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Mechanical verification logic and first test results for the Euclid spacecraft

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Abstract. Euclid is an optical/near-infrared survey mission of the European Space Agency (ESA) to investigate the nature of dark energy, dark matter and gravity by observing the geometry of the Universe and the formation of structures over cosmological timescales.
The Euclid spacecraft mechanical architecture comprises the Payload Module (PLM) and the Service Module (SVM) connected by an interface structure designed to maximize thermal and mechanical decoupling.
This paper shortly illustrates the mechanical system of the spacecraft and the mechanical verification philosophy which is based on the Structural and Thermal Model (STM), built at flight standard for structure and thermal qualification and the Proto Flight Model (PFM), used to complete the qualification programme. It will be submitted to a proto-flight test approach and it will be suitable for launch and flight operations.
Within the overall verification approach crucial mechanical tests have been successfully performed (2018) on the SVM platform and on the sunshield (SSH) subsystem: the SVM platform static test, the SSH structure modal survey test and the SSH sine vibration qualification test. The paper reports the objectives and the main results of these tests.

Keywords: Euclid mission; spacecraft; mechanical verification; mechanical testing; vibration; modal survey test

1. Introduction

Euclid is an optical/near-infrared survey mission (Racca *et al.* 2016) of the European Space Agency (ESA) to investigate the nature of dark energy, dark matter and gravity by observing the geometry of the Universe and the formation of structures over cosmological timescales.

To accomplish the mission, ESA has selected Thales-Alenia Space (TAS Torino, Italy) for the implementation phase of the spacecraft (S/C) and its Service Module (SVM); Airbus Defence and Space (ADS Toulouse, France) for the Payload Module (PLM) and the "Euclid Consortium" as the single team having the scientific responsibility of the mission including the scientific instruments. Concerning the main sub-systems of the spacecraft, the following industries have been selected:

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Airbus Defence and Space (ASE Madrid, Spain) as responsible for the SVM platform structure and the spacecraft thermal control; SpaceTech GmbH (Immenstaad, Germany) as responsible for the overall Sunshield (SSH) which includes the photovoltaic system; RUAG Schweiz AG (Zürich, Switzerland) as responsible for the structure of the SSH.

Euclid spacecraft is equipped with a 1.2 m Korsch telescope designed for a large field of view, feeding two instruments, VIS, a high quality visible imager, and NISP, a near infrared spectro-photometer. The spacecraft launch date is planned in 2022. It will be launched by a Soyuz rocket from ESA's spaceport in Kourou and then travel to the Sun-Earth Lagrangian point 2 for a 6 years mission.

Among the recent space telescopes developed by ESA, the Herschel Space Observatory and the Gaia spacecraft have some significant similarities with Euclid. In fact these spacecraft, in addition to have the general purpose of studying the Universe, they share some orbital parameters such as the Sun-Earth Langrangian Point 2 and relevant environments, and also they have comparable launch mass: Euclid expected launch mass of about 2100 kg is close to the Gaia mass of 2000 kg; Herschel has a higher mass, 3400 kg. Concerning the mechanical systems, the stringent requirements on high thermal and mechanical stability have induced ESA to select the silicon carbide (SiC) technology. In particular the Euclid telescope is "full-SiC", because both mirrors and structure are made of SiC material. Nowadays the Euclid telescope is the largest full-SiC Korsch instrument ever made in the world. More details can be found in (Bougoin and Lavenac 2011) and (Bougoin *et al.* 2018).

Euclid spacecraft successfully passed its critical design review (CDR) in 2018. The successful outcome of this major milestone provided the formal authorization to manufacture the flight hardware and also provided full confidence that the science can be done. The structural-thermal models (STMs) of the spacecraft were manufactured prior to CDR and the qualification process started.

This paper provides a short overview of the mechanical architecture of the spacecraft and the overall logic of the mechanical systems verification. Furthermore the objectives and the main results of some significant mechanical tests, which have been performed in 2018 as a prerequisite for the mechanical qualification at spacecraft system level, are reported.

