ANALYTICAL INVESTIGATIONS ON LIGHT-WEIGHT STRUCTURES FOR SATELLITE STRUCTURAL FRAME APPLICATIONS THROUGH 3D MODELING

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Abstract

Different kinds of medium/small weight-scale satellites with total weights around 2000kg are developed or under their ways of developments for global environment-observation objectives. In our study, light-weight structures such as honeycomb sandwich panels as applied for those medium/small weight-scale satellites' structural frames were analytically investigated to improve the performances between satellite dynamic-rigidities and weights and then result to the cost down of satellite-launches.
Several approaches to improve the total-weight and dynamic-stiffness performance of satellite systems were carried out using 3-dimensional (3D) modeling analysis and reported in this paper. At first the light-weight and higher-mechanical stiffness/strength honeycomb sandwich panels having advanced composite laminate as panel faces and honeycomb structure as panel cores were investigated to be applied for satellite structural frames. Secondly satellite structural frames with different shapes and sizes were 3-dimenssionally modeled and the dynamic stiffness was evaluated through modal analysis.

1 Introduction

As well-known that satellites are stored inside the fairings which are installed in the top of the launch vehicles. The shapes and sizes of fairings are due to different launch vehicles (rockets). Fig.1 shows the 4S 4[m] diameter fairing for H-IIA rockets [1] with all the size constrains on satellite structural frames. On the other hand, dynamic rigidity requirements for satellites are also depended on the launch vehicles. Some different dynamic rigidity requirements for satellites from different launch vehicles are shown inTable.1. Most commonly medium and/or small weight-scale satellites with total weight around 2000kg can be launched by 4S 4[m] diameter fairing and H-IIA rockets. Then in this study, the target dynamic rigidities for satellites were set at 30Hz in launch direction and 10Hz in the orthogonal direction to launch direction, based on the cases of H-IIA rocket launches.

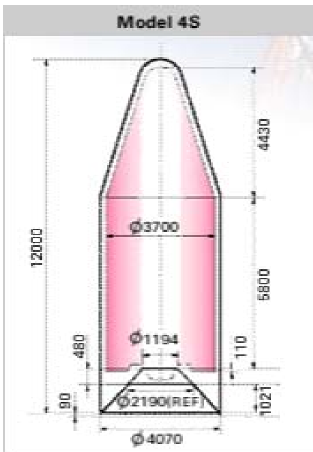


Fig.1. Shape and size of 4S type fairing @JAXA

Table.1 Dynamic rigidity requirement for satellites

Launch vehicle	Dynamic rigidity requirement	
	Launch Direction	Orthogonal to Launch Direction
H-IIA	30Hz~	10Hz~
ARIANE5	31Hz~(~4.5ton) 27Hz~(~4.5ton)	9Hz~
DELTA- II	35Hz~	15Hz~(DELTA79XX) 20Hz~(DELTA73XX /74XX)

Commonly satellite includes two subsystems as listed in Table.2. The first one is the mission subsystem including different sensors and data measurement/handling equipment to reach the satellite missions; and second one is the bus subsystem including satellite attitude & orbit control subsystem, structural frame and thermal control subsystem etc. to support the satellite missions.

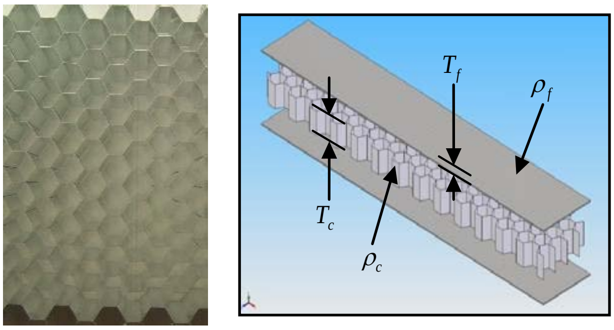
Table.2 Two Subsystems for Satellites

Mission Subsystem	AMSR (Advanced Microwave Scanning Radiometer)
	TEDA (Technical Data Acquisition Equipment)
	DM (Deployment Monitor)
	MDHS (Mission Data Handling System)
Bus Subsystem	TT&C (Tracking Telemetry and Control Subsystem)
	EPS (Electrical Power Subsystem)
	AOCS (Attitude & Orbit Control Subsystem)
	TCS (Thermal Control Subsystem)
	STR (Structural Frame)
	RCS (Reaction Control Subsystem)
	INT (Integration Hardware Subsystem)
	PROP (Propulsion Subsystem)

