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Design & Analysis of Body Mounted Composite Solar Array Substrate for Small Spacecraft Application

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Abstract - *The space programs worldwide are experimenting for the reduced dependency on large satellites and is moving towards development of small satellite systems to take advantage of cost-effective access to space. Demand for Small satellites that are capable of performing the same functions that in the past would have been occupied by large spacecraft is increasing. Therefore, the design requirements of major spacecraft systems to be met within guidelines of weight, cost and reliability conditions have to be reassessed in the context of small spacecraft philosophy. The solar array of a satellite, the power source of spacecraft - that it converts solar energy into electric power, is evolving over the years to meet small satellite requirements. In accordance with the improvements, structurally efficient solar array substrate, the base structure that supports the solar cells, needs to be developed for effective utilization of new solar cells for small satellites. This can be obtained by utilizing most efficient materials and optimizing the geometry of the structure.*

The present project deals with the design considerations, methodology, analysis and development process of a typical composite solar array substrate in body mounted configuration for small spacecraft application. Body mounted rigid solar arrays are complex to design and manufacture since they require a stiff, lightweight substrate that sustain the launch induced static and dynamic loads and on-orbit thermal loads without failure or excessive distortion.

Key Words: Small Satellite, Efficient Materials, Optimizing The Geometry, Lightweight Substrate, Launch Induced Loads, On-Orbit Thermal Loads

1. INTRODUCTION

Satellite industry is one of the most dynamically developing discipline of world economy, beside of satellite communications other applications, like navigation and positioning systems, observation of the Earth and space, stay more important. Development of small satellites (usually around 500 kg) for low Earth orbits (LEO), is gaining worldwide momentum for special applications other than communication. Small satellites though have smaller dimensions and mass do not differ from large ones and practically utilizes the same systems and blocks and realizing the same functions. Classical satellites are large and expensive, and process of their building lasts for many years and requires vast financial expenditures. Technology development leading to miniaturization of electronic elements has allowed to build small satellites that could be used in different applications. Short time of building and smaller costs of launch makes use of these satellites very attractive. Small satellites can be used in many applications.

1.1 Classification of Laminate

The laminates are classified depending upon the stacking sequence nature with respect to the midplane. This classification is helpful in the analysis.

Symmetric Laminates

Angle and thickness of the layers are same above and below the mid-plane.

Cross-Ply Laminates

The plies used to fabricate the laminate are only 0˚ and 90˚.

Angle-Ply Laminates

Plies will be of same thickness and material and are oriented at +θ and - θ. For example [45/-45/-30/30].

Anti-symmetric Laminates

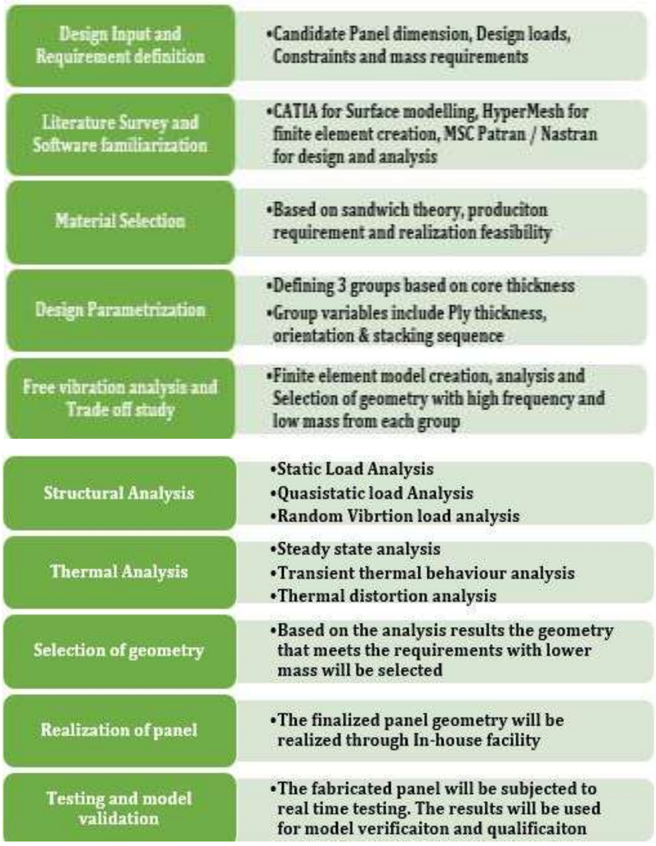
The material and thickness of the plies are same above and below the mid-plane but the orientation of the plies at same distance above and below the mid-plane have opposite signs. For example [45/-30/30/-45].

