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Dynamic Characteristic Studies on Honeycomb Core Filled Cylinder for Spacecraft Structure

Gayathri D
M.E Student/Dept of Aerospace Engineering
Madras Institute of Technology
Chennai, India.
welcomegayathri@gmail.com

Muralidhar.K.V
Head, Structural Analysis Section
Structures Group
ISRO Satellite centre
Bangalore, India
muralidr@isac.gov.in

S.Ilakkiya
Assistant Professor/Dept of Aerospace Engineering
Madras Institute of Technology
Chennai, India.

Abstract— **In any spacecraft mission, structure is the primary load bearing member. Most of the spacecraft structures are cuboidal in shape with a central cylinder and ring that interface with launch vehicle. This central cylinder plays an important role in satisfying overall stiffness and strength requirement of satellite structure, which undergoes various loads during launching and in orbit conditions. Most popular and efficient among cylinder construction is CFRP face-skin sandwiched with Aluminum Honeycomb Core. Cylinder construction using these structures is mainly developed with OX core to get the curved shape, as normal core suffers anticlastic curvature while bending which makes them unsuitable for the cylinder construction. In order to satisfy various stiffness requirements for different missions with the launch vehicle interface geometry constraint, it is not always possible to change the diameter of the cylinder to increase the stiffness. Next efficient alternative is to increase the core thickness to improve stiffness. But manufacturing cylinder honeycomb core with higher thickness is difficult even with the OX core because of anticlastic effects. Thus new design modification for improving the cylinder stiffness is done by inserting the higher thickness core into thin gridded CFRP cylinder which enhances the efficiency. In this paper trade off studies on dynamic and strength characteristics of typical spacecraft structure using this cylinder are studied. Stiffness characteristics are verified for the modified cylinder with that of launch vehicle stiffness constraints. The effect of modified cylinder on the dynamic characteristic of satellite structure is studied using Finite element modeling and analysis.**

Keywords- Free Vibration, DynamicCharacteristics, Sandwich Construction, Spacecraft Structure

I. INTRODUCTION

Spacecraft is an orbiting system that is developed to operate in space serving specific requirements. Spacecrafts are commonly known as artificial satellites. They are mainly developed for communication, remote sensing and scientific exploration purposes. The spacecraft system consists of many subsystems like structure, mechanisms, power, electronics, sensors, thermal, control systems etc. Structure is the main mechanical load carrying member and protects all sensitive elements during launch and in operating environments. The structure of a typical Spacecraft can be classified as primary, secondary and tertiary structures. Primary structure plays a vital role in transmitting the loads to the base of the satellite mainly launch loads. In the process of satellite launching, satellites experiences wide range of vibration loads that are transmitted to satellite along with thrust of the rocket engine. Failure of this primary structure leads to complete collapse of satellite. Hence it is essential to take special care while designing the primary structure. In essence the spacecraft structure is designed to meet the stiffness, strength, stability and pointing requirements with different geometrical constraints and least mass.

Most of the spacecraft structures are cuboidal structure with central cylinder and interface ring that provide attachment provisions to launch vehicle. Sometimes the payload support structure also requires cylinder to transfer the load to primary structures. Over the years many types of cylinders are being developed using material available and considering mass minimization, stiffness and strength requirements. Some of them are Monocoque cylinder, Corrugated cylinder, Metallic cylinder, Grid stiffened cylinder, Honeycomb sandwich cylinder etc. At present most popular and efficient construction of main cylinder is CFRP (Carbon Fiber Reinforced Plastic) Aluminium honeycomb sandwich cylinders. In most of the conventional spacecrafts, central cylinder is the prime load bearing member that also dictates the lateral frequency of the spacecraft. Launch vehicle specifications include the lateral and longitudinal frequency constraint that spacecraft structure should always satisfy. The stiffness requirement is expressed in terms of natural frequency constraint for global modes of the spacecraft in lateral and longitudinal directions. Dynamic characteristics are these natural frequencies, corresponding mode shapes and effective masses. As the mass and size of the spacecraft increases, improving the spacecraft lateral frequency becomes difficult as diameter of cylinder cannot be increased because of volume and diameter constraint of launch vehicle. This necessitates studying alternate or improvement over the existing design. Hence it is always a challenge for structural designers to configure a design that should be light weight and adequately stiff and strong. Approach followed in such cases is to workout designs for certain class of mass and CG of the spacecraft considering the identified launch vehicle load and specifications. Advent of light, high strength alloys, CFRP substrates, Honeycomb cores etc, has given enough opportunity for designers to look for alternative designs that are more efficient. Use of these advanced materials are always challenging due to manufacturing difficulties and exorbitant cost. In this paper these constraints are considered and using the combination of core and local stiffening with inner grids a novel design of cylinder is being studied. This will give the details of stiffness characteristics improvement over the existing design.

