Design Optimization Study of Conical Shroud Structure

Riswana N P, Phani Charan Nidamarthi , Nisha Varghese

Abstract — Launch vehicle design is a complex and multidisciplinary engineering activity. In the recent decades, it become more challenging with the major objectives of faster realization, repeatability, lesser mass, higher reliability and lower cost. To attain these, design cycles are important in terms of time, quality and cost. Optimization of the design of the structure is necessary to get the best structure. In structures designed for impulse loading, transient response analysis help to find out the response of the structure during time varying load. Integrally stiffened structures provide many advantages over other configurations of launch vehicle structures. This paper discusses the design studies of conical shells in launch vehicles. The present study is described in three sections i.e., the linear static analysis and free vibration analysis of Conical Shroud Structure using orthogrid and isogrid construction, size optimization of the structure, and finally the transient response analysis of the structure. FEAST software is used for modelling and analysis. Design optimization is carried out using NASTRAN software.

Index Terms— Design optimization, Isogrid, Lower conical shroud structure, Orthogrid, Transient response analysis

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1 INTRODUCTION

Aerospace Structures play a pivotal role in many aspects of launch vehicle design. Some of the major roles include, to provide an external shape as per aerodynamic considerations, to be able to withstand the ground and flight loads and to provide housing for the payload, propulsion, guidance and control system. The major constraints required for the design of aerospace structures are based on the structural integrity and low mass construction. Structural integrity means that the structure should not fails during its service life. Weight of an aircraft can have an adverse effect on the performance of the flight. To improve the load carrying capacity of structural parts in launch vehicle various types of construction are used. The main criteria are weight reduction, ease of fabrication, cost saving conforming to strength and stiffness requirements. A particular type of construction is chosen based on its advantages over other techniques. The different types of structural configurations used in launch vehicles are, monocoque construction, semi monocoque construction and integrally stiffened construction. This study mainly deal with isogrid and orthogrid structure which are coming under integrally stiffened construction.

2 ORTHOGRID

It consists of a lattice of ribs forming an array of repetitive square or rectangular pattern. Orthogonally stiffened shell structure is also called waffle structure , where the shell is stiffened by the use of longitudinal stiffeners and circumferential rings. The stiffeners can be oriented either in 45 degree or 90 degree. This wall stiffening helps in increasing the buckling strength without increasing the weight, when compared to monocoque structures. Fig. 1 shows the orthogrid panel.

3 ISOGRID

Isogrid consists of a lattice of stiffening ribs forming an array of equilateral triangles. Since the equilateral triangle pattern has isotropic strength characteristics (equal properties measured in any direction), it is named isogrid. The triangular pattern is very efficient because it retains rigidity while saving material and therefore weight. Aerospace isogrid structure include payload shroud and boosters, which must support the full weight of upper stages and payload under high gravity loads. Fig. 2 shows the isogrid panel.