2. Spacecraft mechanical architecture

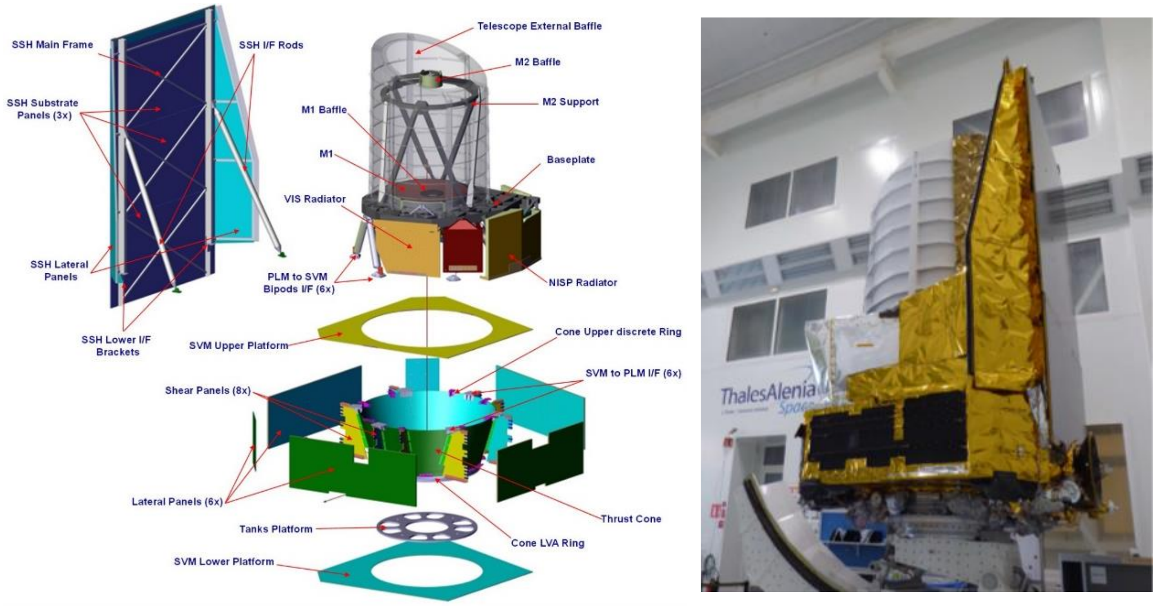
The Euclid spacecraft mechanical architecture (see Fig. 1) comprises the Payload Module and the Service Module connected by an interface (I/F) structure designed to maximize thermal and mechanical decoupling. This interface consists of a quasi-isostatic mounting composed by three equally spaced bipods.

The Service Module comprises the spacecraft subsystems supporting the payload operation, hosts the payload warm electronics, and provides structural interfaces to the PLM, the SSH, and the launch vehicle. The SVM is composed by:

• a platform, that is an irregular hexagonal-base prism built around a central cone that provides the interfaces with the launcher and with the PLM and encloses the propellant tanks;

• the sunshield, shielding the PLM from solar radiation and hosting the photovoltaic assembly supplying electrical power to the spacecraft.

The SVM mechanical architecture is inherited from the Herschel satellite design, with a primary structure formed by the central thrust cone and eight shear panels. The central thrust



(a) (b)

Fig. 1 (a) Euclid Mechanical Architecture 1 and (b) Euclid STM spacecraft

structure is connected to six lateral panels by means of the eight shear panels. Upper and lower floors, connected to the shear panels as well, close the volume between the lateral panels and the central cone. The internal part of the cone accommodates the four cold gas tanks of the Micro-Propulsion System and the hydrazine tank of the Reaction Control System. The lateral panels of the platform accommodate the subsystems equipment, grouped by function, and host the instruments warm electronics, which functionally belong to the PLM.

The SVM platform supports the sunshield/solar array subsystem.

The sunshield is mounted on the SVM platform by means of two rods interfacing with the top of platform itself and two brackets fixing the bottom of the sunshield structure. The SSH structure consists mainly of CFRP skinned aluminium honeycomb sandwich panels and CFRP filament winding profiles. The structure consists of the following main elements: support structure, (including the frame, wings and the optical baffle), substrate panels, radiation shields and main struts. The frame consists of the following elements: poles, stiffeners, main brackets, mechanical ground support equipment interfaces, substrate panel cleats and sensor brackets.

The Euclid PLM mainly consists of the three-mirror Korsch type telescope and of two instruments, VIS and NISP, developed by the Euclid Consortium and delivered by ESA to the industrial Prime Contractor as “customer furnished items”. The PLM provides mechanical and thermal interfaces, i.e., radiating areas and heating lines, to the instruments.