II. CONFIGURATION

A. Monocoque Sandwich Cylinder

Cylinder construction can be done using several methods some of the approach includes Monocoque construction which uses only skin surface to make the cylinder. These types of cylinders are strengthened with longitudinal members called as stiffeners to form the Semi Monocoque construction [1]. Another type include corrugated cylinder with and without external stiffening are found attractive on strength/mass basis. During seventies isogrid cylinder construction is considered as efficient structure with triangulation truss concept. All this construction made the weight of the structures to increase drastically which lead to the use of sandwich construction. Among them honeycomb core that consists of very thin foils in the form of hexagonal cells perpendicular to the facings is the most popular. Some advantage of sandwich construction includes high strength to weight ratio, outstanding rigidity, design versatility, elimination of welding and excellent structural efficiency [2]. As the composite technology evolved manufacturing of the CFRP sandwich honeycomb cylinders with low density aluminium core and composite skin further reduced the weight and increased the stiffness of the cylinder[3]. Normal hexagonal cores lead to anticlastic effect while forming it to cylindrical shape. To avoid this over expanded core named OX (Over Expanded) core is used to develop cylinder. This is true with low thickness (~12mm) cores. Whenever thickness of the core needs to be increased to achieve higher stiffness even OX core cannot be used. With the advent of CFRP cores, manufacturing of OX core itself is not possible and not preferred. Hence, new designs are worked out and are explained briefly as follows.

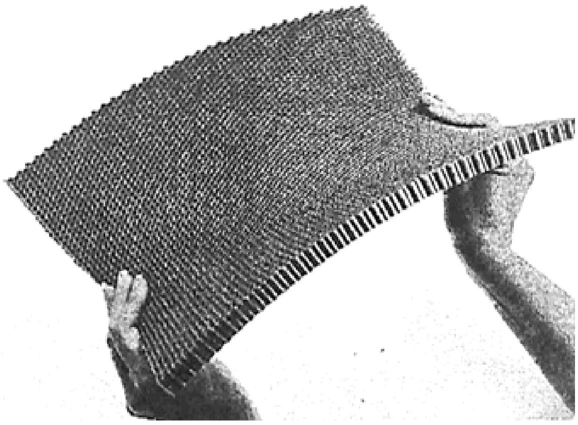


Fig.1. Anticlastic Curvature of Honeycomb Core

B. Sandwich Cylinder Construction

As mentioned Sandwich cylinder consists of honeycomb core sandwiched between two thin face skins (sheets). It is popular and efficient to use many layers of CFRP prepregs in the required orientation. As the Length to Diameter ratio (L/D) changes the optimum orientation to get best lateral stiffness changes. In this study, first trade off studies is carried out to get the optimum orientation for L/D ratio of 1.1 and 2.6 cases. Aluminum honeycomb cores are sandwiched between these optimized CFRP layers and for bonding between core and face skin film adhesives are normally used. A stiff metallic mold is used to lay these layers and cured at elevated temperature in an autoclave with vacuum bagging and external pressure. In the figure given below procedure of an OX core is laid over face skin is illustrated.

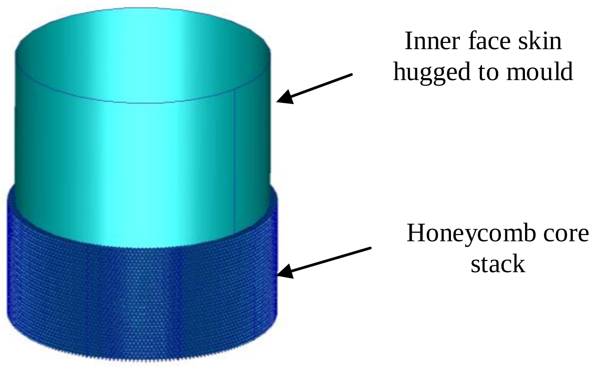


Fig.2. Schematic representation of CFRP Honeycomb Sandwich Cylinder

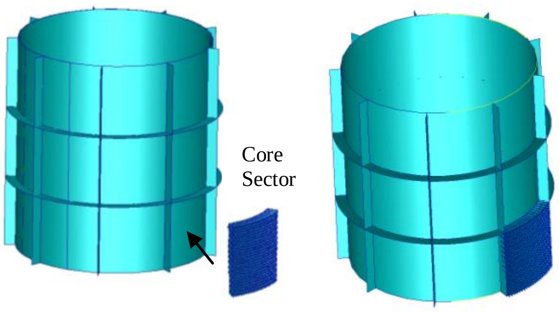


Fig.3. Schematic representation of Honeycomb core sector filling

Ox cores are stacked over inner face skin along the height. For clarity in the Fig.2 bottom portion of core only is given.

