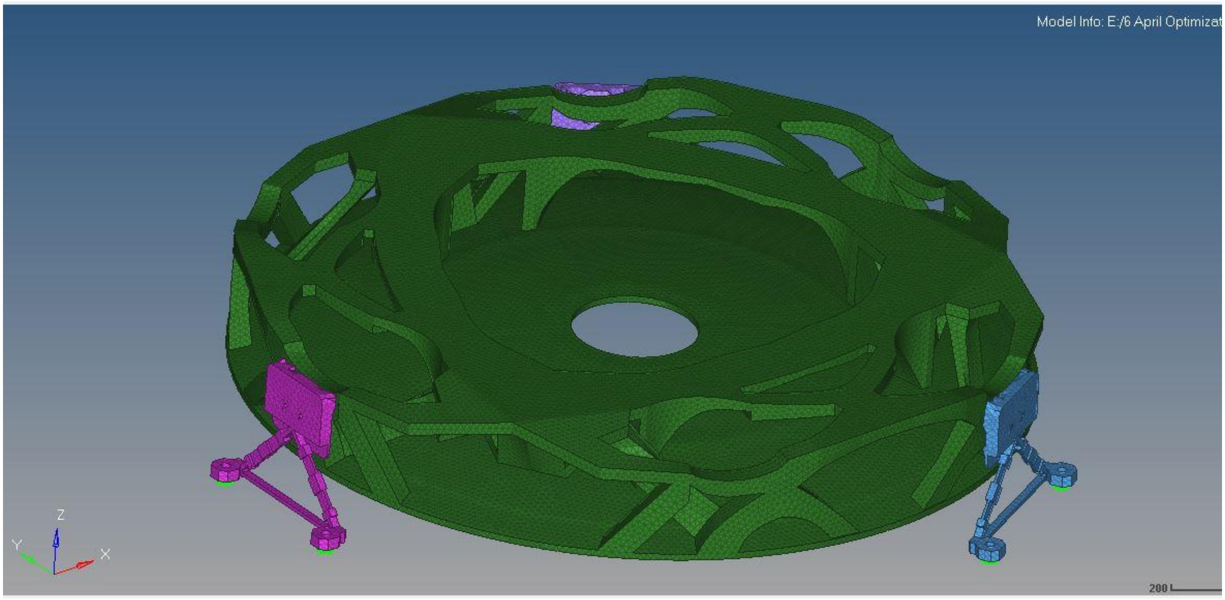


Figure 6 FE model of optimized mirror

Table 7 Optimization results

Sr. No.	Response type	Response label	Subcase	Response Value	Objective Reference/Constraint Bound
1	Mass	Mass	-	5.918e-02	-
2	Equation	Defocus	1	3.002e-03	6.000e-04
3	Equation	Defocus	2	3.055e-03	6.000e-05
4	Equation	Coma X	1	8.778e-04	6.000e-04
5	Equation	Coma X	2	3.944e-03	6.000e-05
6	Equation	Astigmatism X	1	5.954e-04	6.000e-04
7	Equation	Astigmatism X	2	4.925e-03	6.000e-05
8	Equation	Coma Y	1	5.779e-04	6.000e-04
9	Equation	Coma Y	2	1.453e-03	6.000e-05
10	Equation	Astigmatism Y	1	3.734e-04	6.000e-04
11	Equation	Astigmatism Y	2	2.882e-03	6.000e-05

V. CONCLUSION

Structural optimization of a 1.2 m diameter non-active space mirror was carried out using OptiStruct tool of HyperWorks 14. Zernike surface errors causing selective optical aberrations; defocus, coma and astigmatism, are approximated with simplified displacement functions of nodes on active mirror surface. Constraints were imposed on these displacement functions instead of RMS surface error. The optimized design weighs around 60 kg and has Zernike coefficients of surface errors corresponding to selected optical aberrations of the order of 10^{-3} or less, which complies with the target of this study.

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