Balanced Laminates

It has pairs of plies with same thickness and material and the angles of plies are +θ and - θ. However, the balanced laminate can also have layers oriented at 0˚ and 90˚.
Here the used one is the symmetric laminates.

2. PROPOSED APPROACH

The project aims to optimally design the solar array substrate for the design loads. The design variables are core thickness, core density, face sheet (ply) thickness, orientation angles and stacking sequence. The methodology is explained in the flow chart.



Design Input and Requirement definition	•Candidate Panel dimension, Design loads, Constraints and mass requirements
Literature Survey and Software familiarization	•CATIA for Surface modelling, HyperMesh for finite element creation, MSC Patran / Nastran for design and analysis
Material Selection	•Based on sandwich theory, produciton requirement and realization feasibility
Design Parametrization	•Defining 3 groups based on core thickness •Group variables include Ply thickness, orientation & stacking sequence
Free vibration analysis and Trade off study	•Finite element model creation, analysis and Selection of geometry with high frequency and low mass from each group
Structural Analysis	•Static Load Analysis •Quasistatic load Analysis •Random Vibrtion load analysis
Thermal Analysis	•Steady state analysis •Transient thermal behaviour analysis •Thermal distortion analysis
Selection of geometry	•Based on the analysis results the geometry that meets the requirements with lower mass will be selected
Realization of panel	•The finalized panel geometry will be realized through In-house facility
Testing and model validation	•The fabricated panel will be subjected to real time testing. The results will be used for model verificaiton and qualificaiton

Chart -1: Methodology

3. DESIGN INPUT DEFINITION

3.1 Design Philosophy

Design of structural sandwich composite involves different phases that are dependent to each other. The dimensioning of a solar array substrate is initialized primarily based on the panel dimensions and satellite constraints. The layout of cells determines the height and width of the substrate and therefore, the free variable is the thickness of the substrate. The thickness of the substrate in turn depends on core and face thicknesses and no of laminates. The initial estimate is governed by launch vehicle constrains such as frequency, inertial loads and dynamic loads. The process begins with frequency analysis where minimum natural frequency constrain must be fulfilled by the determined geometries. Thickness of the core and face sheet materials are estimated and it will be updated until these requirements are met. Different geometries will be evaluated on the basis of better performances. These geometries will be analyzed under launch induced loads in order to verify thickness.

3.2 Design Criteria

- Shall lead to an item that is to be strong and stiff
- Materials used shall have known, reliable & reproducible properties
- Structure mass shall be minimized
- Shall be manufactured by methods that are reliable and repeatable

2.3 Design Input definition

The dimension of the candidate panel, shown in figure 2.1 and typical hold down requirement is given by design team. The panel is body mounted to one of the upcoming small satellites. The stated design requirements are

- The frequency of the designed panel should be higher than 120Hz.
- The mass shall not exceed 2kg.
- Shall be capable enough to withstand static, dynamic and thermal loads without any deformation