In the new design proposed, the grids are formed (Fig. 3), and the shaped honeycomb core pieces are inserted between grids. In this configuration the grids can be formed to suit any thickness and cores are not bent, hence anticlastic problem is avoided. This design not only enhances the global stiffness but also improves the local buckling strength characteristics. This design is free from anticlastic effects and thus reduces the manufacturing difficulties.

C. Finite Element Modelling

With the excellent development in the field of CAE, design of spacecraft structure is iterated using Finite Element Method based structural analysis tools. In this work MSC.Patran is used to build the Finite element model and MSC.Nastran solver is used for analyzing the model.

The geometric dimension of the central cylinder is worked out considering the Launch vehicle interface and geometric dimensions. Inner radius of cylinder is 443mm and the height is 1m. For bigger Spacecraft requirements, cylinder height considered is 2.4m keeping the same inner radius. The assumption made during this Finite Element analysis of CFRP honeycomb sandwich construction between the core-core interface and face skin core interface are perfectly bonded. 2D shell elements are used to model the cylinder and assigned layer properties. The material used for face skin and core is UDM55J and Low Density Aluminum Honeycomb core respectively. The initial layup angle optimization for the face skin layers with fixed core thickness trade off studies is done by varying the layup angle with respect to cylinder axis. The properties of the face skin and core are given as composite laminate option and the base fixed boundary conditions are given (both translation and rotation fixed) at the base of the cylinder. The mass of the Spacecraft are lumped at the CG (Center of Gravity) of the spacecraft and the free vibration analysis is carried out by varying the layup angle from 0 to 60 degrees. The angle which contributes for highest stiffness is taken and further analyses are carried out.

D. 3D modelling

As the core thickness is increased, the effect of flexural rigidity increase to be appropriately accounted, this will be appropriately accounted only with 3D elements. In this study, 3D HEXA elements for the honey comb core and 2D shell elements for the face skin is used for analysis. The equivalent 3D orthotropic properties of the honey comb core are assigned to the solid elements and analysis is carried out. The base fixed boundary conditions are applied and the variation of skin thickness and core thickness variation on the dynamic characteristics has been studied.

III. PLY ANGLE OPTIMIZATION

The conventional CFRP Honey comb sandwich construction consist of skin layer which is made up of composite laminates with different ply orientation .In order to choose the optimized ply angle for the new design construction, the stiffness variation with different ply angle is studied.

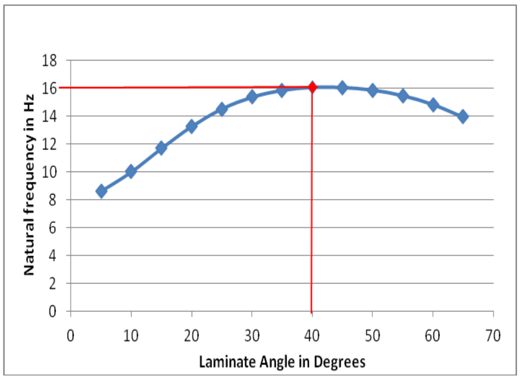


Fig.4. Natural Frequency Variation of Lateral Mode of L/D Ratio=1.1

The layup details for the 1m cylinder with core thickness of 12mm are given as θ/0/0/0/-θ/core/-θ/0/0/0/θ. Here, '0' degree refers to orientation of fiber in prepreg layup along the cylinder axis. The ply angle of 40 degrees is optimum for L/D ratio of 1.1(Fig. 4) and ply angle of 20 degree is optimum for

L/D ratio of 2.6(Fig.5) for lateral mode of cylinder and the Layup details are [θ/- θ / θ /-θ /0/0/0/-θ/ θ /-θ/ θ $]_s$.