The PLM mechanical and thermal architectures aim at allowing independent development of the telescope and of the NISP and VIS instruments. It is organised around the silicon carbide baseplate which supports on one side the telescope primary (M1) and secondary (M2) mirrors, and on other side the remaining optical elements and the two scientific instruments.

A more detailed description of the mechanical architecture and design of the Euclid spacecraft is reported in (Calvi and Bastia 2016).

3. Mechanical verification logic and plan

The mechanical load specifications for design and testing have been established starting from (Soyuz User's Manual 2012), where the fundamental requirements and mechanical environments applicable to the spacecraft are reported, and then by a classical flow-down of requirements at lower levels of assembly. In particular the load level specifications have been produced by means of mechanical analyses at S/C system level. More details can be found in (Calvi 2016) and (Bellini and Calvi 2014).

The spacecraft thermo-mechanical verification philosophy is based on the following models:

• The Structural and Thermal Model, built at flight standard, for structure and thermal control system qualification. The S/C STM includes the SVM STM and the PLM STM and will be equipped with dummies or STMs of the equipment.

• The Proto Flight Model, used to complete the qualification programme. It will be submitted to a proto-flight test approach and it will be suitable for launch and flight operations.

The decision to manufacture and testing the STMs of the spacecraft was taken by ESA at the earliest phases of the programme. Despite this decision would have certainly involved more complex activities and would have required additional effort and resources, the STMs and relevant tests were included in the verification programme mainly to reduce the development risks associated with the challenging design of the Euclid spacecraft. In particular the high performances required to the telescope and the high accuracy of the scientific data to be provided by the instruments, had imposed stringent requirements to the thermo-mechanical system in terms of:

• Thermal and thermo-elastic stability

• Mass constraints (the total launch mass of the spacecraft including the launch vehicle adapter, the instruments and system margins could not exceed 2160 kg)

• Structural stiffness and strength, to cope with the specified mechanical environments (Soyuz User's Manual, 2012)

For the design, verification and testing aspects of the Euclid spacecraft the documents published by the European Cooperation for Space Standardization (ECSS) have been applied or considered, in particular (ECSS-E-ST-10-02C, 2009), (ECSS-E-ST-10-03C, 2012), ECSS-E-ST-32C, 2008 and (ECSS-E-ST-32-10C, 2009). The overall approach concerning the main mechanical tests for the mechanical verification is depicted in Fig. 2. The Table 1 reports the relevant test matrix including the loads levels and durations. It should be noted that according to (ECSS-E-ST-10-03C, 2012) the general approach for proto-flight tests is to select test levels as per qualification levels and test durations as per acceptance durations.

The STM of the SVM platform (for simplicity indicated as "SVM" in the figure) starts with a static test of the structure. The SSH starts its qualification program by a sine vibration tests performed after a modal survey test of the structure which had to provide early confidence on the stiffness, overall adequacy of the structure and data for the validation of the relevant FE model. The PLM STM performs a rather complete qualification by both sine vibration and acoustic noise tests. Since the PLM STM will become a "flight spare", the PLM vibration tests were initially planned to be performed at acceptance duration. This to preserve the lifetime of the structure. However at the time of the PLM STM mechanical test campaign (April 2019), the evaluation of the PLM structural lifetime was reassessed and the test duration revised in line with a full qualification approach.

After assembling the STMs of SVM Platform, SSH and PLM, the S/C STM undertakes a

Table 1 EUCLID Spacecraft Test Matrix (excerpt: mechanical loads tests; X = to be performed)

Tests	STM				(P)FM			
	SVM	SSH	PLM	S/C	SVM	SSH	PLM	S/C
Static Load	QL	--	--	--	--	--	--	--
Sine Vibration (including Modal Survey & Sine Burst for PLM STM)	--	QL/QD	QL/QD	QL/QD	--	--	QL/AD	AL/AD
Acoustic Noise	--	--	QL/AD	QL/QD	--	AL/AD	QL/AD	AL/AD
Launcher (LVA) Fit-check and Separation Shock	--	--	--	X	--	--	--	X

