8th IAA Planetary Defense Conference – PDC 2023
3-7 April 2023, Vienna, Austria

IAA-PDC-23-0X-XX

Mechanical Analysis and Testing of the ASPECT Payload for Milani CubeSat

Swati Thirumangalath (1), Leevi Salonen (1), Antti Näsilä (2) and Hans Toivanen(3)
(1)(2)(3) *VTT Technical Research Centre of Finland Ltd., Espoo, Finland*
+358503060378, swati.thirumangalath@vtt.fi

Keywords: *Milani Cubesat, Aspect, hyperspectral imager, structures, vibration, finite element analysis*

ABSTRACT

Hera is the European component of the international Asteroid Impact and Deflection Assessment (AIDA) project. In early 2027, HERA intends to deploy two CubeSats, named Milani and Juventas in the near proximity of the binary asteroid Didymos. Milani is a 6U CubeSat and has 6-DOF maneuvering capabilities, to control both its attitude and translational motion. Utilizing the hyperspectral imager ASPECT built by VTT, Milani intends to provide a detailed mineralogical map of Didymos' (primary of the binary system) and Dimorphos' (secondary) surfaces [1].

The ASPECT miniaturized hyperspectral imager covers the optical spectrum from visible to the shortwave infrared (SWIR) range. There are four measurement channels on the instrument, one for visible light (VIS), two for near infrared (NIR), and one for SWIR. SWIR is a single-point spectrometer, while VIS and NIR are imaging spectrometers [2,3]. Asteroids' surfaces will also be characterized by ASPECT in terms of space weathering, shock effects, surface material transfer, and roughness. There will be finer detail images of selected features, such as the spacecraft's impact on Dimorphos in 2022, where DART (Double Asteroid Redirection Test) was launched.

A summary of the FEA analysis and vibration testing for the ASPECT instrument is presented in this paper. As per the ESA (European Space Agency) specification guidelines, shock response analysis was the most critical module to assess. Mode shapes were calculated as a pre-requisite to the shock response analysis, modal analysis being the most fundamental of all dynamic analyses. Modal analysis was carried out for the X, Y, and Z axis non simultaneously. The fundamental frequency from the first mode shape was around 850 Hz which was within the acceptable range. The shock response of the ASPECT structure was then investigated with a response spectrum analysis. The maximum stresses within the ASPECT components were below the specific material ultimate strength values.

The ASPECT components meet the requirements for Modal and Shock response studies. Three steps involving an LLSS (low-level sine sweep), random vibration test, and shock response tests were conducted on the FPI (Fabry Perot Interferometer) assembly. No noticeable damage was observed on the structure post the three vibration test stages. Furthermore, for the set of LLSS tests performed, the natural frequency did not vary by more than 15 %.

ESA Requirements

The requirements specified by ESA included the following [5]:

1. The maximum stress within ASPECT components should be below the specific material ultimate strength values [4].
2. The predicted MOS (Margin of Safety) for all the critical components should also be above 1.
3. FPIs should survive the vibration tests involving an LLSS (low-level sine sweep), random vibration test, and shock response tests.

Simulation setup assumptions

Various simplifications and approximations were made to model the behavior of the ASPECT structure. The simulation models are based on the major dimensions and features of the CAD model. The simplifications and approximations were made on a conservative basis to account for worst case scenarios.
The assumptions include the following:

1. Linear behavior, i.e. the spring coefficient K is constant and the displacements U are small.
2. The natural frequencies were solved in an unloaded condition, i.e. free vibration of the model.
3. For random vibration and shock response analysis, there is assumed to be a 2% modal damping. This damping includes the material damping and damping from connections, such as microslip at bolted connections.

ASPECT mounting to MILANI CubeSat

The ASPECT payload is mounted onto the satellite platform via 12 helicoil threads and bolts. 12 fixed surfaces are used to replicate 6 helicoil bolted threads on two sides.