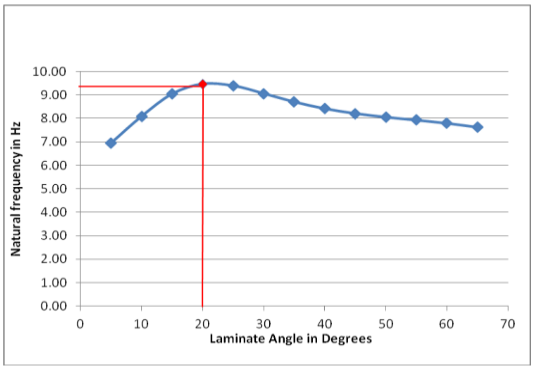


Fig.5. Natural Frequency Variation of Lateral Mode of L/D Ratio=2.6

IV. DYNAMIC CHARECTERISTICS –TRADE OFF STUDIES

The dynamic characteristics of different core thickness variation has been studied for L/D ratio of 1.1 and 2.6 with mass of the Spacecraft as 2000kg and 4000 kg lumped at C.G. Here, option available is to increase the number of layers in face skin or to increase the core thickness Minimum number of layers for strength, stability can be worked out first and stiffness can be satisfied by increasing the core thickness. Alternative to this, face skin layers can be increased first to satisfy the stiffness requirement and then verify for strength and stability. Almost all cases of bigger spacecraft design, if we adopt second approach strength and stability requirement will be automatically satisfied. Spacecraft designers will always look into two aspects a) to reduce mass b) to reduce manufacturing time and cost. In this study these are considered and design is worked out. First, considering 2000kg mass, for L/D ratios of 1.1 and 2.6 is considered. The faceskin of the cylinder is developed using the combinations of 40 and 0 degree laminates for cylinder with L/D ratio of 1.1. Similarly 20 and 0 degree laminates for L/D ratio of 2.6 cylinder. Following Table 1 and 2 gives the summary of this.

Table 1	**Lateral Frequency for core thickness variation for L/D ratio=1.1**			
	Core Thickness in mm	***Face skin layup***	***Lateral Frequency in Hz***	***Mass of cylinder in Kg***
Spacecraft Mass 2000kg	12.5	(40/-40)$_2$/(0)$_6$/(40/-40)$_2$	22.8	13.1
	25		23.3	14.5
	50		24.2	17.2
	75		25.2	20.0
Spacecraft Mass 4000kg	12.5	(40/-40)$_3$/(0)$_{22}$/(40/-40)$_3$	16.0	13.1
	25		16.5	14.5
	50		17.1	17.2
	75		17.8	20.0

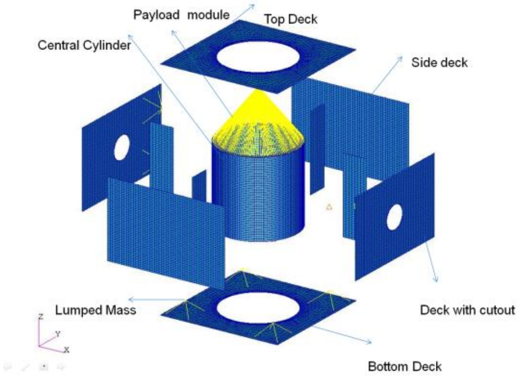
Table 2	**Lateral Frequency for core thickness variation for L/D ratio=2.6**			
	Core Thickness in mm	***Face skin layup***	***Lateral Frequency in Hz***	***Mass of cylinder in Kg***
Spacecraft Mass 2000kg	12.5	(20/-20)$_3$/(0)$_{22}$/(20/-20)$_3$	17.0	73.0
	25		17.3	76.0
	50		18.0	84.0
	75		18.6	92.0
Spacecraft Mass 4000kg	12.5	(20/-20)$_3$/(0)$_{22}$/(20/-20)$_3$	12.0	73.0
	25		12.3	76.0
	50		12.7	84.0
	75		13.2	92.0

Typically in spacecrafts the lateral frequency requirement is above 15 Hz. This varies with mass, inertia and the Launch vehicle requirements. For heavy spacecrafts above 4000kg class requirement is above 12Hz. These results given in table indicate that there is frequency improvement with increase in the core thickness variation with marginal increase in the mass of the cylinder. Similarly for L/D ratio of 2.6 the basic layers required to achieve the required frequency is much higher than that of L/D ratio of 1.1. As the mass, inertia is higher; contribution of face skin is comparatively lesser. In such cases using higher core thickness is highly beneficial.