Because the dynamic rigidities of satellites are mainly depended on the structural frames (STR: Bus STR and Mission STR) [2], several analytical approaches on different type of structures such as honeycomb sandwich panels, advanced grid structures etc. for satellite structural frame applications were analytically executed to improve the light-weight and higher dynamic rigidity performances of satellites for vehicle launches.

2 Analytical Approaches on Mechanical Performance of Honeycomb Sandwich Panels

Honeycomb structures are very light-weight because of the higher air ratio of 95%~99% & lower material volume ratio of 1%~5% as well known, and usually utilized with FRP (Fiber-Reinforced Plastic) laminate together as faces of honeycomb sandwich panels. Fig.2(a) shows a sample photo of aluminum honeycomb structure and Fig.2(b) shows the image of honeycomb sandwich panels with all the design parameters of ρ_f(the face material density: kg/m^3); T_f (the face thickness: mm); ρ_c(the honeycomb volume density: kg/m^3) and T_c (the core thickness: mm). Bending elastic modulus and volume density properties of such honeycomb sandwich panels can be controlled by changing the combinations of these design variables and then affect the dynamic rigidities and weight properties of the applied structural frames and then the whole satellites. Then evaluations on bending elastic modulus and mass property of such honeycomb sandwich panels under different design parameters were carried out by using of 3-dimensional CAD tools and finite element analysis software.



(a) (b)

Fig.2. Honeycomb and Sandwich Panel

Honeycomb sandwich panels which are made from aluminum honeycomb cores and CFRP laminate faces were analytically investigated. For sandwich panel cores, aluminum alloy honeycomb having 0.0254mm (0.001 in.) foil thickness and cell size of 4.7625mm (3/16 in.) were fixed as shown in Fig.3 and the examined design variables were defined as CFRP panel face thickness within 0.5 ~ 2.0 mm and aluminum honeycomb core thickness within 6.0 ~ 25.0 mm shown in Fig.2.

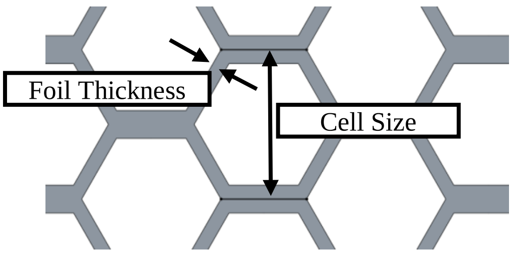


Fig.3. Honeycomb Foil Thickness and Cell Size

3D models of each honeycomb sandwich panels were made combined with different CFRP face thickness and aluminum honeycomb core thickness for mass properties and bending stiffness evaluations of sandwich panels through 3-point bending analysis. Material properties of aluminum and CFRP for analytical approaches are shown in Table.3.

Table.3 Material Properties of Aluminum and CFRP

Material Properties	Aluminum 5052	CFRP Laminate
Elastic Modulus [MPa]	70000	5.9000
Poisson's Ration	0.3	0.30
Density [kg/m^3]	2600.0	1498.50

Fig.4 shows the plots of volume density of such honeycomb sandwich panels obtained from 3-dimennsional modeling.

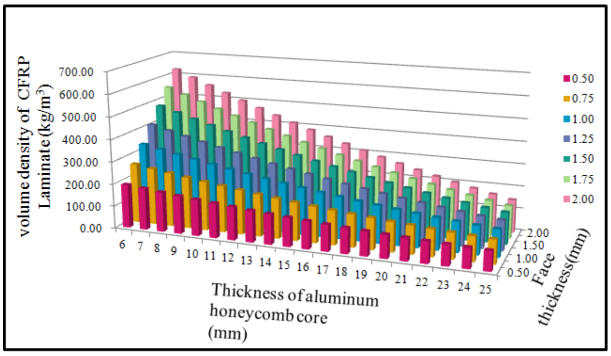


Fig.4. Volume Density of Sandwich Panels

From the above results, the volume density of honeycomb sandwich panels can be approximated as Equation (1) with a represented the CFRP face thickness (mm) and $\boldsymbol{x}$ represented the aluminum honeycomb core thickness (mm).

