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Optimum Design of a Composite Base Structure of a Spacecraft

K.K. Sairajan
Scientist/Engineer
ISRO Satellite Centre
Bangalore

P.S. Shamnad
Scientist/Engineer
ISRO Satellite Centre
Bangalore

Thomas K. Joseph
Scientist/Engineer
ISRO Satellite Centre
Bangalore

P. S. Nair
Deputy Director
ISRO Satellite
Bangalore

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Abstract

Use of advanced materials and construction has become essential in spacecraft structures for achieving low mass while satisfying structural and functional requirements related to stiffness, strength, dimensional stability and agility. Reduction of structural mass is important in many ways- it helps to increase payload fraction in a spacecraft, improves agility and also reduces the launch cost. Optimizing the design in terms of topology, shape, material and structural details are very important in arriving at acceptable practical solutions. Spacecraft is subjected to high static/dynamic loads during launch and low amplitude disturbances during on orbit operations. Usually it is the structural dynamic considerations that drive the design. The present paper illustrates how mathematical optimization tools are used to arrive at the design of a composite base structure of a typical spacecraft. The example problem involved replacement of an existing metallic structure with a composite part with improved mass and other properties but without affecting interface and overall dynamic behavior. The design is checked for its performance under combined quasi-static loading and other aspects. The stresses are well within allowable limits and the design meets the stringent requirements of stiffness and dimensional stability. The part is made of laminated construction with distribution of number of layers and their orientations optimized. The optimized design resulted in weight saving of approximately 15% of mass (with respect to the initial composite design) without compromising on interface requirements and structural performance.

Introduction

A thrust cylinder with a launch vehicle-spacecraft interface ring at the bottom is the main load bearing member of a spacecraft structural system. Several major improvements were implemented in these structures in recent times achieving significant mass reduction. Use of advanced composite materials and sandwich construction has been the main contributing factor. Options involving alternate structural forms have also been attempted especially in low mass spacecraft. In all these cases the base structure, especially the interface ring remained metallic due to a number of practical considerations. Such metallic base structures are normally integrally machined parts and contribute to a significant part of the spacecraft structure mass. The requirements from commercial launch vehicles do require a metallic interface. The upper interface of such structures made of aluminum alloy often poses serious problems of dimensional accuracy and stability when such requirements are mandatory. These base structures are used mainly for the compatibility between the launch vehicle payload adaptor, clamp band release mechanism and other requirements. Recently there have been attempts on the use of lightweight materials like composites for the construction of spacecraft structural elements. These are specially designed for meeting the stringent requirements of stiffness, dimensional stability, impact resistance and fatigue.

The performance of a mass efficient and dimensionally stable structure plays an important role in the success of a spacecraft mission. All structural elements in a spacecraft must meet certain constraints on stiffness, strength and should be able to withstand the launch loads. The general design practice now is to make the design safe by ensuring margin of safety such that the component does not fail under critical loads. Over design is not a matter of concern. The computer aided design/analysis tools help the designer in identifying the under stressed and overstressed areas helping him to improve the design. When the constraints and the design variables are many and requirements relate structural dynamics manual procedures are very difficult or impossible. The mathematical optimization tools such as those available in Hyperworks come in very handy in such situations. In this paper, the design process is explained with respect to an example problem of replacing an existing metallic part by a structurally equivalent part without affecting interfaces and spacecraft dynamic characteristics. The structure under study is a composite base structure of a 600 Kg class spacecraft. It is a conical shell type structure; the spacecraft bus elements are attached to it through horizontal decks and radial panels as shown in Figure 1. In addition, a heavy alignment sensitive payload is also attached at one end. All spacecraft loads are transferred to the launch vehicle adaptor during launch trough this part. This interface structure is made of carbon fiber reinforced plastic (CFRP) with symmetric/ or non-symmetric lay-up and varied reinforcement types, geometries, orientations and metallic parts at a few interfaces.

To get the full advantage of composites it was decided to optimize the new CFRP interface structure. The proposed composite interface ring is designed in such a way that to meet future satellite mission's stability requirement and load carrying capacity. In this example the design optimization focuses on this one part but taken together with the rest of the spacecraft. Generally the design of spacecraft structures often requires the analysis of different structural configurations. Structure consists of a large number of parts and subassemblies such as sandwich shell structures, panels, decks and interface ring, etc. The design process involves choosing geometric configuration, structural form/construction/ materials type and associated parameters to meet all requirements. Reduction mass of structure is always a goal due to the fact that efficiency of any given spacecraft structural design depends on this.