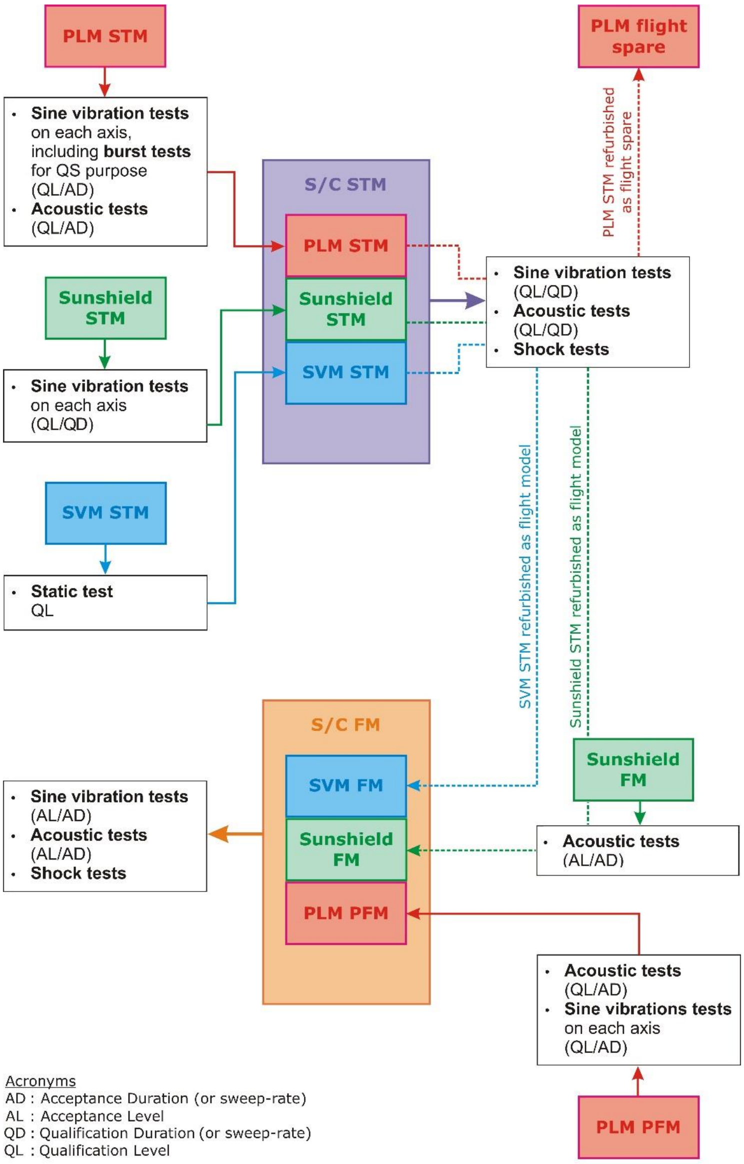


Fig. 2 Mechanical tests - baseline at spacecraft CDR

complete qualification programme which includes sine vibration, acoustic noise and shock (clamp-band release) tests. The levels and durations of the S/C STM tests are, respectively, qualification levels (QL) and qualification duration (QD), to qualify the structure and to cope with the launcher requirements.

For what concerns the verification of mechanical loads, the availability of the STM model allows in particular to:

• Verify the structural strength of primary and secondary structures and to achieve the qualification of the spacecraft structure

• Confirm the structural loads for subsystems and equipment

• Correlate and validate the spacecraft finite element (FE) model by the exploitation of the test data, e.g., the data provided by the experimental modal analysis performed as part of the sine vibration test campaign

• Verify the interface to launcher adapter

• Verify the mechanical interface between the PLM and the SVM

Following the S/C STM qualification, the PLM STM is refurbished as “flight spare”, the STM SVM Platform is refurbished as flight model (FM) and similarly the sunshield STM is refurbished as FM.

The SSH FM starts its acceptance programme by a dedicated acoustic noise test, while the PLM Proto-flight model (PFM) undertakes a quite complete proto-flight test campaign which involves sine vibration and acoustic tests.

After assembling the (P)FMs of SVM Platform, SSH and PLM, the S/C (P)FM undertakes a complete acceptance programme which includes sine vibration, acoustic noise and shock (clamp-band release) tests.

It should be noted that according to (Soyuz User’s Manual 2012) the flight model of the spacecraft should undertake a proto-flight test programme, nevertheless due to the very extensive testing activities performed by the Euclid STM spacecraft, a pre-agreement is already in place between ESA and the Launcher Authority to perform a pure acceptance test programme, having the aim of reducing the risk of overtesting and over-verifying the flight hardware.