$$(-0.045a^2+0.0207a+0.5151)x^2 + (-2.5544a^2+0.4306a-34.705)x + (-51.054a^2-48.062a+869.16) \quad (1)$$

Fig.5 shows the plots of bending elastic modulus of honeycomb sandwich panels obtained from the three-point bending modeling. From these results, bending elastic modulus of honeycomb sandwich panels can be approximated as Equation (2) with a_1 represented CFRP face thickness (mm) and $\boldsymbol{x_1}$ represented aluminum honeycomb core thickness (mm), just like in the case of volume density.

$$(10^6a_1^3-9\times10^6a_1^2+3\times10^7a_1-106022)x_1^2 + (-9\times10^7a_1^3+7\times10^8a_1^2-2\times10^9a_1-4\times10^8)x_1 + (7\times10^8a_1^2-9\times10^9a_1+7\times10^{10}) \quad (2)$$

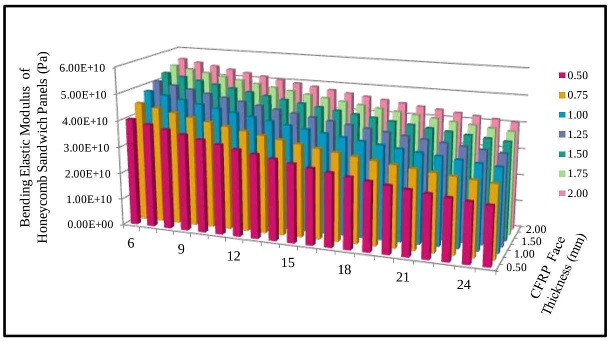


Fig.5. Bending Elastic Modulus of Sandwich Panels

3 Effects of Honeycomb Sandwich Panels as Applied on Satellites

Fig.6 shows the original 3D model of satellite system and Fig.7 shows the detail models of each subsystem for analytical approaches.

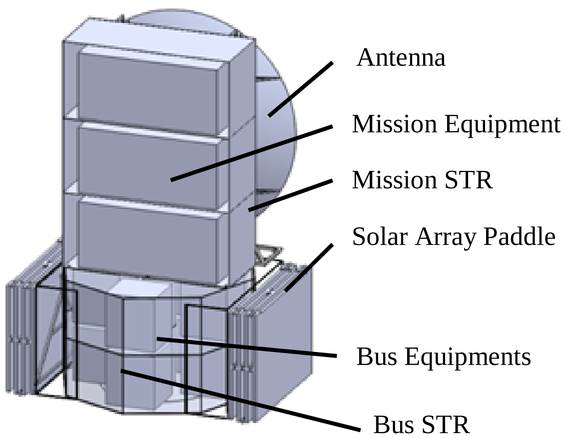


Fig.6. 3D Model of Satellites

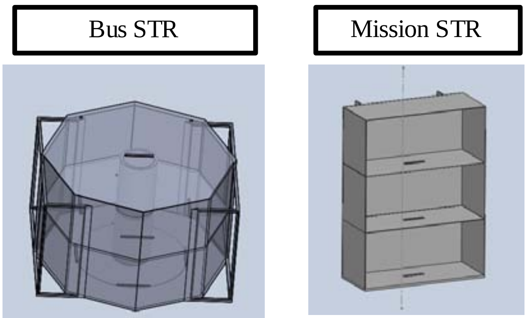


Fig.7. Structural Frames (STR) for Satellites

Fig.8 shows the connected/fixed conditions between all the satellite subsystems and material properties of these satellite subsystems are listed in Table.4 for modal analysis.