Objective

Objective of the study is to arrive at an optimum design of the base/interface structure to serve as a replacement for the existing metallic part to achieve significant mass reduction. The new design should not alter significantly the structural dynamic characteristics of the spacecraft. Also interface with respect to other parts and subsystems should not be altered. This is even more important in spacecraft missions where reduction of mass/inertia has several added non-structural advantages.

Background

The wide spread interest in the development of light weight - low cost composites can be attributed to their high specific strength and stiffness. Composites are tailored in composition for use in applications where their performance must meet increasingly demanding requirements such as stability, along with stiffness, strength, impact and dimensional stability over wide temperature range. Proper choice of material, process, and design are the major governing factors for the development and performance of composite components. Because of the stiff competition or driven by the technical requirements, designers cannot afford over-designed parts or lengthy, iterative product-development cycles. Thus, the part design and performance, to a large extent, depend on the efficiency of the design technology that allows creating cost-effective product design with the optimal material and process selection. With the incorporation of composite materials into the structural design, the complexity of the design process was greatly increased compared to design with metallic materials. The variability of ply thickness and orientations added a significant increase in the design space and thus prohibited the use of general design rules as was done with metallic structure designs. Optistruct optimization module offers the required tools for analysis and optimization of composites. It offers the flexibility to define and compute layer-by-layer properties of symmetric as well as non-symmetric stacks, which in turn are useful in evaluating the performance of composites. It can handle the thickness and orientation of plies as design variables in conjunction with other design parameters and constraints.

Methodology

Conventionally, spacecraft base structures/interface rings have been designed using the aluminium forgings. This type of design is quite conservative and is generally heavier. Here in this study CFRP composite interface ring is used as a substitute for the existing interface of the spacecraft. The basic design methodology followed in this work was to optimize the mechanical design using FEM. It was observed that the dimensional stability of payload that is attached to the interface structure; depend considerably on the interface region. The weight as well as the stiffness of the ring largely depends on the materials as well as the thickness of that region. Several values of this parameter need to be tried out, to arrive at an optimum design. This implies that several mathematical models have to be made and analyzed. The general purpose FE software does not bring out the effect of modification of this design parameter automatically. This, along with the fact that a number of model are required to be analyzed to clearly arrive at an optimum design, that led to the use of mathematical optimization tool along with FE analyses for the structural design.

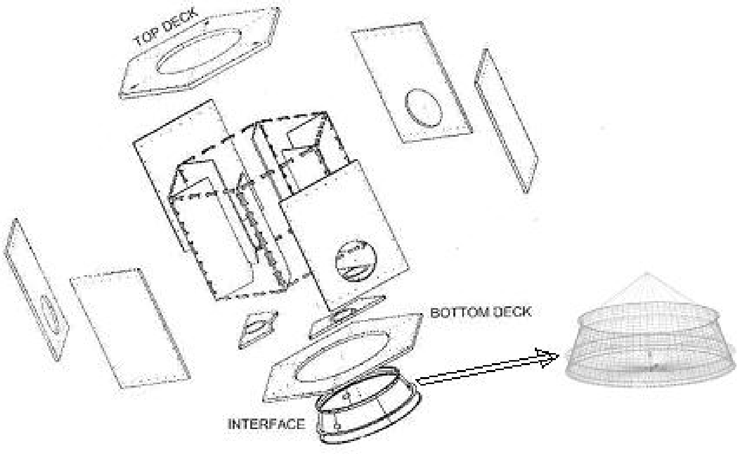

Figure 1: Exploded View Of Spacecraft Structure Showing Base/Interface Ring

Finite element method is used to evaluate the stiffness and stress levels under the launch loading conditions. The structure is modeled with thin shell elements. Optimization software program, Optistrut is used for the structural optimization of the spacecraft interface ring. The constraints on stiffness, ply orientations and shell thickness are applied to arrive at the optimum design using optimization technique. To further evaluate the design of interface ring a comparison of these results with existing Aluminium structure will be done in terms of stiffness, strength, etc. Validation of the analysis by actual static loading and dynamic will follow.