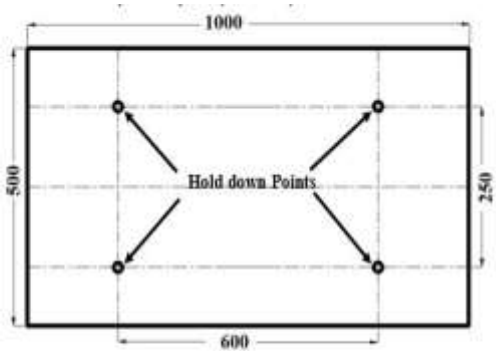


Figure 1: Dimensions of candidate panel

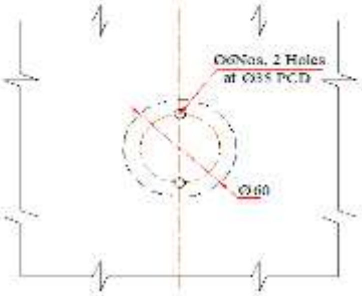


Figure 2: Typical Hold down dimensions

4. MATERIAL SELECTION

4.1 Structure of SA Substrate

The objective in the design of substrate is to achieve the required natural frequency with minimal mass and dimensional stability. The array stiffness is the major factor and hence sandwich construction is the best suited structure.

4.2 Core Material

The core should have good stiffness and shear modulus to withstand the shear stresses and resist buckling due to the applied loads. Honeycomb sandwich panel made of aluminium has high stiffness and shear strength and these panels are available in different densities (Expressed in pcf: pounds per cubic foot). Considering various parameters like design heritage, thermal conductivity, heat capacity, strength, ease of availability and fabrication procedures, AA 5056 aerospace grade aluminum honeycomb is selected.

4.3 Face material

CFRP laminates are best suited for use with aluminium honeycomb core as they are thin but strong with sufficient stiffness to withstand the stresses. Amongst different choices of CFRP, M55J/M18 laminate is chosen due to its

- Excellent strength to weight ratio, compared to other materials
- Suitable for complex contours and designs
- High stiffness and superior fatigue properties
- Very low coefficient of thermal expansion

4.4 Material Properties

Composites materials are orthotropic in nature and it involves parameters in both the longitudinal and transverse direction. Determining these properties involves special equipment and test setup. Therefore, for the selected material of the core and the face sheets the material the properties were supplied by CMSE.

Table-1: Properties of M55J/M18 Carbon/Epoxy Uni-directional composite

SL.NO	PROPERTY	UNIT	VALUES
1	Longitudinal Modulus	GPa	270 #
2	Transverse Modulus	GPa	5.535#
3	Longitudinal Tensile Strength	MPa	1350*
4	Longitudinal Compressive Strength	MPa	600*
5	Transverse Tensile Strength	MPa	22*
6	Transverse Compressive Strength	MPa	117 *
7	In-plane Shear Strength	MPa	70
8	Inter Laminar Shear Strength	MPa	47.6
9	In-plane Shear Modulus	GPa	3.87
10	Major Poisson's ratio	---	0.365
11	Density	kg/m^3	1760
12	CTE in Fibre direction	(/ °C)	-0.98×10^{-6}
13	CTE in Transverse direction	(/ °C)	$+29.0 \times 10^{-6}$
14	Cured Ply Thickness	mm	0.1

Table-.2: Properties of AA-5056 Honeycomb Cores

PROPERTY	UNIT	VALUES	
Designation		1/8-5056-	1/8-5056-
Nominal Weight	pcf	2.3	4.5
Thickness	mm	22.86	22.86
Type		Rigid	Rigid
a) Compressive			
Bare strength	MPa	1.00	3.28
Stabilized strength	MPa	1.07	3.45
Stabilized modulus	MPa	400.00	1275.33
b) Plate shear			
Strength (L)	MPa	0.89	2.41
Modulus(L)	MPa	220.63	482.63
Strength(W)	MPa	0.43	1.41
Modulus(W)	MPa	103.42	193.05

5. DESIGN AND ANALYSIS OF SOLAR ARRAY SUBSTRATE

5.1 Substrate Design Features

The sandwich consists of face skins (entire area) & local reinforcements (along & around hold-downs) using M55J/M18 CFRP composite and AA-5056 honeycomb core. The M55J/M18 composite has 0.1mm ply thickness. The reinforcements are laid connecting the interface points and all along the edges of the substrates. The local reinforcement layers are designed to take care of the higher stresses arising due to static and launch loads. Similarly, the core has a density of 2.3pcf over entire panel area except at the hold-down locations. The hold-down locations are designed to have a core with a density of 4.5pcf.