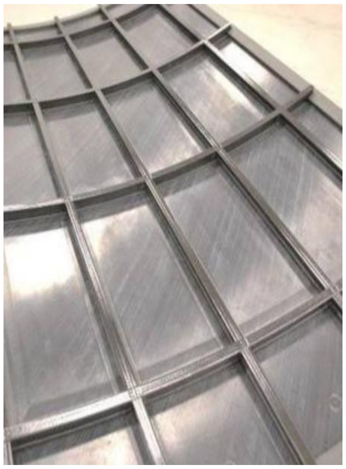

Fig.1 Orthogrid panel

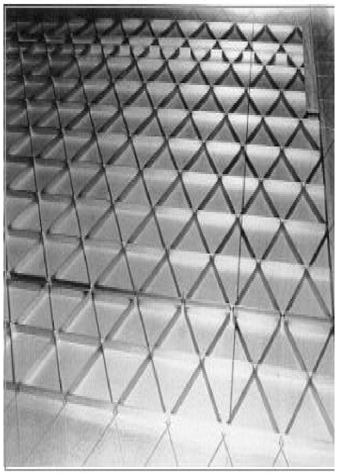

Fig. 2 Isogrid panel

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4 FINITE ELEMENT MODEL

4.1 Lower Conical Shroud (LCS) Structure

This is one of the subsystems in solid strap on systems of launch vehicle,where the whole study is carried out. This is an inverted conical frustum, which interfaces with the lower base shroud (LBS) at the fore end and the flexible thermal boot at the aft end. Rings are provided at both the ends to interface with other structures. L shape ring is provided at the fore end to connect LCS with LBS (FER),U shape ring is provided at the aft end to connect LCS with thermal boot (AER). For assembly feasibility the structure is made in 4 sections. At each 90 degree there will be a connection between 2 sections by means of a splice plate. Because of the increase in stress concentration at the aft end ring we provide L shape splice plate at each 90 degrees to reduce it to a limiting value. Rigid links are provided to connect AER , FER and splice plate to the skin. The dimensions of inverted conical frustum, top diameter=3891mm, base diameter=3400mm, height=400 mm, thickness=2mm, material=aluminium. Fig. 3 shows LCS structure modeled using FEAST software.

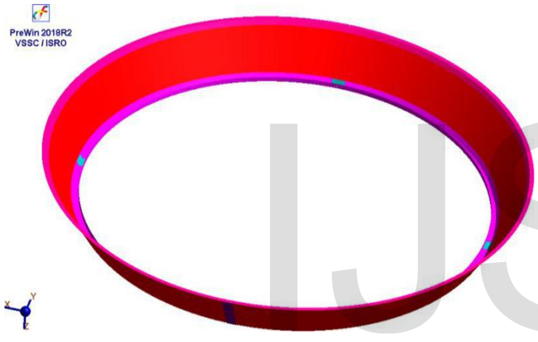

Fig 3 LCS Structure

4.2 Orthogrid

Design parameters required for orthogrid are directly taken from Engineering science data unit (ESDU) chart. Rib spacing (s)=75mm, Rib thickness (t)=2mm, Rib height (h)=10mm, Top and bottom clearance (d)=50mm, material=aluminium. Fig. 4 shows LCS structure with isogrid. The total mass of the structure is 60.1kg.

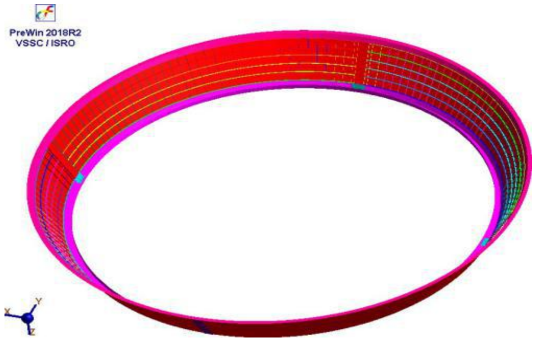

Fig. 4 LCS structure with orthogrid

4.3 Isogrid

Some design steps are available for isogrid, but for comparing both the construction dimensions are taken as same as orthogrid. Rib thickness (t)=2mm, Triangle height (h)=65mm, Side of triangle (a)=75mm, material=aluminium. Fig. 5 shows the LCS structure with isogrid. The total mass of the structure is 78.9kg. While comparing orthogrid and isogrid structures, the total mass of isogrid is more than that of orthogrid with same dimensions.

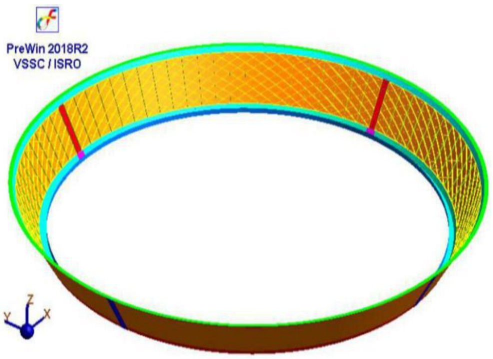

Fig. 5 LCS structure with Isogrid

5 PRIMARY ANALYSIS

During the development stage element in the launch vehicle, static and dynamic structural analyses can be performed for increasing structural reliability and design changes such as reducing its weight or preventing failures resulting from structural deformation or vibrations. Generally, linear static analysis and free vibration analysis are carried out. Both the analyses are carried out using FEAST software.