Design Consideration

Light-weight: The stiffness to weight ratio of the interface ring should be high so that the stability and frequency requirements for spacecraft will be meet due to light-weight.

Stiffness: The design should be such as not to affect the structural dynamic characteristics significantly.

Buckling load factor: The buckling (local and global) load factor of the interface ring should be high.

Deformation/Stress criteria: The stress/strain of the interface at any point should be well within the permissible limits.

Construction

The interface ring is made of CFRP (M55J/914 Unidirectional Prepreg and G837/914 Bi-directional (BD) Fabric and fitted with a titanium ring liner in its inner diameter at top region to facilitate interface requirement for the payload attachment. An aluminum base ring at the bottom is provided to meet the launch vehicle requirements. This conical shell with different parts that offers interfaces to various other structural elements like bottom horizontal deck, payload deck etc. The CFRP interface ring has a layered construction and after preliminary analysis, lay-up sequence has selected as $[\#0_2/0/90/0/90/+45/-45/90/0/90/0/90/0/0]_S$ for entire regions. Here # refers to the BD fabric. Fabrics are selected at the inner and outer surfaces for easy of fabrication process. Properties of the different materials used in the analysis are shown in the Tables 1-4.

Table 1: Properties of Aluminium Alloy 7010 T73651

PROPERTY	VALUE
E	70.0 G Pa
ν	0.3
ρ	2700 Kg /m^3

Table 2: Properties of Ti Alloy (Ti-6al-4v)

PROPERTY	VALUE
E	105 G Pa
ν	0.3
ρ	4630 Kg / m^3

Table 3: Properties of M55j/ 914 Prepreg

PROPERTY	VALUE
Young's Modulus - Longitudinal E_{LL}	270.0 G Pa
Young's Modulus - Transverse E_{TT}	5.535 G Pa
In plane Shear Modulus G_{LT}	3.870 G Pa
Major Poisson's Ratio ν_{LT}	0.365
Mass Density ρ	1760 Kg / m^3
Ply Thickness T_F	0.1 x10^{-3} m
C.T.E - Longitudinal α_L - Transverse α_T	-1.16 * 10^{-6} / °C 32.71 * 10^{-6} / °C
Tensile Strength - Longitudinal σ^T_L - Transverse σ^T_T	1.80 G Pa 0.022 G Pa
Compressive Strength σ^C_L	0. 600 G Pa
In Plane Shear Strength τ_{LT}	0.092 G Pa

Table 4: Properties of G837/ 914 Bd Cured Fabric

PROPERTY	VALUE
Young's Modulus – Transverse $E_{TT} = E_{TT}$	98.9 G Pa
In plane Shear Modulus G_{LT}	4.35 G Pa
Major Poisson's Ratio ν_{LT}	0.03
Mass Density ρ	1555 Kg/ m^3
Tensile Strength $\sigma^T_L = \sigma^T_T$	0.292 G Pa
Compressive Strength $\sigma^C_L = \sigma^C_T$	0.275 G Pa
In plane Shear Strength τ_{LT}	0.055 G Pa

Fem Analysis

Following are the major steps followed in the analysis:

- The creation of the FE model
- Study of design parameters for design optimization
- Design optimization and Finalization
- Evaluation of results

Fem Model

The finite element model is generated using 2-D thin shell linear quadrilateral elements and is shown in Figure 2. The necessary partitions are made to make accurate meshing which satisfies the quality check on the elements. The elements are checked for free edges, distortion level and shell normal consistency to ensure reliable results after the analysis. Same finite element model as shown in Figure 2 is used to carry out the normal mode dynamic analysis, static analysis and optimization. The spacecraft mass is taken as 600 Kg and is applied at the center of gravity of the spacecraft, which is 0.55 m from the base of the interface ring. The FE model contains 2699 nodes and 2865 elements. The interface ring is held from the bottom by a clamp band, which interfaces the ring with launch vehicle payload adapter. The nodes on the region of interface ring where a clamp band is getting attached to the to the payload adaptor are considered to be fixed (*i.e.*, base fixed condition).