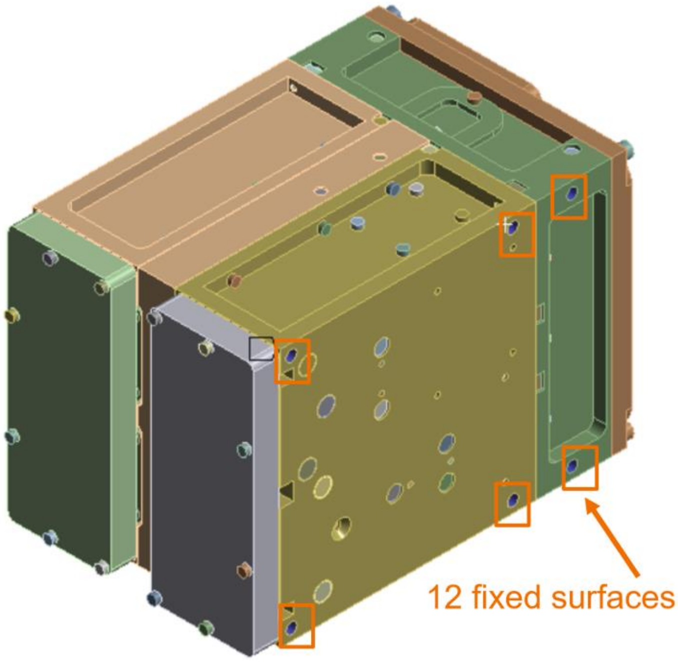

Figure 1: Aspect mounting locations

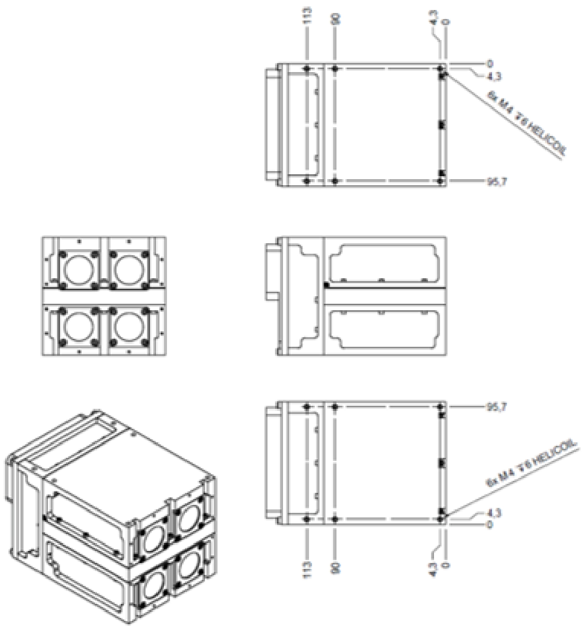

Figure 2: Aspect mounting locations – 3D view

Modal Analysis

Modal analysis is the most fundamental of all dynamic analysis. It is the basis of all other linear dynamic analysis that follow. To determine the ASPECT structural response to shock loads, a non-loaded eigenfrequency solver is performed on the model. The sweep is performed from 5 Hz to 10000 Hz to accommodate all loading scenarios. Only the first six mode shapes are useful for the present discussion, as per RD 4, Chapter 5, section 5.7.

Modal analysis is carried out for X, Y and Z axis non simultaneously. The participation factors are higher in Z and X axis. The mass participation factors are higher for mode shapes 1 and 5 in X axis and for mode shape 2 and 5 in Z axis. The probability of peak stresses and deformations are higher for mode shapes 1,2 and 5 in X and Z directions.

Participation Factor

Mode	Frequency [Hz]	X Direction	Y Direction	Z Direction	Rotation X	Rotation Y	Rotation Z
1	857.54	3.5271e-003	3.435e-005	7.1017e-006	-1.7018e-003	0.23187	1.2695e-003
2	894.22	-6.3851e-006	7.4379e-006	6.1836e-003	-4.2472e-004	-3.1564e-004	1.8272e-004
3	896.76	2.2658e-003	4.2407e-005	3.0741e-005	-2.1136e-003	0.18407	1.7481e-003
4	1019.6	3.3544e-005	-1.3029e-006	3.9325e-003	2.4086e-003	4.0807e-003	-2.7412e-004
5	1205.4	6.4692e-003	6.5199e-005	4.912e-003	0.12861	0.70976	-4.7806e-002
6	1218.6	-8.1923e-003	-4.9726e-004	5.6608e-003	4.5838e-002	-0.80725	-4.3626e-002

Effective Mass

Mode	Frequency [Hz]	X Direction [tonne]	Y Direction [tonne]	Z Direction [tonne]	:otation X [tonne mm mm]	.otation Y [tonne mm mm]	.otation Z [tonne mm mm]
1	857.54	1.244e-005	1.1799e-009	5.0434e-011	2.8961e-006	5.3762e-002	1.6116e-006
2	894.22	4.077e-011	5.5323e-011	3.8237e-005	1.8039e-007	9.963e-008	3.3385e-008
3	896.76	5.134e-006	1.7983e-009	9.4501e-010	4.4675e-006	3.3881e-002	3.056e-006
4	1019.6	1.1252e-009	1.6975e-012	1.5464e-005	5.8015e-006	1.6652e-005	7.514e-008
5	1205.4	4.1851e-005	4.251e-009	2.4128e-005	1.654e-002	0.50376	2.2854e-003
6	1218.6	6.7114e-005	2.4726e-007	3.2045e-005	2.1011e-003	0.65165	1.9032e-003
Sum		1.2654e-004	2.5455e-007	1.0987e-004	1.8654e-002	1.2431	4.1934e-003

Cumulative Effective Mass Fraction

Mode	Frequency [Hz]	X Direction	Y Direction	Z Direction	Rotation X	Rotation Y	Rotation Z
1	857.54	9.8311e-002	4.6353e-003	4.5902e-007	1.5525e-004	4.3249e-002	3.8433e-004
2	894.22	9.8311e-002	4.8526e-003	0.348	1.6492e-004	4.3249e-002	3.9229e-004
3	896.76	0.13888	1.1917e-002	0.34801	4.0441e-004	7.0505e-002	1.1211e-003
4	1019.6	0.13889	1.1924e-002	0.48876	7.1542e-004	7.0519e-002	1.139e-003
5	1205.4	0.46962	2.8624e-002	0.70835	0.88736	0.47577	0.54615
6	1218.6	1.	1.	1.	1.	1.	1.