5.1 Linear Static Analysis

A linear static analysis is an analysis where a linear relation holds between applied forces and displacements. In practice this is applicable to structural problems where stresses remain in the linear elastic range of the used material. It is used to find out the stress and displacement of the structure under the loads.

The structure is subjected to a point load of 790N at aft end ring and a pressure of 0.08MPa at the skin. Two cases are considered in case of pressure, both internal and external pressure. The fore end ring is under fixed condition.

The resulting stress and displacement contours for orthogrid and isogrid construction for both internal and external pressure condition is shown in fig.6, fig.7, fig.8, fig.9.The results are tabulated in table1.

TABLE 1 LINEAR STATIC ANALYSIS RESULTS

	Internal Pressure		External Pressure		Mass (kg)
	Stress (N/mm^2)	Displacement (mm)	Stress (N/mm^2)	Displacement (mm)	
Orthogrid	451.314	12.2241	541.557	13.36996	60.1
Isogrid	421.01	6.8555	405.516	7.88175	78.9

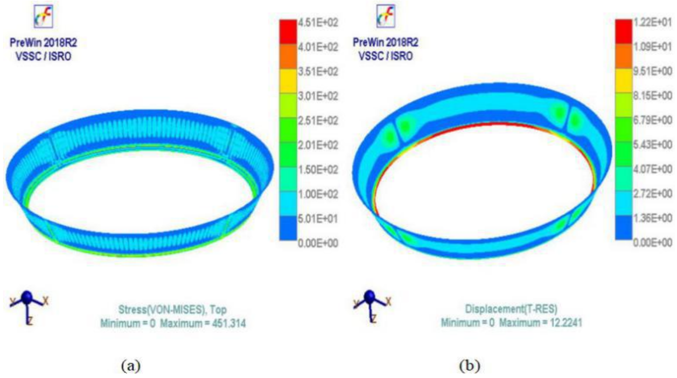

Fig. 6 Orthogrid: Internal pressure case (a) stress (b) displacement

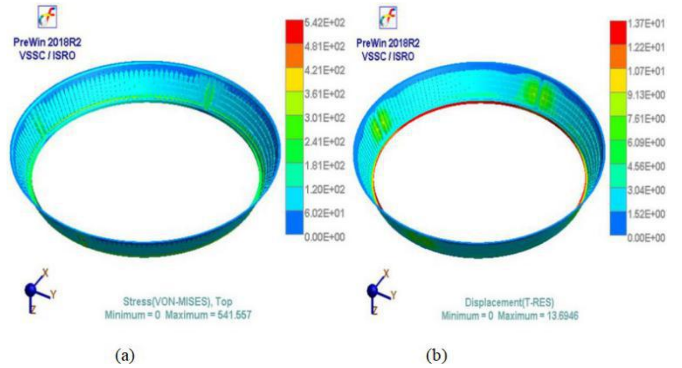

Fig. 7 Orthogrid: External pressure case (a) stress (b) displacement

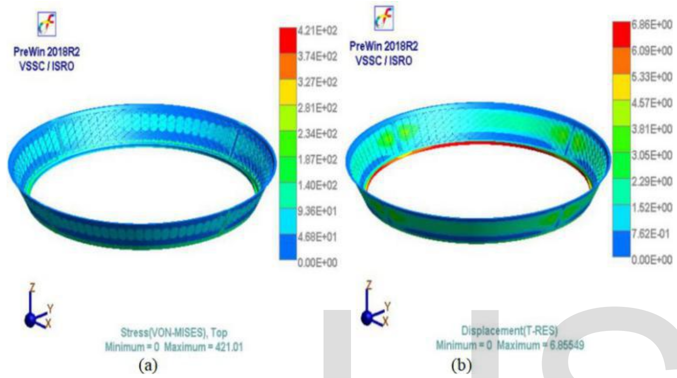

Fig. 8 Isogrid: Internal pressure case (a) stress (b) displacement

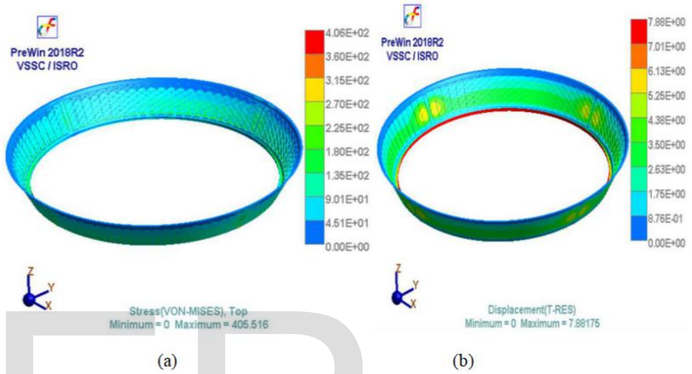

Fig. 9 Isogrid: External pressure case (a) stress (b) displacement

In both the cases the deflection is maximum at the AER because the load is acting in that ring . But at the connection between two sections the deflection is less because we already provide a splice plate. Otherwise the deflection would be maximized with high magnitude. Also the stress is maximum at ribs, which are having rigid link connection with the ring.

Yield strength of aluminium alloy is 380 N/mm² and ultimate strength is 440 N/mm². The results obtained are more than the limit. So reduce those by optimization to get a better structure. In the above table, it shows that stress and displacement in orthogrid structure are more as compared to the isogrid structure in both internal as well as the external pressure case. But the mass of isogrid structure is more than that of the orthogrid construction. Hence there is required of optimization of mass while bringing down the stresses below Yield strength.

5.2 Free Vibration Analysis

Free vibration analysis is used to determine the basic dynamic characteristics of the system. Free vibration occurs when a mechanical system is set in motion with an initial input and allowed to vibrate freely. The mechanical system vibrates at one or more of its natural frequencies and damps down to motionlessness. Generally, in upper stage structures near the satellite, frequency range is around 2 Hz. If the structural frequency in lower stage is close to 2Hz, resonance occurs. To avoid that, the specification of structural frequency above 70 Hz is mandatory. Fig. 9,Fig. 10 shows the first mode shape of orthogrid and isogrid after free vibration analysis.