4. Service module platform static loads test

4.1 Objectives and test cases

The static test of the SVM platform (see Fig. 3) has been performed to:

• Demonstrate that the structure is able to carry the qualification loads, as per applicable specifications, without failure or degradation

• Verify the structural stiffness

• Verify the structure mathematical model

On the basis of the objectives to be reached, the overall test campaign included the following tests:

• Stiffness test, to verify the global stiffness. Two test cases have been performed:

  - o Axial (R1)
  - o Lateral (R2)

• Global strength test, to verify the load carrying capability (loads at qualification level). The following test cases have been performed:

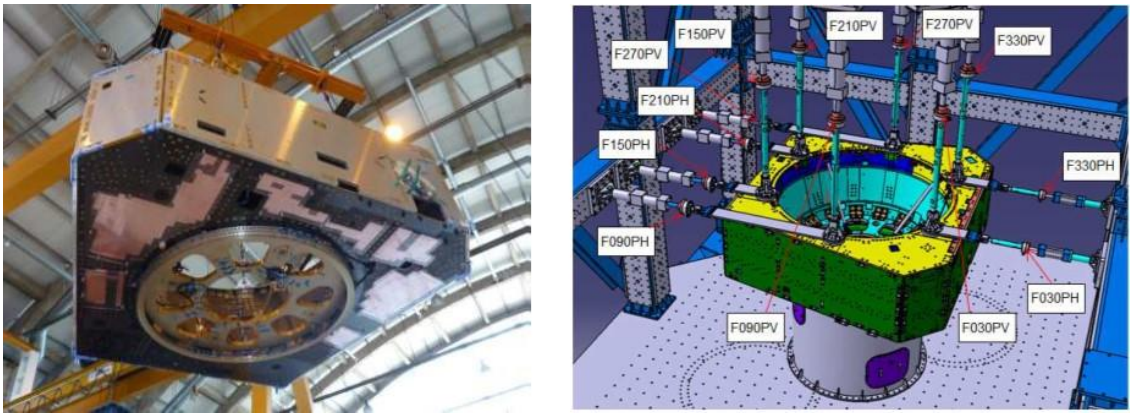


Fig. 3 (a) Euclid SVM general overview (bottom view) and (b) Setup for stiffness and strength global cases

Fig. 4 Test setup for S3 load case (Tank I/F)

- Maximum Compression Flux (S11)
- Maximum Axial Resultant (S12)
- Maximum Tension Flux (S2)

• Local strength test, to verify the load carrying capability of the SVM platform main structural interfaces (loads at qualification level). The following test cases have been performed:

- Tank I/F (S3)
- SSH Main I/F (S4)
- SSH Strut I/F (S5)
- PLM I/F Tension (S6)
- PLM I/F Compression (S13)

In order to represent the actual item under test and the relevant test setup, a specific and detailed FE model of the SVM platform was developed. Specific FE models of the test brackets were also generated with the objective to improve the simulation of the load application.

It should be noted that as part of the test campaign a hoisting test case has also been performed.

The objective of this test was to qualify the SVM Platform lifting points to sustain the overall weight of the spacecraft including the applicable qualification margin. In order to achieve this objective some ballast masses were used and a lifting of the structure was carry out.

4.2 Test setup

The structure was clamped at the Launch Vehicle Adapter (LVA) Ring I/F except than for the hoisting test case. Fig. 3(a) reports a general overview of the test specimen and Fig. 3(b) shows the test configuration (global cases), including the test jigs and the actuators. The loads were applied at the main mechanical interfaces and measured by force sensors connected to the actuators. The displacements were measured by displacement transducers. Also, strain gauges were mounted at critical locations of the structure for deformation measurements and stress recovery. A total of 24 displacement transducers and 418 strain gauge measurement channels have been used in the static test campaign.

Fig. 4 illustrates the setup for the local strength test case S3, i.e., for the tank I/F.

4.3 Test results and conclusions

All planned test cases have been performed and the structure has withstood the defined qualification loads without failure or degradation. The main conclusions can be summarized as follows.

The structure of the SVM platform has been qualified under maximum tension flux and maximum compression flux (ECSS-E-HB-32-26A 2013) at the LVA Ring I/F. The flux values of 44.56 N/mm and -57.25 N/mm, for tension and compression respectively, have been reached.