Figure 3: Participation factor summary

Modes 1 to 6 were captured, and the resulting frequencies range from 857 Hz to 1218 Hz which is nominal.

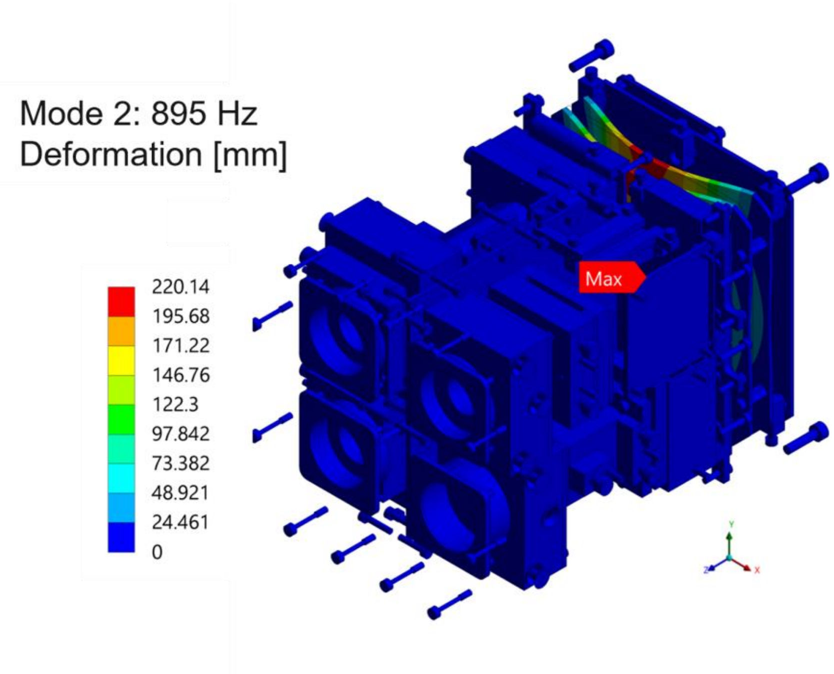

Figure 4: Mode 2

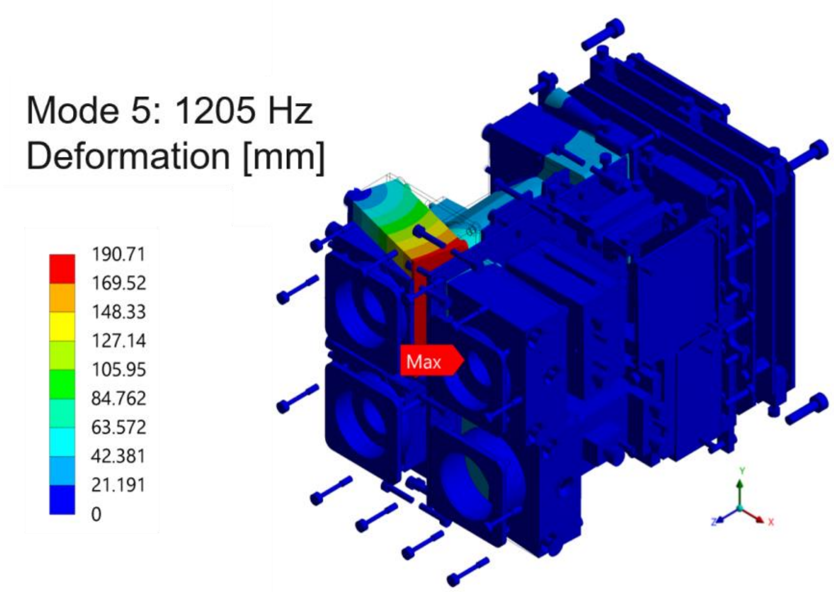

Figure 5: Mode 5

Shock Analysis

The shock response of the ASPECT structure is investigated with a response spectrum analysis. The shock loads from the table are applied to each of the co-ordinate directions non-simultaneously. Shock analysis is also carried out for X, Y and Z axis non simultaneously