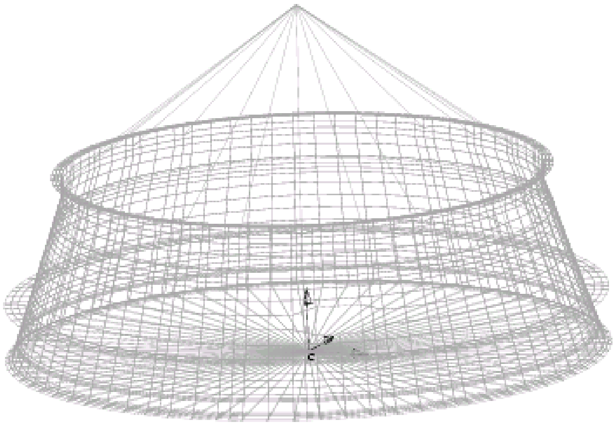

Figure 2: Fe Model of the Composite Interface Ring

Stiffness/Stress Calculations
The base fixed condition of the interface ring is considered for calculation of stiffness and free vibration characteristics and launch/design loads are considered for the calculations of displacements and stresses in the interface ring. Static analysis has been performed to check the initial design and evaluate the performance of the CFRP interface ring under quasi-static loading. Peak stresses in individual plies as a result of the static analysis have been computed and the maximum ply stresses have been compared with allowable strength of the CFRP plies.

Optimization Study

The objective of optimizing the interface ring is to improve the structural performance with minimizing the mass. The most useful information in regard to interface ring structural design comes from the studies of initial free vibration analysis. The design parameters of the interface ring are

- Ply thickness
- Number of plies
- Ply orientation
- Ply materials

All these parameters of the design are set for variation within known limits and the analysis is then carried out to find the effects and the contribution of the each parameter defined for perturbation. It is well understood that stacking sequence design of composite laminates requires discrete programming since ply thickness and orientation angles are restricted to a discrete set of values. This restriction is due to manufacturing limitations because plies are fabricated at certain thickness values. Furthermore, a majority of composite structures are still manually constructed and it is often too difficult to accurately hand-lay plies at odd orientation angles. The thickness and orientation of plies for interface ring are set as design variables. The minimum mass criteria have been taken as design objective of optimization. The following are the constraints:

- The minimum first fundamental frequency should be greater than 80 Hz. This is the fundamental frequency of the existing design as shown in the Table 6.
- The mass of the system should not be more than 8.54 Kg
- The ply thickness should not be less than 0.1 mm.
- The orientations of plies are allowed to vary only in discrete intervals to meet the manufacturing constraints.
- Bi-directional fabric has to be used inside and outside of the laminate for easy fabrication.
- The aluminium base (Part No 1001/1, Figure 3) should not modify in any respect after the optimization, i.e., it is a non-designable region.
- Within the sectors, lay up of the laminates remain same.

Optimization Results

The optimization was carried out using Altair OPTISTRUCT optimization tool with the above said constraints. The constraint imposed assured that, the first natural frequency is above 80 Hz. The comparison of the interface ring performance before and after optimization is shown in the Table.6. It is seen that the mass of the optimized housing has been reduced from 8.54 Kg to 7.74 Kg leading to a reduction of 0.80 Kg. The optimization procedure is started with a uniform thickness laminate of 3 mm, throughout the height of the structure. After optimization procedure, thicknesses at various sections are different as shown in Figure 3. It can also be observe that, the designed region mass has been changed from 5.14 Kg to 4.34 Kg resulting to a 15.56% of saving in the composite structural element mass. The mass break up of individual components is shown in Table 7.

Though the frequency/displacement/stress are within limits even with a lower thickness, only the option shown in the Table.8 has been selected to keep the simplicity of fabrication process, standardized dimensions and ply orientation/thickness as much as possible. The thickness of the ply has been taken as 0.1 mm uniformly, which is safe and fulfilling the structural requirements but the number of plies is different at different sections and hence the lay-up as shown in Table 8. From the output of the design variables such as ply thickness and orientations, rounded-off angles are selected for respective groups.