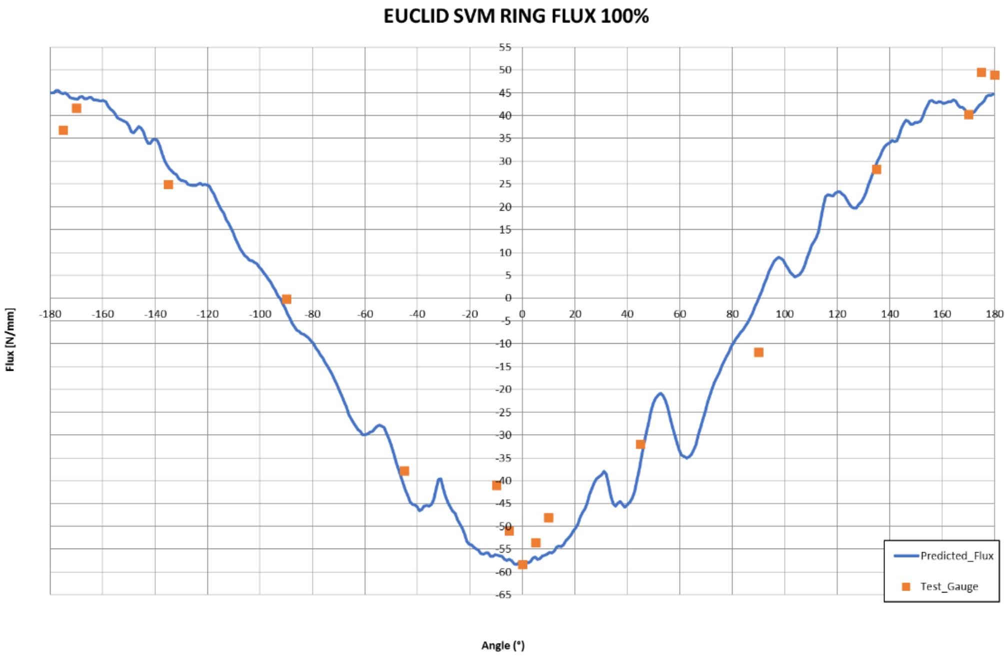


Fig. 5 Flux at LVA ring I/F for test S11, maximum compression flux

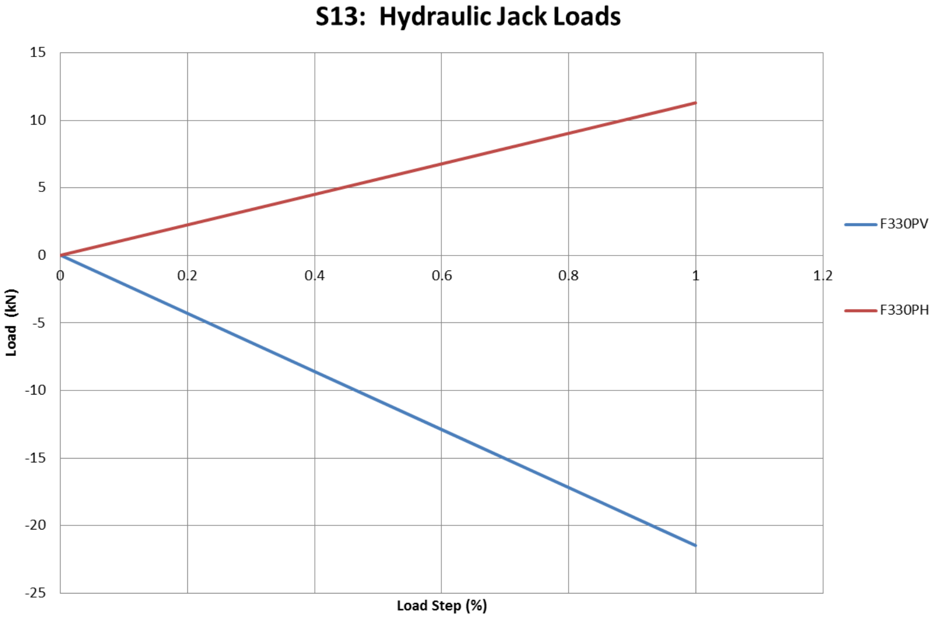


Fig. 6 Hydraulic jack loads for S13 test case (PLM I/F compression)

Fig. 5 shows the fluxes (test and prediction) for the test load cases S11, maximum compression flux at LVA Ring. The test flux is the average between internal and external fluxes at LVA Ring, calculated using the strain gauges readings. The prediction flux is calculated by FE analysis. It should be noted that the flux values from strain gauges and by FE analysis are similar and the qualification maximum compression flux is achieved.