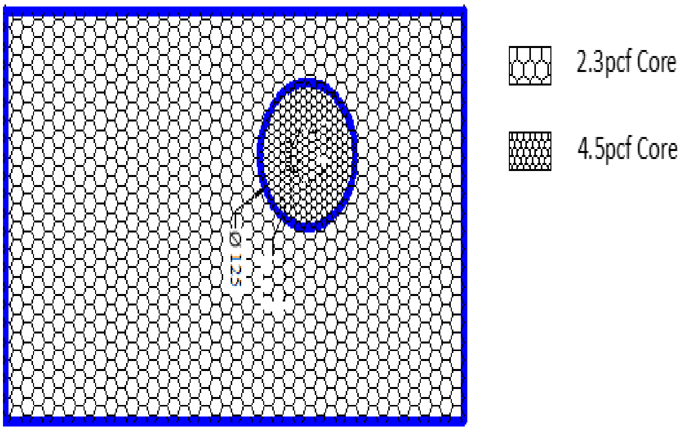


Figure 3: Schematic of change in density of core at hold down location

5.2 Design Parametrization and Topology Formation

The design variables are core thickness, no of reinforcement layers and lay-up sequence. Therefore, three group of geometries are formed with three different core thickness viz., 10, 15 and 20mm. Two different layup sequence [0/90 and 0/60] for basic skin along with four combinations of reinforcement layer lead to 8 different geometries for each group. Thus 24 geometries are formed in total. The reinforcement zones are shown in figure 6.2 and the layup sequence is described in table 6.1/6.2. Free vibration analysis is carried to select suitable geometry from each group.

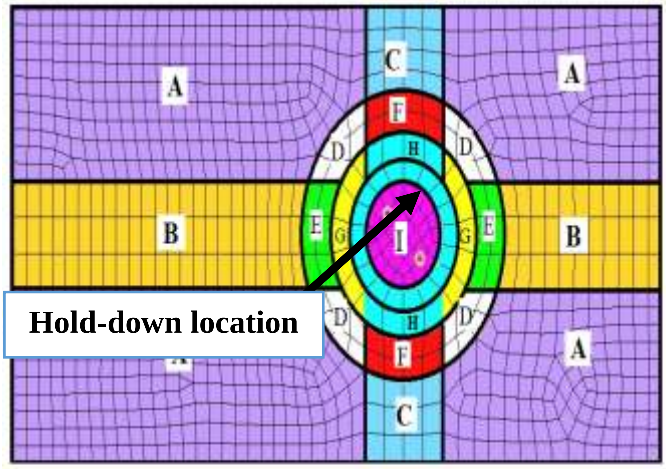


Figure 4: Schematic of reinforcement zones around hold-down location

Symmetric laminate sequence is chosen to avoid warpage during fabrication process i.e., the same sequence will reflect each other at top and bottom face of the sandwich. For simplicity of understanding only top layup is shown in table.