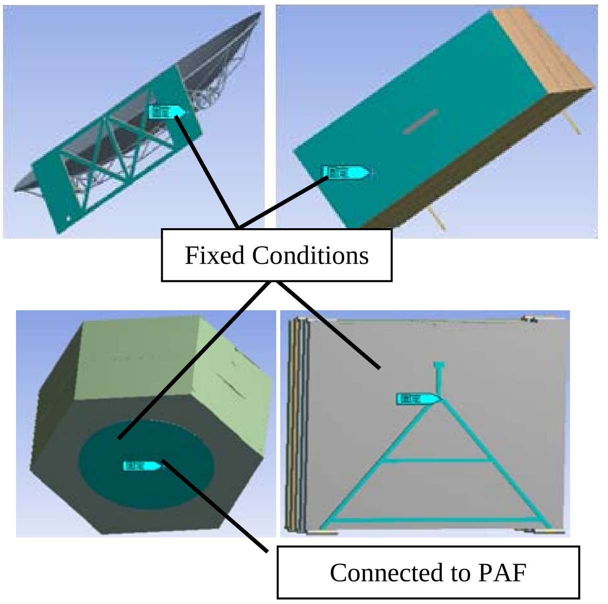


Fig.8. Connected Conditions between Subsystems

Table.4 Material Properties for Modal Analysis

Material property	Alum. 5052 (Antenna)	Advanced Grid Alum. (Antenna)	Honeycomb panel (STR)
Elastic Modulus [MPa]	70000	70000	56032
Poisson's Ration	0.3	0.3	0.3
Density [kg/m^3]	2600.0	504.4	442.9
Material property	Mission Equipment	Bus Equipment	Honeycomb Panel (STR)
Elastic Modulus [MPa]	70000	70000	27286
Poisson's Ration	0.3	0.3	0.3
Density [kg/m^3]	442.9	628.6	120.5

Based on the above mentioned initial satellite model, some approaches on applications of honeycomb sandwich panels for structural frames were executed.

Approach 1:
Applied target: Bus STR
Initial fixed conditions:
Cell size 3/16[inch]
Foil thickness 0.001[inch]
Honeycomb core thickness 25[mm]
Design parameter:
CFRP face thickness 0.5~2.0[mm]

The total change of satellite mass property and dynamic rigidity for orthogonal to the launch direction are shown in Fig.9 and Fig.10. From these result, one can see that the dynamic rigidity increased linearly with the total mass increased linearly too.

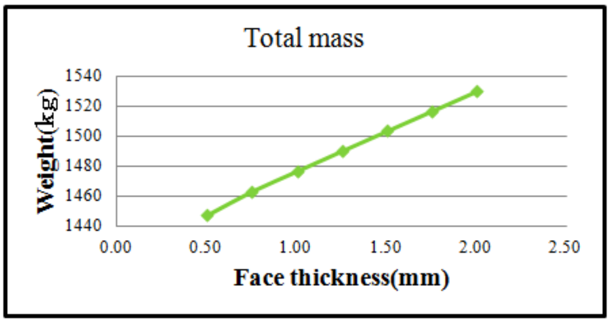


Fig.9. Mass Property due to CFRP Face Thickness

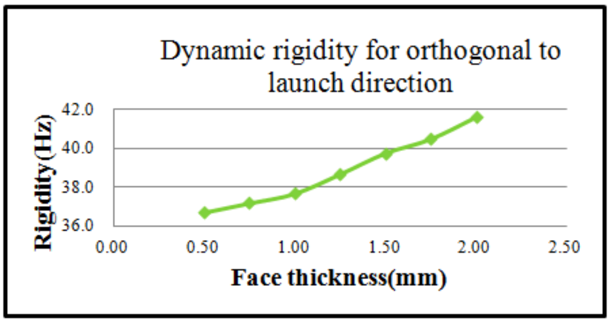


Fig.10. Dynamic Rigidity due to CFRP Face Thickness

Approach 2:
Applied target: Bus STR
Initial fixed conditions:
Cell size 3/16[inch]
Foil thickness 0.001[inch]
CFRP face thickness 0.5[mm]
Design variable:
Honeycomb core thickness 6~25[mm]

In this approach, different effectiveness of the honeycomb panels on the mass property and dynamic rigidity of satellites were obtained as shown in Fig.11 and Fig.12.