The structure has been qualified under maximum axial resultant (-136 kN), maximum lateral resultant (49 kN) and maximum bending moment resultant (56 kNm) at the LVA Ring I/F.

The main external I/Fs of the SVM platform structure have also been qualified, that is:

• PLM I/F (2 load cases, S6 tension, and S13 compression, having vertical and horizontal load components; S6: F_V = 25.200 kN and F_H = -14.490 kN; S13: F_V = -21.500 kN and F_H = 11.300 kN). Fig. 6 reports the hydraulic jack loads for S13 test case.

• SSH Main I/F (qualification load = 15.780 kN)

• SSH Strut I/F (qualification load = -9.490 kN)

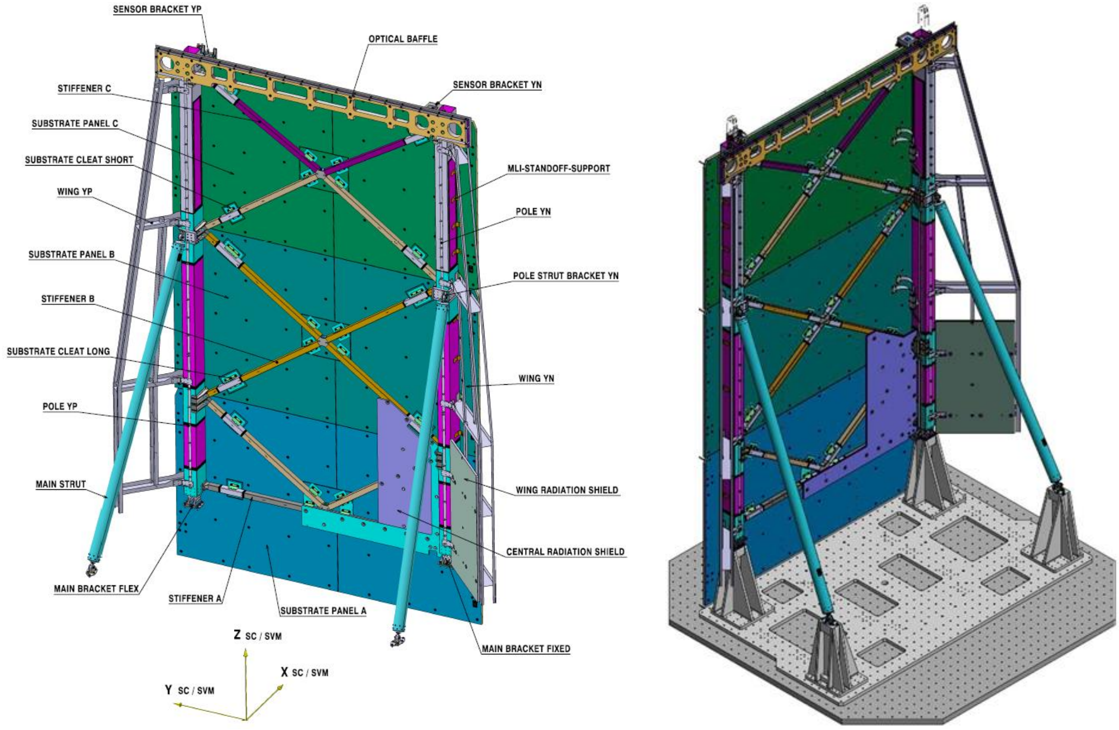
• Hydrazine Tank I/F (qualification load = -20.575 kN)

As a final remark, the results of the stiffness tests have shown a good agreement with the analytical predictions, however some refinements of the FE model were needed. A number of sensitivity analyses have been performed in order to improve the correlation of the FE model with respect to both stiffness and strength test results and some changes in the SVM platform FE model have been implemented.

5. Sunshield structure modal survey test

5.1 Test objectives

The modal survey test of the sunshield structure was performed with the objective to obtain the



(a) (b)

Fig. 7 (a) Sunshield Reference Frame and structural design overview and (b) SSH structure on the Test Adapter

modal properties, i.e., natural frequencies, mode shapes and modal damping, of the structure under test. These values were needed to perform a correlation with the modal analysis results provided by the existing FE model with the aim to validate it. The frequency range analysed was from 15 Hz to 120 Hz.