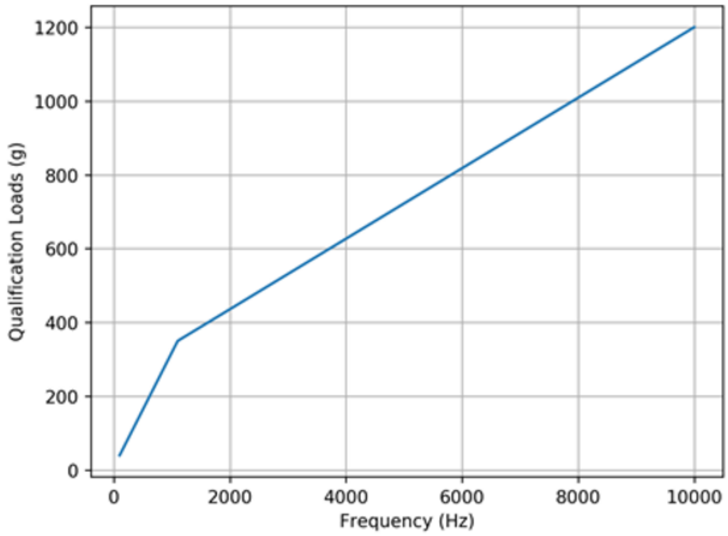

Figure 6: Shock response loads

As discussed earlier, the requirements involved the following:

1. The goal is to ensure that the MOS (margin of safety) values exceed 1.
2. Peak deformations for all loading conditions should be below 1mm.

The peak stresses in X, Y and Z directions are below the Yield stresses for Al-6061 (Housings) and FR-4 (PCBs). The figures 7 to 9 represent the Von Mises Stresses for X, Y and Z axis loading conditions respectively.