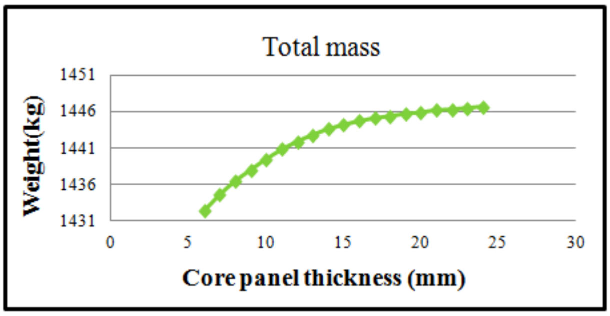


Fig.11. Mass Property due to Honeycomb Core Thickness

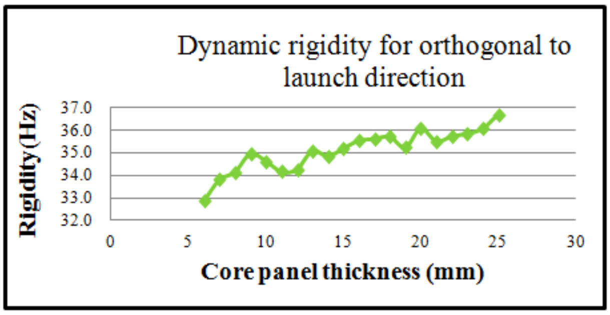


Fig.12. Dynamic Rigidity due to Honeycomb Core Thickness

Approach 3:
Applied target: Mission STR
Initial fixed conditions:
Cell size 3/16[inch]
Foil thickness 0.001[inch]
Honeycomb core thickness 25[mm]
Design variable:
CFRP face thickness 0.5~2.0[mm]

In this approach, different effectiveness of the honeycomb panels on the mass property and dynamic rigidity of satellites were also obtained as shown in Fig.13 and Fig.14.

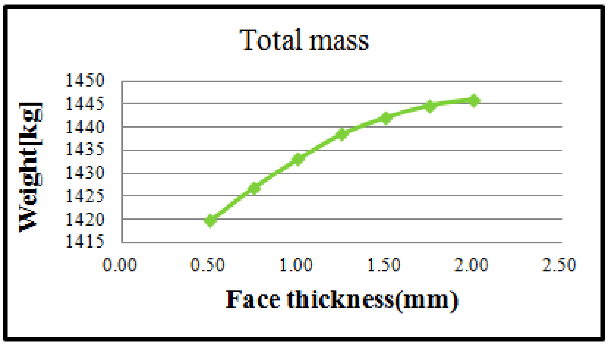


Fig.13. Mass Property due to CFRP Face Thickness

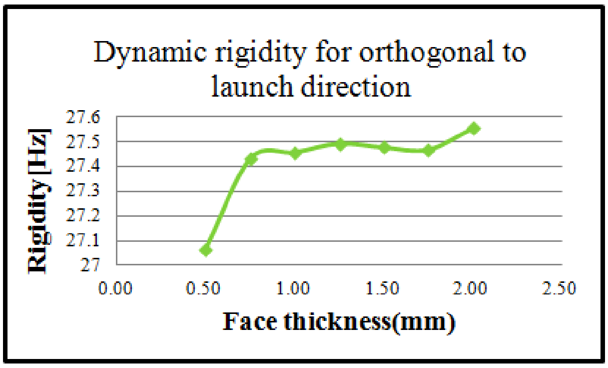


Fig.14. Dynamic Rigidity due to CFRP Face Thickness

Approach 4:
Applied target: Mission STR
Initial fixed conditions:
Cell size 3/16[inch]
Foil thickness 0.001[inch]
CFRP face thickness 0.5[mm]
Design variable:
CFRP face thickness 6~25 [mm]

In this approach, different effectiveness of the honeycomb panels on the mass property and dynamic rigidity of satellites were also obtained as shown in Fig.15 and Fig.16. From Fig.16, one can see that the applications of honeycomb sandwich panels will not effect on the dynamic rigidity of satellites when the honeycomb core thickness larger than 11mm thickness. This can be considered that the mission STR will stretched out to the layout of bus STR and mission STR will not contribute to the dynamic rigidity of satellites. This concluded that less than 11.0 mm thick honeycomb cores will be desired to improve the weight-dynamic rigidity performance for satellites.