Trade off studies on dynamic characteristics by considering the mass efficiency versus frequency improvement shows that, the results are encouraging for 4000kg class with L/D ratio of 2.6. In these cases increasing face skin layers after attaining the threshold stiffness will not be efficient. Hence,it is better to increase core thickness with the approach explained above. This efficiency can be further enhanced by using more number of layers in the outer skin compared to the inner skin. In this study, (20/-20)$_3$/(0)$_{52}$/(20/-20)$_3$ layup is worked out for inner skin and (20/-20)$_3$/(0)$_{80}$/(20/-20)$_3$ layup is worked out for outer skin with 12.5mm core thickness with 4000kg spacecraft mass for L/D ratio of 2.6. However, for same spacecraft with 75mm core thickness; the inner and outer skin layers are (20/-20)$_3$/(0)$_{42}$/(20/-20)$_3$ and (20/-20)$_3$/(0)$_{64}$/(20/-20)$_3$ respectively. This layup is optimum in which frequency and mass matches. All these layups are worked out using Uni Directional (UD) carbon fibre M55J with the M18 resin epoxy system. sometimes, combination of uni and bi direction layers are used. In such cases optimum angle and layers may slightly vary.

V. SPACECRAFT APPLICATIONS

Further, these designed cylinder dynamic characteristics' effect on the spacecraft structure is studied using the Finite element model of the spacecraft main bus structure and the new design cylinder. The main bus structure of a typical satellite structure consists of top deck, bottom deck, side deck with and without cut outs, shear panels, end rings etc. The mass of the electronic equipments and payloads are modeled as lumped masses at its particular CG location. Exploded view of FE model is given in Fig. 6. Finite Element Modeling of all these parts including the cylinder is performed in a systematic way. For verifying Stiffness, Strength, Stability requisite structural analysis is performed [4].



The effects of increased core thickness on the spacecraft dynamic characteristics are studied for core thickness of 50mm. Obtained lateral frequency is above 15Hz that satisfies typical launch vehicle constraint. The details of the model and results

Fig.6. Exploded view of Spacecraft FE model

Table 3.	**Geometric Properties of Cylinder with Spacecraft Main structure.**
Inner Radius	0.443m
Core Thickness	50mm
Height	1m
Boundary Condition	Base fixed condition both Translational and Rotational
Material Used	Low density honey comb core 3/16-5056-0.0007 UDM55J CFRP skin with 0.095mm per layer. (L/D ratio 1.1 layup)
Spacecraft structure	Cuboidal
Side Dimension	1.5m
Lateral Frequency for 2000kg Spacecraft	36.7Hz
Lateral Frequency for 4000kg Spacecraft	15.5 Hz

The strength and stability of the design is verified for quasi-static loads. These are applied as inertial loads with factor 8.75g (compressive) along the cylinder axis and 2.5g along the lateral axis and static analysis is carried out. Hoffmann failure criterion is used and verified CFRP face skin strength margins. Highest Failure index obtained is 0.63, that satisfies requisite strength margin.

Similarly buckling load factor is obtained by carrying out Eigen value analysis and ensured the buckling load margins. Also, minimum number of layers required to satisfy buckling load factor 3 is worked using following Eq. (1). [5].

The allowable buckling axial load for sandwich conical shells can be expressed as

$$P_{cr} = \gamma \frac{2E_f}{\sqrt{1-\nu_f^2}} h_c t_f \; 2\pi \left\{ 1 - \frac{E_f}{2\sqrt{1-\nu_f^2}} \frac{t_f}{RG_c} \right\} \tag{1}$$

g= Knock –down factor for sandwich = 0.6

u_f = Poison's Ratio (face skin)

R = Radius of cylinder

h_c= core thickness =12mm

t_f = face sheet thickness

G_c = Shear modulus of core =1.40E+08 N/m^2

E_f = Young's modulus = 149 GPa (Effective)

Substituting above values in Eq.1 minimum number of layers required for 2000kg spacecraft with inertial load of '10g' is 8 for face skin. This gives critical buckling load factor with a factor of 3. In all the cases, face skins consist of more than 8 layers in each face skin, which confirms required stability criteria. It is to be noted that the core thickness is directly proportional to buckling load; hence as the core thickness increases the buckling load capacity increases.

VI. CONCLUSION

This study explains the new methods of increasing the Lateral stiffness of honeycomb sandwich cylinder. Adding core thickness is the efficient method to improve Lateral stiffness for the L/D ratio of 2.6. Also, Increasing core thickness and or by increasing the face skin layers can improve the lateral stiffness in the case of L/D ratio equal to 1.1. As the mass, inertia and CG of the spacecraft increases higher thickness core with less number of layers in inner skin and more number of layers in outer skin is the best procedure to achieve the required stiffness. The new design proposed in this work enhances the buckling load capacity.

Manufacturing cost is less with lesser number of CFRP prepreg layers compared to core thickness increment. The spacecraft main bus structure with this new design is studied for its dynamic characteristics. The strength and stability of this new design cylinder also studied for spacecraft applications and satisfies all the requirements with sufficient margins.

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