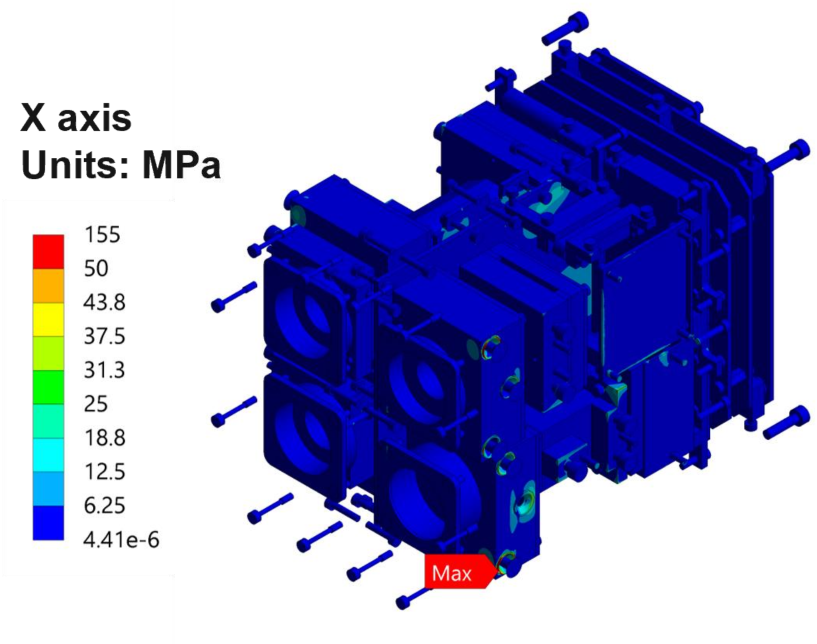

Figure 7: Von Mises Stress – X axis

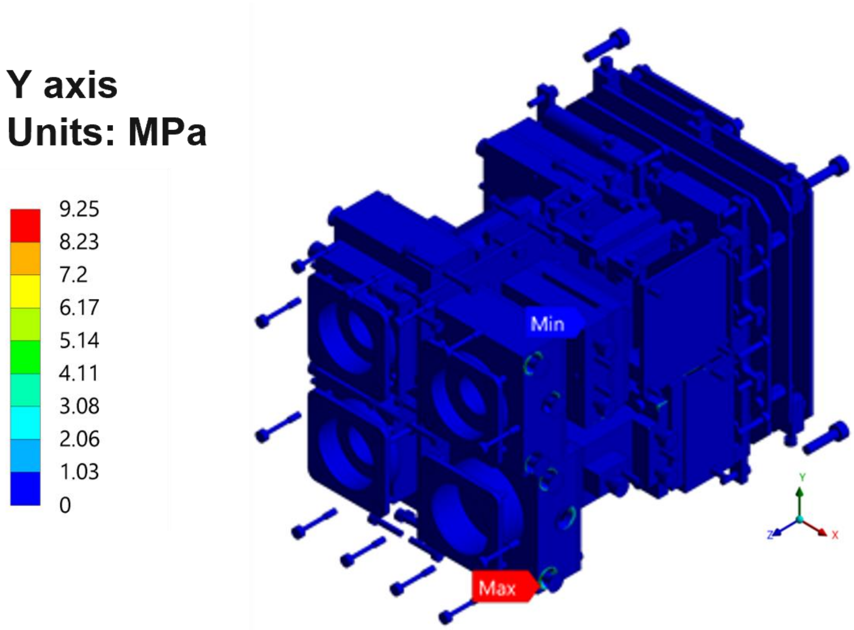

Figure 8: Von Mises Stress – Y axis

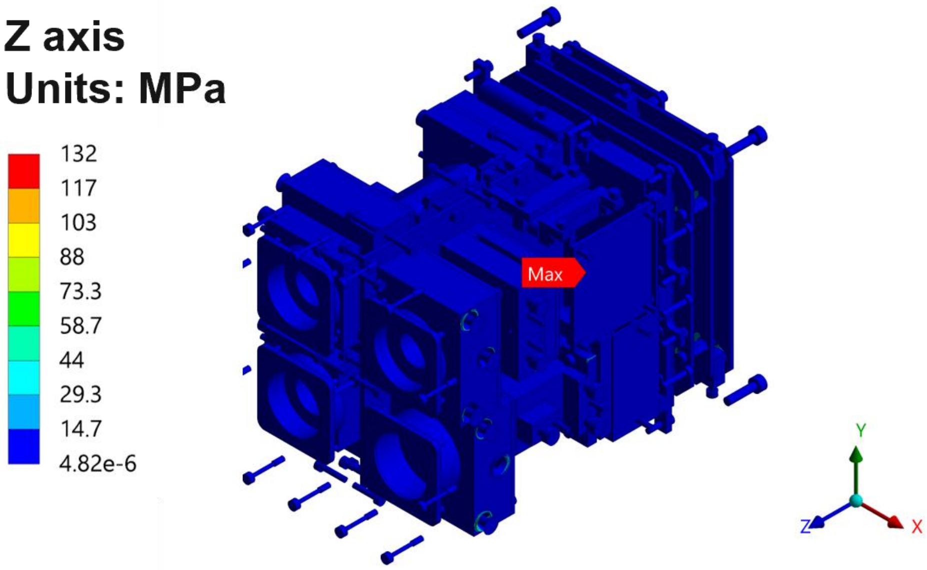

Figure 9: Von Mises Stress – Z axis

A factor of safety (FOS) is assigned to the critical components of ASPECT. The margin of safety can then be calculated as:

Margin of safety = Yield stress / (FOS * Design Yield stress) - 1

- Assumed FOS values:
    1. Housing and Al parts- 1.2
    2. PCB – 1.9
    3. Bolts- 1.6
    4. Lens – 1.4