Table -3: Description of reinforcement lay-up orientation and sequence

Case No	1.a	1.b	1.c	1.d
A	[0/90]	[0/90]	[0/90]	[0/90]
B	[0/90] (0/0)	[0/90] (0/0/0)	[0/90] (0/0)	[0/90] (0/0/0)
C	[0/90] (90/90)	[0/90] (90/90)	[0/90] (90/90/90)	[0/90] (90/90/90)
D	[0/90] (45/-45)	[0/90] (45/-45)	[0/90] (45/-45)	[0/90] (45/-45)
E	[0/90] (45/-45/0/0)	[0/90] (45/-45/0/0/0)	[0/90] (45/-45/0/0)	[0/90] (45/-45/0/0/0)
F	[0/90] (45/-45/90/90)	[0/90] (45/-45/90/90)	[0/90] (45/-45/90/90/90)	[0/90] (45/-45/90/90/90)
G: 4.5pcf core	[0/90] (45/-45/90/90)	[0/90] (45/-45/90/90/90)	[0/90] (45/-45/90/90/90)	[0/90] (45/-45/90/90/90)
H: 4.5pcf core	[0/90] (45/-45/90/90/0/0)	[0/90] (45/-45/90/90/90/0/0)	[0/90] (45/-45/90/90/90/0/0)	[0/90] (45/-45/90/90/90/0/0)
I: 4.5pcf core	[0/90] (45/-45/90/90/0/0)	[0/90] (45/-45/90/90/90/0/0)	[0/90] (45/-45/90/90/90/0/0)	[0/90] (45/-45/90/90/90/0/0)

[ ] - Indicates basic skin (outermost lay-up). ( ) – Indicates reinforcement

Table -4: Description of reinforcement lay-up orientation and sequence

Case No	1.e	1.f	1.g	1.h
A	[0/60]	[0/60]	[0/60]	[0/60]
B	[0/60] (0/0)	[0/90] (0/0/0)	[0/90] (0/0)	[0/90] (0/0/0)
C	[0/60] (90/90)	[0/60] (90/90)	[0/60] (90/90/90)	[0/60] (90/90/90)
D	[0/60] (45/-45)	[0/60] (45/-45)	[0/60] (45/-45)	[0/60] (45/-45)
E	[0/60] (45/-45/0/0)	[0/60] (45/-45/0/0/0)	[0/60] (45/-45/0/0)	[0/60] (45/-45/0/0/0)
F	[0/60] (45/-45/90/90)	[0/60] (45/-45/90/90)	[0/60] (45/-45/90/90/90)	[0/60] (45/-45/90/90/90)
G: 4.5pcf core	[0/60] (45/-45/90/90)	[0/60] (45/-45/90/90/90)	[0/60] (45/-45/90/90/90)	[0/60] (45/-45/90/90/90)
H: 4.5pcf core	[0/60] (45/-45/90/90/0/0)	[0/60] (45/-45/90/90/90/0/0)	[0/60] (45/-45/90/90/90/0/0)	[0/60] (45/-45/90/90/90/0/0)
I: 4.5pcf core	[0/60] (45/-45/90/90/0/0)	[0/60] (45/-45/90/90/90/0/0)	[0/60] (45/-45/90/90/90/0/0)	[0/60] (45/-45/90/90/90/0/0)

[ ] - Indicates basic skin (outermost lay-up). ( ) – Indicates reinforcement

5.3 Finite Element Analysis of Solar Panel Substrates

In the FEA tool software, MSC PATRAN, material property of the whole sandwich structure can be established by laying-up top and bottom surface layers and honeycomb core with equivalent parameters obtained. The CFRP face sheets and core materials with different core thickness and is modeled as orthotropic lamina. In this project, the surface model is created in CATIA for one-fourth of panel dimensions (quarter model). The geometry is then discretized in HyperMesh and elements are reflected upon the symmetry axis to get the full model. The solar panel substrate reinforcement details, designated material, property, stacking sequence are modelled with Msc Patran and analyzed by Msc Nastran. The FE model is done in the XY plane such that the Solar Panel length 1000mm is along the X-axis, the Solar Panel width 500mm is along the Y-axis, & Z-axis is perpendicular to the Solar Panel. 4-noded iso-parametric membrane-bending plane stress quadrilateral layered shell element (CQUAD4, PCOMP) is used for modelling the basic sandwich construction. But at a few locations near the transition zones & boundaries, 3-noded iso-parametric membrane-bending plane stress triangular layered shell element (CTRIA3, PCOMP) is also used. The mass of the adhesives, hold-down inserts, harness/connector clamping & harness routing inserts and Kapton film are smeared with the honeycomb core densities at respective locations. Solar cell/harness blanket mass is uniformly distributed over the entire substrate as non-structural mass except at hold-downs. Rigid link RBE2 is modelled at the hold-down locations.