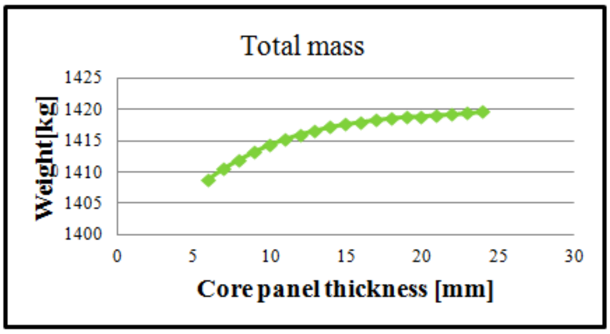


Fig.15. Mass Property due to Honeycomb Core Thickness

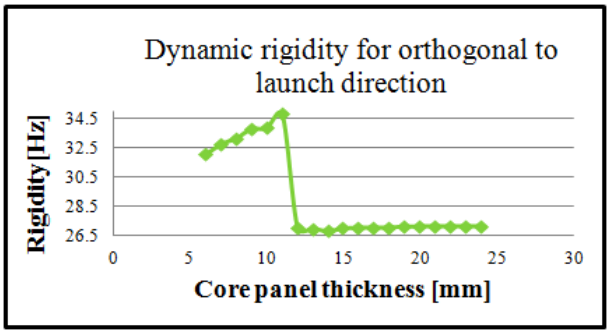


Fig.16. Dynamic Rigidity due to Honeycomb Core Thickness

4 Structural Approaches on Structural Frames to Improve Satellite Light-weight & Higher Dynamic Rigidity Performance

Different approaches were also executed just on the structural changes for satellite structural frames. Based on the above mentioned approaches, 7[mm] thick honeycomb sandwich panels applied satellite structural frames were used here for start model. Under this condition, dynamic rigidity of satellite in orthogonal to launch direction is 37.8[Hz] with the total mass of 1465.1[kg]. Fig.17 shows the typical eigenmode in orthogonal to launch direction.

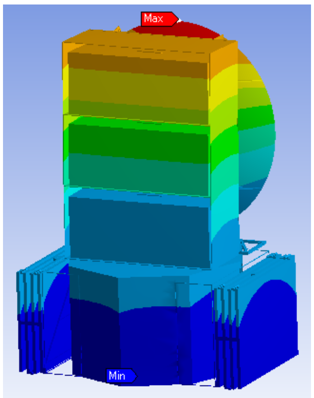
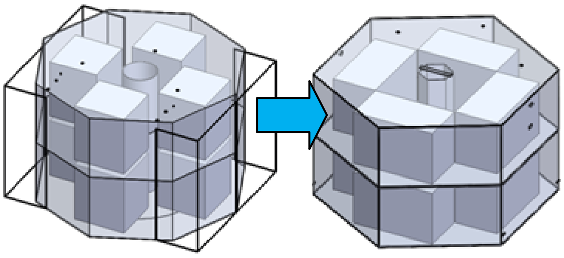


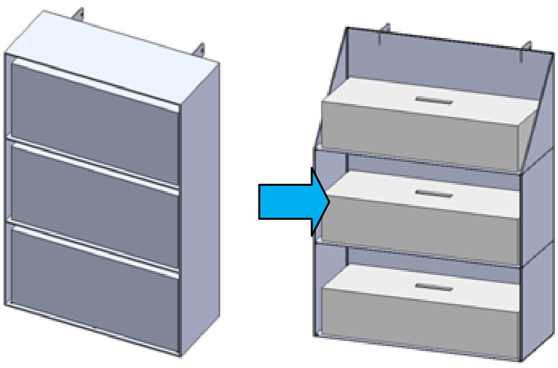
Fig.17. Eigenmode in Orthogonal to Launch Direction

Approach 5:
Shape changes on Bus STR and Bus Equipment:



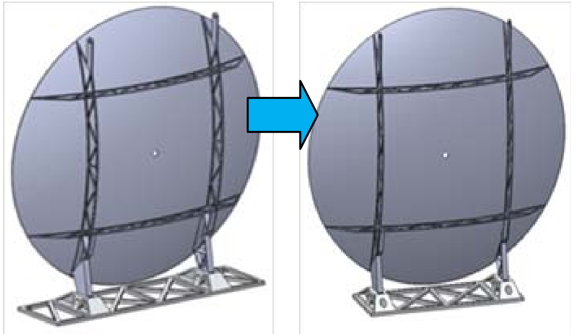
Mass : 53.2[kg] Rigidity : 91.2[Hz]	Mass : 57.9[kg] Rigidity : 119.3[Hz]

Approach 6:
Shape changes on Mission STR and Mission Equipment:



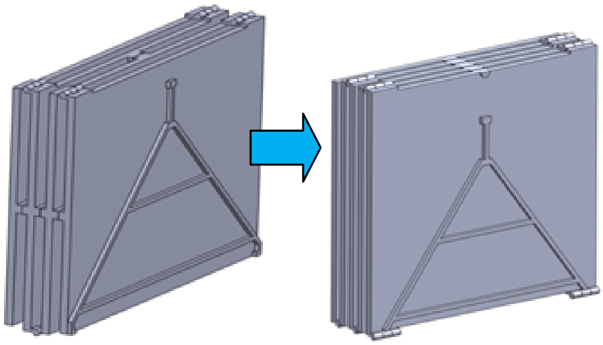
Mass : 34.1[kg] Rigidity : 26.5[Hz]	Mass : 41.7[kg] Rigidity : 56.8[Hz]

Approach 7:
Shape changes on Antenna Support:



Mass : 57.4[kg] Rigidity : 28.5[Hz]	Mass : 62.5[kg] Rigidity : 28.5[Hz]

Approach 8:
Shape changes on Solar Array Paddle with fixed Solar Array Paddle Area:



Mass : 34.7[kg] Rigidity : 175.1[Hz]	Mass : 36.8[kg] Rigidity : 169.2[Hz]

Combine all the approaches above mentioned, final improved light-weight with safely dynamic rigidity satellite model was obtained. Fig.18 shows the satellite model and eigenmode for orthogonal to launch direction.

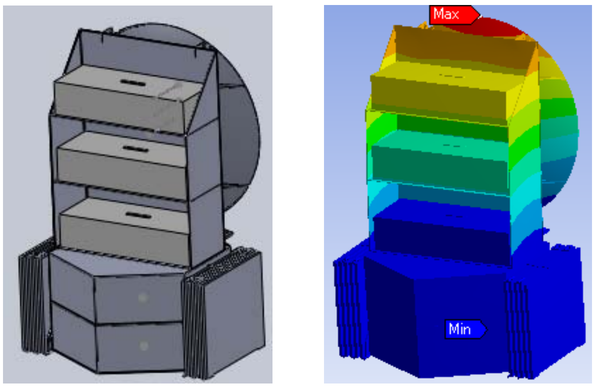


Fig.18. Improved light-weight satellite

The improved total mass and dynamic rigidity properties are shown in Table.5. From these results, one can see that more than 50.0 kg mass reduction was carried out with the dynamic rigidity of satellite having the safety ratio about 2.28 corresponding to the dynamic rigidity requirement for orthogonal to the satellite launch direction. More mass reduction should be possible from the safety ratio view point.

Table.5 Improved Mass Property with respect to Dynamic Rigidity of Satellite

Satellite	Total mass [kg]	Dynamic rigidity for orthogonal to launch direction [Hz]
Initial model	1465.1	37.8
improved model	1414.7 (-50.4)	22.8 (-15.0)

5 Conclusion

Light-weight structural types such as honeycomb sandwich panels with lighter weight & higher mechanical property performance for medium/small weight-scale satellites' structural frame applications were investigated through 3-dementiobal modeling. Analytical results shown in Table.5 indicated that more than 50kg lightweight was obtained with the safety ratio of 2.28. From this result more light-weight investigations on satellite structural frames could be reached under the safety ratio around 1.5 as generally required for launch vehicles.

6 Reference

[1] http://www.jaxa.jp/

[2] M. Shigehara, *Space System Introduction-Satellite Design and Development*, Baifukan