- MOS Values are above 1 for critical components

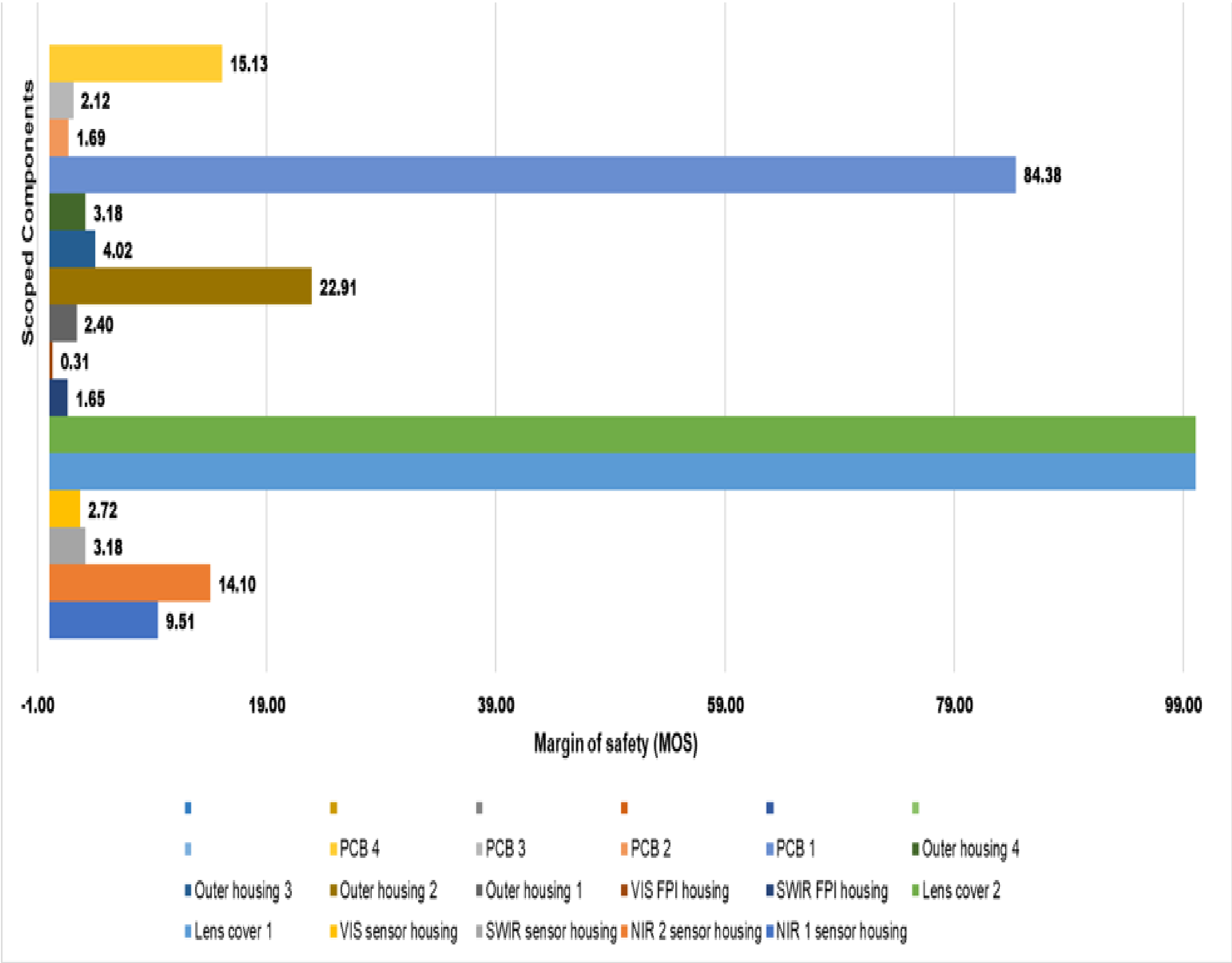

Figure 10: Margin of Safety (MOS)

The peak displacements in X, Y and Z directions are below 1mm and meet the requirements criteria.