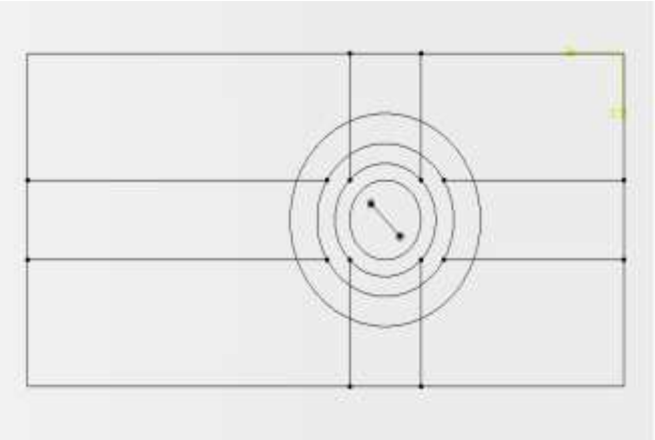


Figure 5: Quarter Model of the Solar Panel Substrate created in CATIA

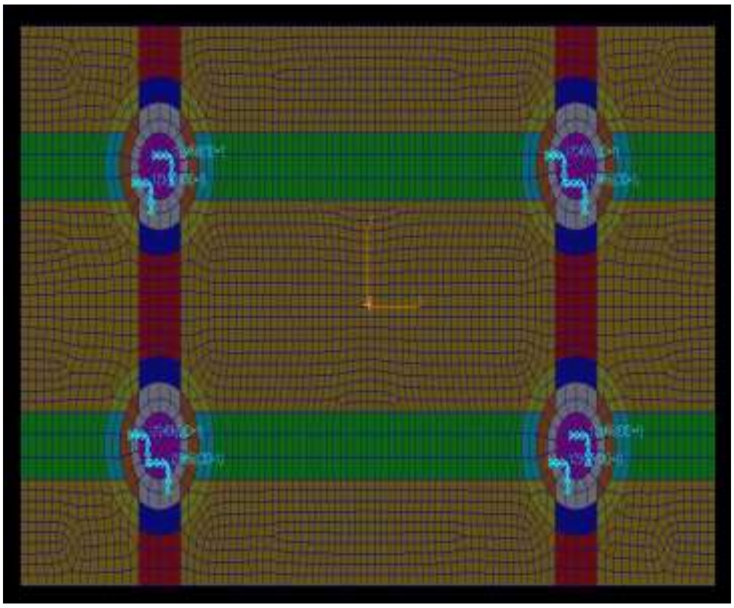


Figure 6: Finite element discretization with hold down constraints

5.4 Frequency Analysis of Solar Array Substrate

Frequency analysis of the panel substrate is performed both to determine the natural frequencies and modes of the solar panel substrate. These frequencies are the values at which a structure would vibrate if it is first excited by a transient load and then allowed to oscillate freely. These vibrations and corresponding values for common shapes such as beams, plates, shells etc. can be found in various engineering books. However, these formulas, in the case for a plate, which represents the solar array substrate, is for simple boundary conditions such as simply supported or clamped edges. More accurate determination of natural frequencies and modes shapes to fulfill the design requirements, could only be realized by utilizing finite element analysis. These natural frequencies are a design constraint and dependent on the stiffness of the structure along with employed materials and mass. Therefore, the frequency analysis of different substrate geometries is evaluated in Msc Patran/Nastran with constrains at hold down locations. This in-turn evaluates the sensitivity of the substrate stiffness and mass to the core and ply thickness, fiber orientation and lay-up sequence. The results of the analysis are tabulated in table 6.3. The typical mode shapes predicted through the analysis is shown in figure.5 and 6