Fig.9 Orthogrid- Mode shape 1

Fig.10 Isogrid- Mode shape1

Here we get frequencies 146.355 Hz and 167.33 Hz in orthogrid and isogrid respectively. These are above the required range. From the results ,it can be concluded that the structure is correct acceptable and result obtained from the analysis are further reliable based on free vibration analysis.

6 OPTIMIZATION

In order to reduce mass and achieve high product quality, the concept of structural optimization has been adapted in all stages of the design cycle. The basic requirement for an efficient structural design is that the response of the structure should be acceptable as per various specifications. There can be large number of feasible designs, but it is desirable to choose the best from these several designs. The best design could be in terms of minimum cost, minimum weight or maximum performance or a combination of these. In this study optimization is carried out using NASTRAN software. Some of the terms in optimization and optimization code in NASTRAN are,

Design variable : In design optimization, design variables are the quantities that are modified by the optimizer during the search for an improved design. **DESVAR** is the code used to define it.

Design constraint : Is defined as an inequality, which must be satisfied in order to indicate a feasible design. The design constraint is a function of design variables, structural responses, and grid coordinates.**DCONSTR** is the code used to define it.

Analysis model : Defines the geometry, element connectivity, material properties,and load associated with the FE analysis. The analysis model may be varied according to the design model, which uses responses computed from the analysis model to guide the design process. To defines the relation between an analysis model property and design variables the code **DVPREL1** is used.

Design objective : Is the function of design variables that the optimizer seek to minimize. **DRESP1** is used to defines a set of structural responses that is used in the design either as constraints or as an objective.

6.1 Orthogrid

Nine optimization cycles are carried out to get the best structure. There is an increase in mass from initial to final cycle result is 60.1 kg to 64.2 kg. That means there is an increase in thicknesses. And the stress reduced from 451.314 N/mm^2 to 373.757 N/mm^2. The stress is within the limit of yield strength of aluminium alloy.Fig.11 and fig.12 shows the mass Vs cycle No and stress Vs Cycle No graph respectively.