The stress levels on the optimized interface ring are analyzed and ply failure index are calculated using Tsai-Wu failure criteria. The highest value of ply failure index is 0.328 and is found in the fifteenth layer of the lop lip laminate. Since the failure index is much lower than 1, it can be concluded that, design is safe in strength wise. The thickness of the interface ring can be reduced further by adopting better manufacturing techniques and modify the constraints on ply thickness. Those techniques are costlier and would result in less weight but there may not be any cost benefit. The new design of the interface ring has to be tested and further correlation or modification can be incorporated if necessitated.

Table 6: Comparison of Results

EXISTING DESIGN			OPTIMIZED DESIGN		
Mass Kg	First Natural Frequency Hz	Second Natural Frequency Hz	Mass Kg	First Natural Frequency Hz	Second Natural Frequency Hz
8.54	78.91	78.97	7.74	81.49	81.53

Table 7: Mass Distribution

COMPONENTS	PART NUMBER	MASS (Kg)
Aluminium Base	1001/1	3.40
CFRP Main Structure	1001/2	2.36
Ou Outer Lip	1001/3	0.79
Inner Lip	1001/4	0.32
Ti Insert	1001/5	0.26
Top Lip	1001/6	0.04
Top Stiffener	1001/7	0.49
Bottom Stiffener	1001/8	0.08
TOTAL		7.76

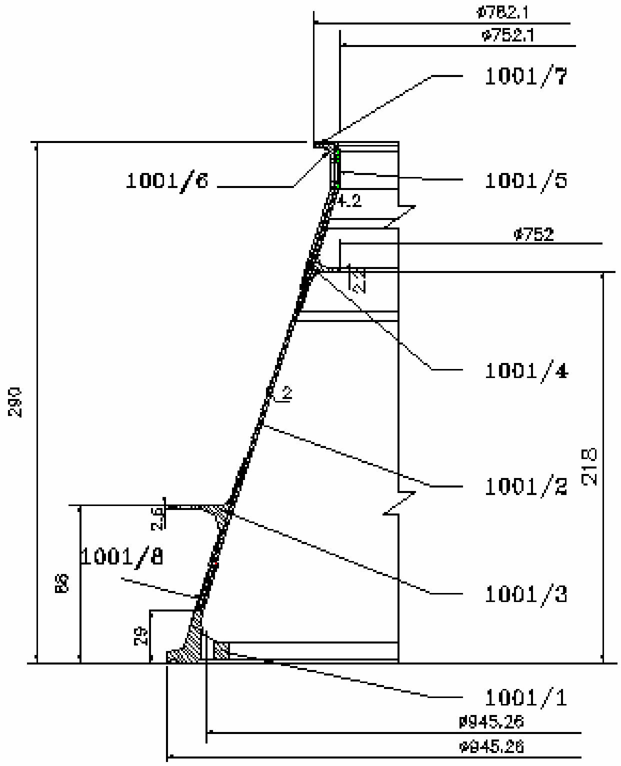

Figure 3: Sectional View of the Composite Interface Ring

Table 8: Laminates

COMPONENTS	PART NUMBER	LAMINATE
CFRP Main structure	1001/2	$[\#0_2 /0_2/+45/-45/0_4]_s$
Outer Lip	1001/3	$[\#0_2/90_2/0_2/+45/-45/0_2/90/0_2]_s$
Inner Lip	1001/4	$[\#0_2 /0/90/0/+45/-45/0_4]_s$
Top Lip	1001/6	$[\#0 /0/90_5/\#0]_s$
Stiffner-1	1001/7	$[\#0_2 /0/90_3/+45/-45/90/0/90/0]_s$
Stiffner-2	1001/8	$[\#0 /0_2/+45/\#0]$

Conclusions

The mathematical optimization technique is successfully used for analysis and design optimization of the composite interface ring of a typical spacecraft without sacrificing strength and stiffness and leading to saving on the material and launch cost. Hence the new proposed design of interface ring forms an efficient stable support platform for the spacecraft. The study has given good inputs to the design of the composite interface ring and simplified the tedious process of design optimization. The optimization study also made possible to look into alternative ways to minimize the mass by improving stability and stiffness of the present configuration. The mathematical optimization technique for designing composite interface ring has helped in increasing the strength and rigidity of interface ring by optimum utilization of material. The design parameters, which are limited by the manufacturing process, design limitations or materials, are also can be included in the future optimization studies.

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