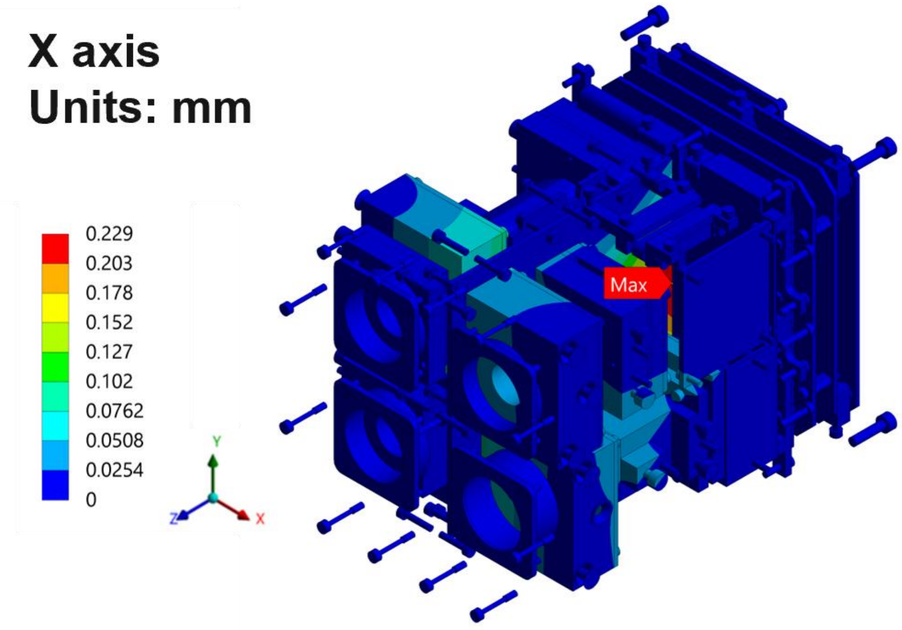

Figure 11: Displacement in X axis

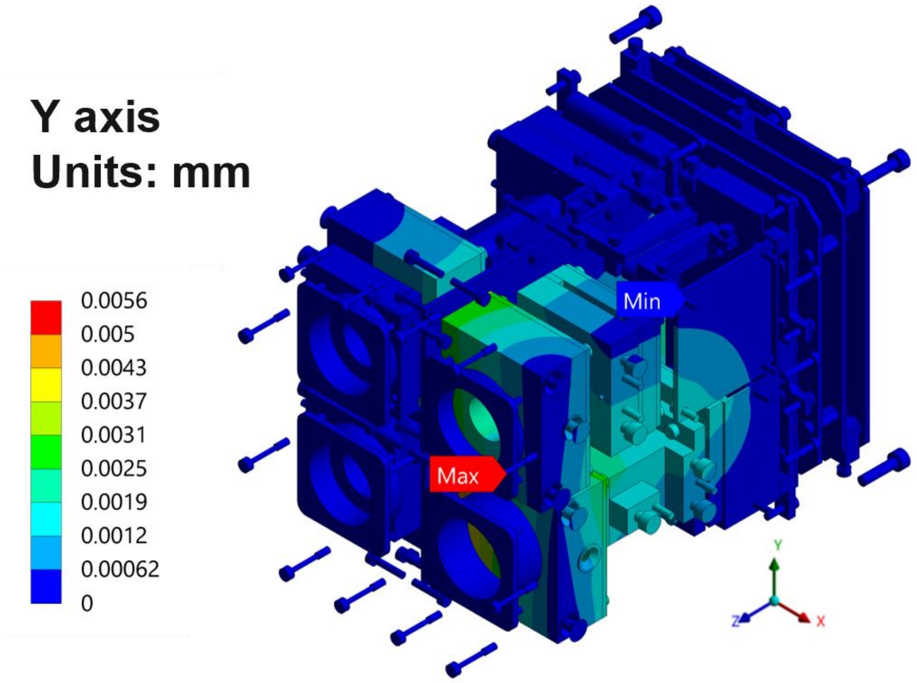

Figure 12: Displacement in Y axis

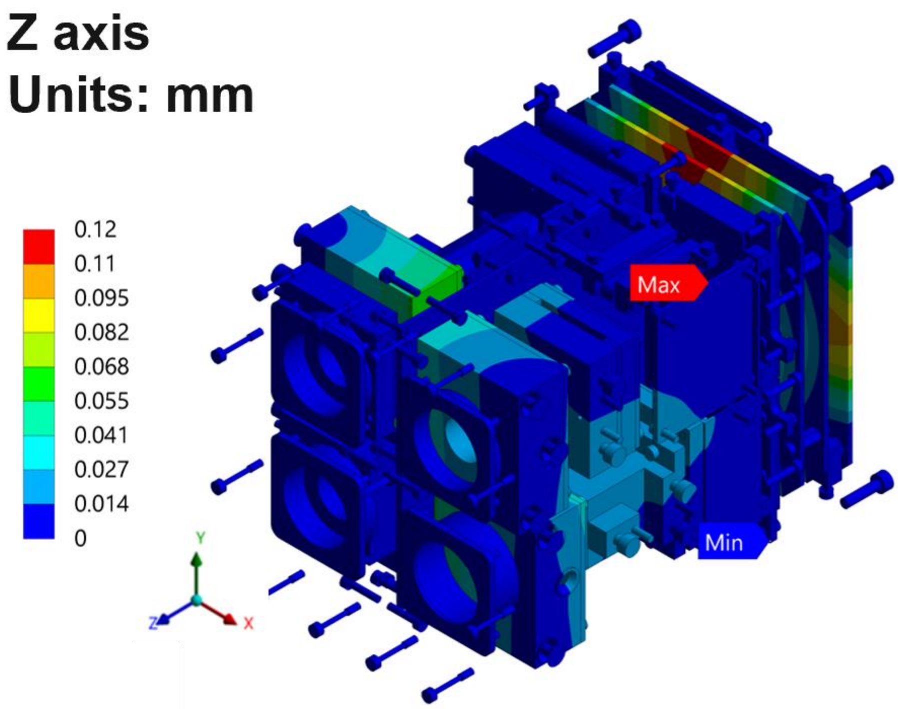

Figure 13: Displacement in Z axis

Design concerns & improvements suggested from FEA studies

Additional support struts can be added at the PCBs to reduce the bending moments.

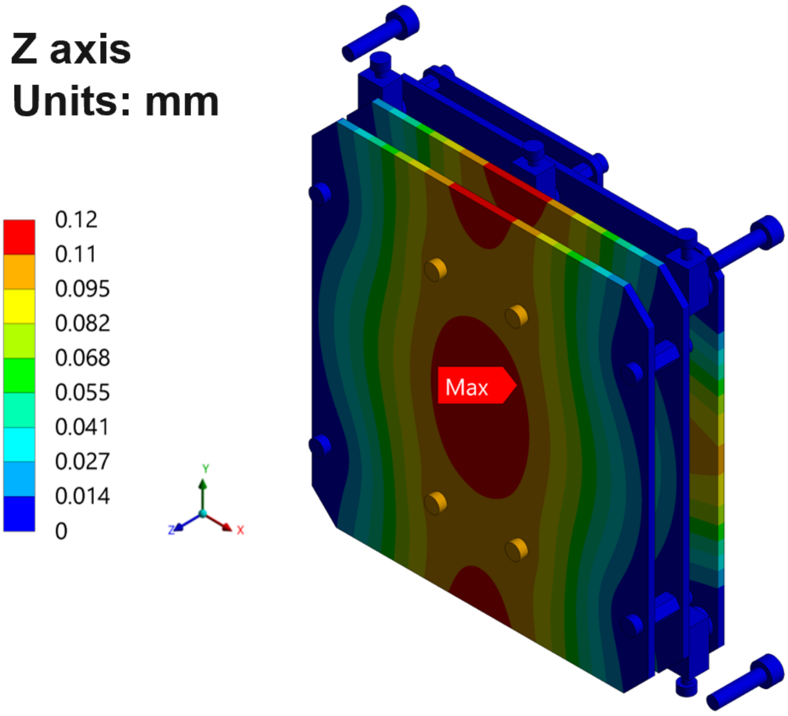

Figure 14: PCB displacements

Lab Vibration Tests

Simulations and durability of optomechanical parts are validated with vibration test machine at the Eurofins facility. The test bench makes use of a large electromagnetic relay that is controlled with programmable signal. This vibrates the payload along each of the X, Y and Z axis individually and accelerometers attached to the payload measure the vibration response.

Low Level Sine Sweep (LLSS) is used to find natural frequencies for each of axis individually. These frequencies can be considered as weak spots of structure and therefore they are used as a base in Random Vibration Test. RVT was carried out in three phases of dampening -6 db, -3 db and 0 db. After random vibration test LLSS tests are repeated for each axis to see if natural frequency has changed.