6.2 Isogrid

Similar optimization is carried out for isogrid and thirteen optimization cycles are done to get the best structure. The stress is reduced from 421.01 N/mm^2 in the initial structure to 265.711N/mm^2 in the last cycle. Also the mass reduced from 78.9 kg to 75.3 kg.Fig.13 and fig.14 shows the mass Vs cycle No and stress Vs Cycle No graph respectively.

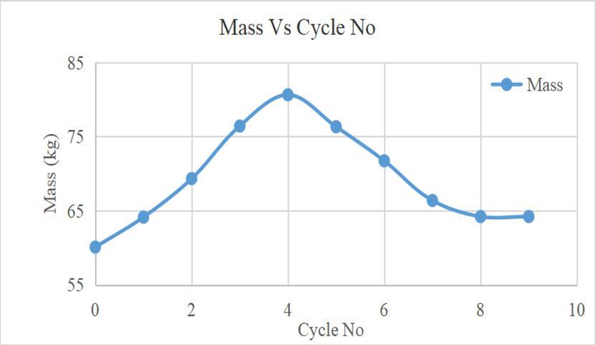

Fig.11 Orthogrid: Mass Vs Cycle No

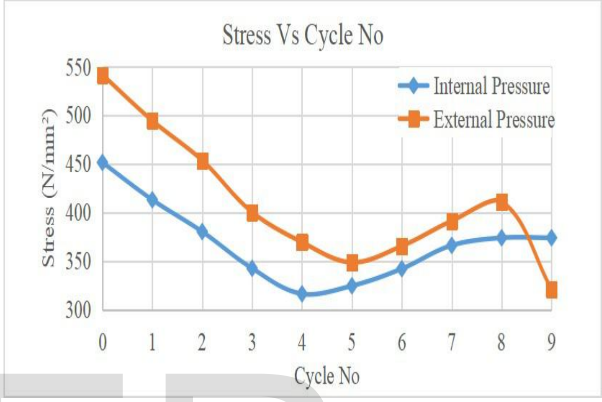

Fig.12 Orthogrid: Stress Vs Cycle No

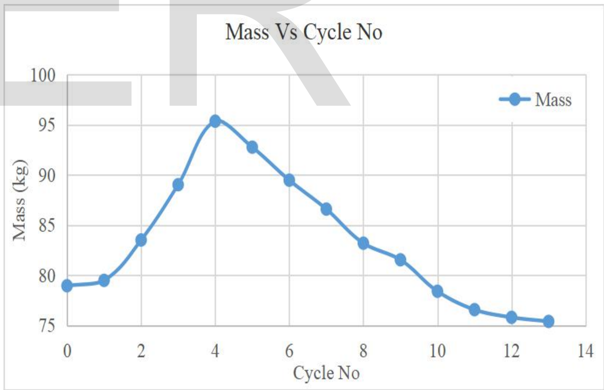

Fig.13 Isogrid: Mass Vs Cycle No

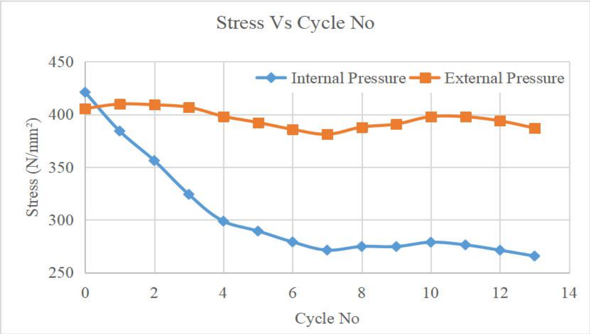

Fig.14 Isogrid: Stress Vs Cycle No

In cycle No 3 of orthogrid and cycle No 11 of isogrid have similar masses (76kg) with stresses 342.357N/mm² and 276.294N/mm² respectively. So for the same mass the isogrid has less stress than orthogrid. From the results it can be concluded that isogrid construction is better than orthogrid construction.Optimization final cycle results of orthogrid and isogrid are shown in table 2.