Case No	1.a	1.b	1.c	1.d	1.e	1.f	1.g	1.h
Frequency (Hz)	93.2	93.14	87.89	87.82	78.98	78.88	72.07	71.97
Mass (kg)	1.817	1.794	1.769	1.747	1.817	1.794	1.769	1.747

Case No	1.a	1.b	1.c	1.d	1.e	1.f	1.g	1.h
Frequency (Hz)	133.58	133.51	126.37	126.3	112.9	112.77	103.32	103.18
Mass (kg)	1.916	1.893	1.869	1.846	1.916	1.893	1.869	1.846

Case No	1.a	1.b	1.c	1.d	1.e	1.f	1.g	1.h
Frequency (Hz)	171.34	171.26	162.41	162.33	144.54	144.39	132.46	132.3
Mass (kg)	2.015	1.993	1.968	1.945	2.015	1.993	1.968	1.945

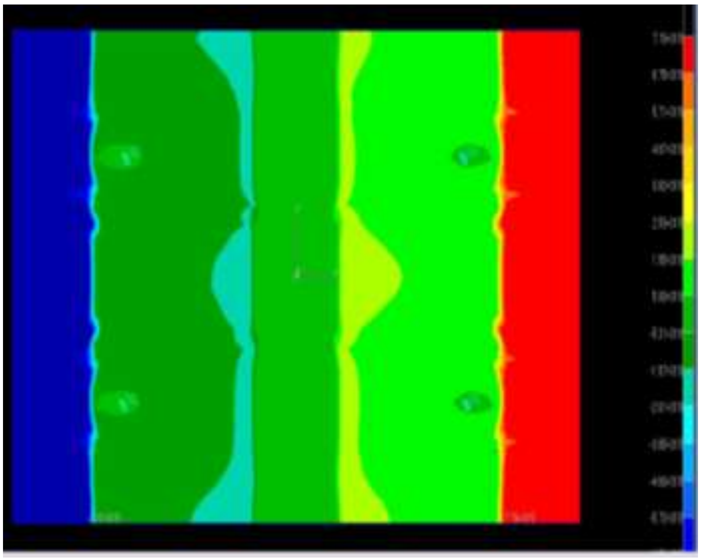


Figure 7: Typical Free Vibration Plot

5. TRADE-OFF ANALYSIS AND CONCLUSION

The free vibration frequency analysis indicates the natural frequencies of the different geometries along with the layup sequence. The criteria for trade off analysis is that the mass has to be the lowest and frequency shall be meeting the design criteria. Therefore, the geometry that has frequency higher than 85 Hz with least mass is the requirement. Cases 1.a to 1.d, 2.a to 2.h and 3.a to 3.h all meets the frequency requirements. However, the mass varies from 1.747 to 2.015kg, a spread of around 250 grams. Satellite component design has strict guideline on the mass of each system and even a 50gram mass saving has huge impact on the energy, cost and life of the satellite. Considering this it is decided to select the case 1.b, 2.b and 3.b to carry forward for further analysis where launch phase loads will be tested against the selected design. The geometry that meets the loading and thermal design goals of launch phase and in-orbit condition and provides a stable structure both structurally and thermally will be selected as the final design.

Thus, in the preceding chapters design methodology was profoundly described. Design criteria for the array substrate are established considering conventional spacecraft structures and particular requirements for the operation and objective of the structure. A careful attention was paid to the sandwich structures and candidate materials for the face and core of the panels. The same density core materials were applied to the substrate core by employing an approach which is based on the sandwich theory. The result of these analyses presented that carbon, fiberglass and aluminum honeycombs core materials have very similar results. Different cured ply thickness and stacking up of plies are employed and results of natural frequencies are evaluated. Once best performance materials and configurations were determined, solar array substrate geometries were analyzed based on different core and face thicknesses were obtained. For the core materials, three aluminum core materials with different densities and cell sizes were considered. In phase-2 of the project, the design and analysis of the substrate shall be focused on the launch induced loads and also thermal issues during operation and thermal properties of the structure shall be evaluated through analyses.

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