The shock response test involves dropping a known mass of an object next to the payload which is placed upon a critically damped surface. Few accelerometers are used for collecting the result data. Shock frequency is tuned by placing dampening material at the point of impact. After shock testing LLSS is carried once again. The figure below shows the test setup for the ASPECT FPI payload.

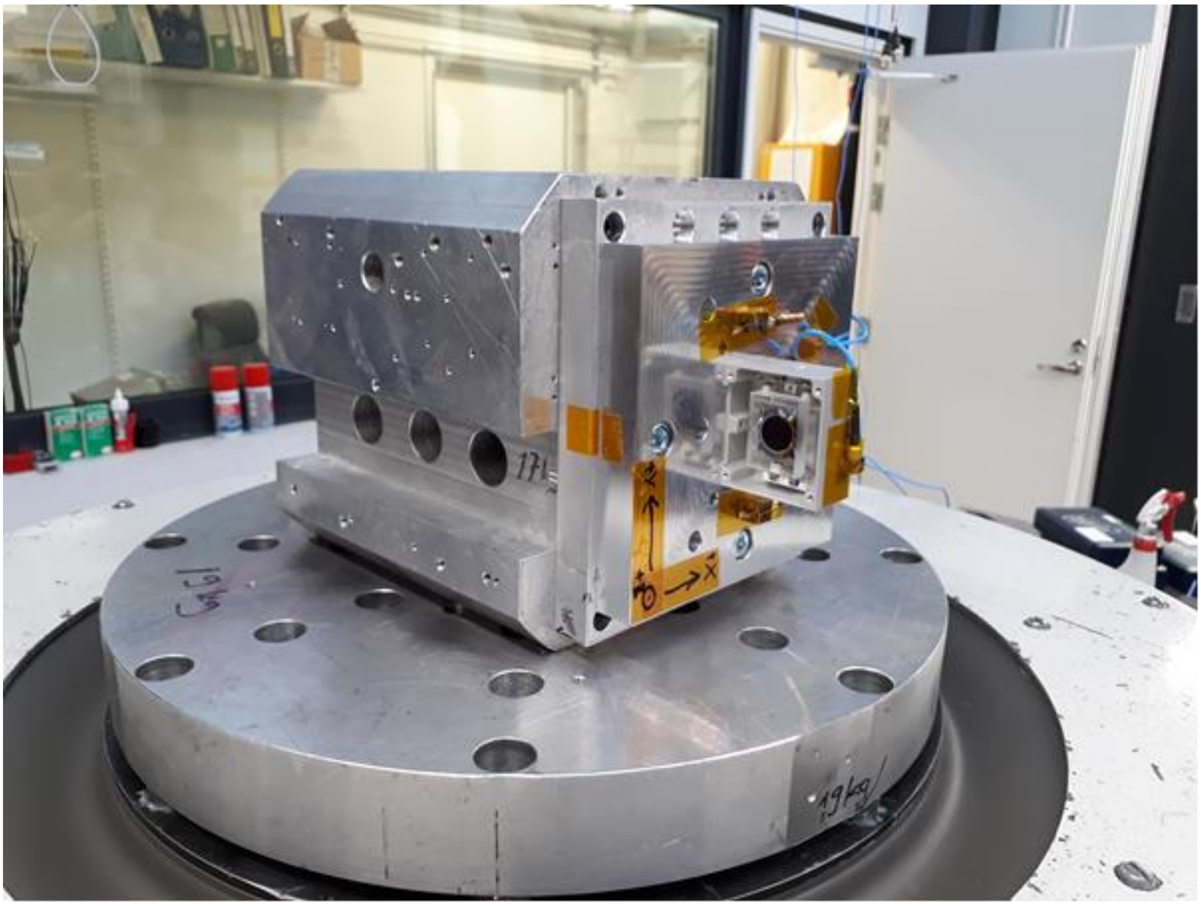

Figure 15: FPI vibration test assembly

Conclusion

The FPIs being the core component for the ASPECT payload meet the structural requirements stated by ESA. This has been validated in both simulations and lab tests. The FPIs can withstand the specified shock response loads in both simulation and lab tests. They also qualify for the random vibration tests.

References

1. The ESA Hera Mission: Detailed Characterization of the DART Impact Outcome and of the Binary Asteroid (65803) Didymos, Michel, Patrick, 7th July 2022.

2. Miniaturized Spectral Imaging Instrumentation for Planetary Exploration, Näsilä, A & Kohout, IEEE Aerospace Conference, 3rd March 2020.

3. The Hera Milani CubeSat Mission, Planetary Defense Conference, F. Topputo and the Milani Team, 26th April 2021.

4. ECSS-E-ST-32-03C – Structural finite element models, 31st July 2008.

5. Hera CubeSats Interface Document, CID) ESA-TECSP-RS-017168, Issue 1 Rev. 4.