TABLE 2 OPTIMIZATION FINAL CYCLE RESULTS OF ORTHOGRID AND ISOGRID

	Internal Pressure		External Pressure		Mass
	Stress (N/mm²)	Displacement (mm)	Stress (N/mm²)	Displacement (mm)	(kg)
Orthogrid	373.755	8.135	321.02	6.555	64.2
Isogrid	265.711	7.37388	387.05	8.29213	75.3

7 TRANSIENT RESPONSE ANALYSIS

Transient response analysis is the most general method for computing forced dynamic response. The purpose of a transient response analysis is to compute the behavior of a structure subjected to time-varying excitation. Transient response analysis is most commonly applied to structures with linear elastic behavior.The transient excitation is explicitly defined in the time domain. All of the loads applied to the structure are known at each instant in time. Loads can be in the form of applied forces and enforced motions. The results obtained from a transient response analysis are typically displacements, velocities, and accelerations of grid points, and forces and stresses in elements.

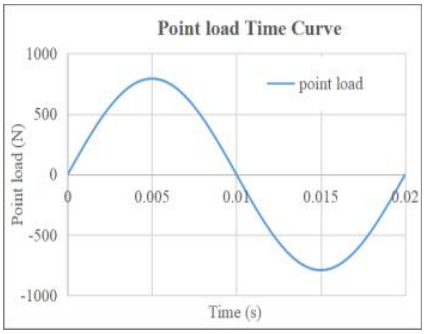

Fig.15 Point load time curve

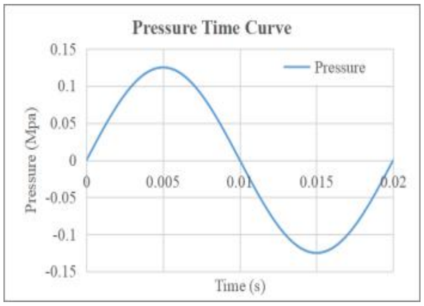

Fig.16 Pressure time curve

Transient response analysis is carried out in optimization final cycle structure in both orthogrid and isogrid, using FEAST software. First a time varying force and pressure are applied in the structure. Force is applied in the AER and pressure is applied on the skin.Input force time curve and pressure time curve is shown in fig. 15and fig.16 respectively. The time is in between 0 and 0.02s. From the graph it is observed that positive and negative peak pressure and force at 0.005s and 0.015s respectively.

7.1 Orthogrid

The graphs of displacement and stress Vs time are shown in Fig.17 and fig.18 respectively.

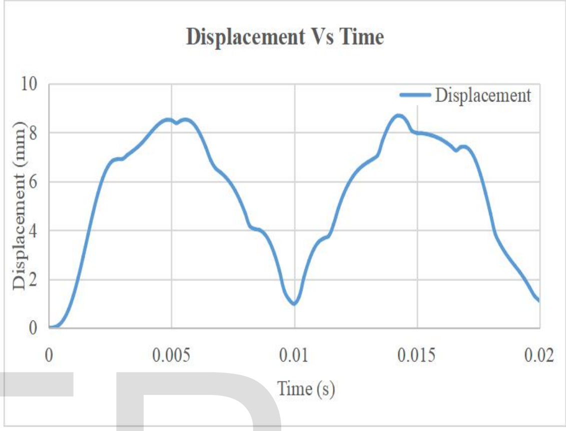

Fig.17 Displacement Vs Time

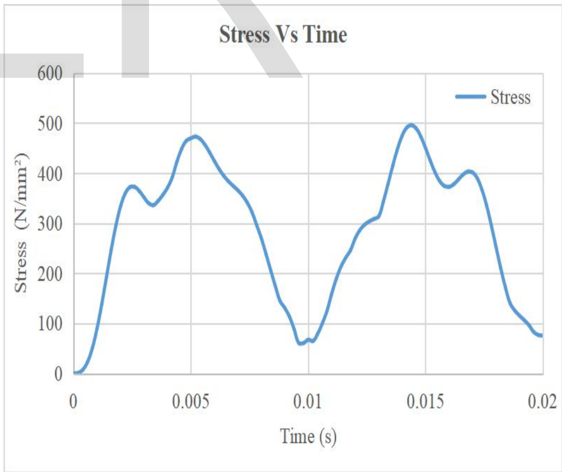

Fig.18 Stress Vs Time

7.2 Isogrid

The graphs displacement and stress Vs time is shown in Fig.19, fig.20 respectively. Transient response analysis results are tabulated in table 3.

In input pressure time curve positive peak pressure at 0.005 s and negative peak pressure at 0.015 s. But maximum stress from transient response analysis in orthogrid and isogrid at 0.0144 s and 0.0056 s respectively. That means the structural response is different from input response, 0.0006 s earlier in orthogrid and 0.0006 s delayed in isogrid.

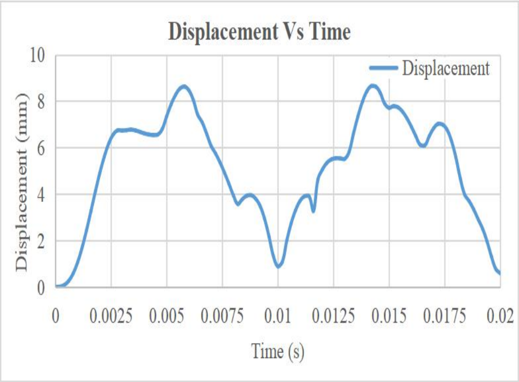

Fig.19 Displacement Vs Time

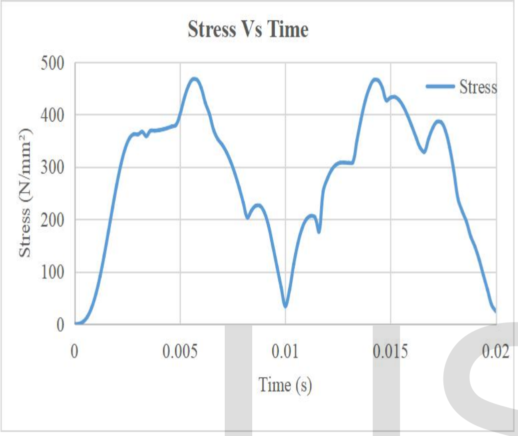

Fig.20 Stress Vs Time

TABLE 3 TRANSIENT RESPONSE ANALYSIS RESULTS

	Time (s)	Stress (N/mm^2)	Displacement (mm)
Orthogrid	0.0144	495.952	8.648
Isogrid	0.0056	467.467	8.539

The duration of peak stresses above the Yield strength is for shorter duration of the order of 0.6millisec which is not detrimental. Hence the design is capable of withstanding transient loads also.From the results it can be conclude that for the given loading isogrid construction is better than orthogrid construction.

8 CONCLUSION

Through this study, the importance of design optimization in aerospace structures is explained in detail. For this study conical shroud structure is taken. Orthogrid and isogrid construction are provided for a comparative study between them.The modeling and analysis are carried out using FEAST software. Design optimization is carried out using NASTRAN. In the optimized model transient response analysis is done to computing the response of the structure towards time-varying loads.

The following conclusions are developed from the findings of this study,

- After the linear static analysis the displacement and stress resulting in isogrid is less as compared to orthogrid structure.
- For the given structure, frequency is more than 70 Hz, which is required for lower stage structures in the launch vehicle.
- After optimization the stress is reduced to within the limit in both orthogrid and isogrid constructions. In orthogrid the stress reduces to 373.755 N/mm2 and mass is increased to 64.2kg. In case of isogrid the stress reduced to 265.711 N/mm2 and mass is reduced to 75.3kg.
- For the same mass structure (76kg) the stresses are 342.357 N/mm2 and 276.294N/mm2 for orthogrid and isogrid respectively. So isogrid has less stress than orthogrid. Hence isogrid is better than orthogrid construction.
- In transient response analysis structural response is different from the input response by 0.0006 s earlier in orthogrid construction and 0.0006 s delayed in isogrid construction.The duration of peak stresses above the Yield strength is for shorter duration of the order of 0.6 milliseconds which is not detrimental. Hence the design is capable of withstanding transient loads also.
- According to the findings, isogrid construction is better than orthogrid construction.

ACKNOWLEDGMENT

The first author wish to thank VSSC, ISRO, India, for providing the facility to carry out the project work.

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