It should be noted that a valid FE model was needed to better define the notching philosophy for the sine vibration qualification test at SSH level. The selection of the target modes to be identified and correlated was also based on this target.

5.2 Test setup and procedure

The SSH structure, having a mass of about 92 kg, was installed on the SSH Multi Test Adapter (MTA). The MTA has been loaded by a mass of about 1200 kg in order to simulate a rigid fixation of the MTA to ground. In practice the test adapter was standing on the cleanroom floor and was not fixed to it.

The test item was attached via the two main brackets and the two strut brackets to the MTA. The measurement plan included 44 three-axial and 4 uniaxial accelerometers, applied over the entire structure.

The SSH structure has been excited by sine sweeps generated by an electrodynamic shaker positioned at both main struts to the pole interfaces (see Fig. 8). The shaker excitation points have

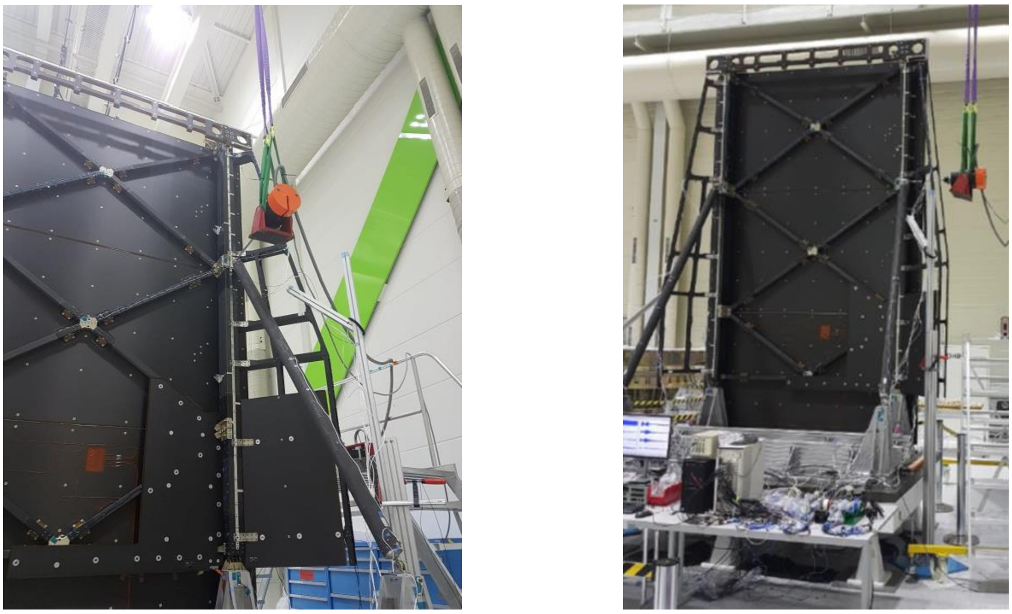


Fig. 8 SSH structure: overall test setup (rear side) and shaker excitation points for modal survey test

been selected on the basis of different criteria such as adequacy for target modes identification and accessibility. The forces have been applied in X and Y direction separately and not simultaneously. The system was firmly connected to the test structure via a coupling rod and the excitation force was measured by a force gauge located between the shaker and the test article.

All accelerometers had been calibrated prior to the test. Their sensitivities were used for each measurement, to get the correct physical values of the accelerations. Sensor locations were determined in order to achieve "optimal" mode shapes identification and discrimination. In practice this was obtained by evaluating the off-diagonal values of the auto-MAC (Modal Assurance Criteria) of the predicted modes. Overall the instrumentation included 140 "channels". No strain gauges have been used.

It should be noted that the selection of the sensor locations was also driven by the needs of the SSH sine vibration qualification test (base-shake test), as for example accelerometers to be used for notching purposes (ECSS-HB-32-26A 2013). Indeed most of the locations/accelerometers have also been used during the test on the shaker.

Summarizing, the accelerometer locations have been selected on the basis of the following rationale:

• measurements at main interfaces to control the main load path

• measurements on the framework key locations to monitor the overall vibration and to adequately distinguish the mode shapes (auto-MAC criterion)

• measurements on the three solar array support panels, to get information on the panel vibration modes and, in view of the forthcoming SSH test at qualification level, to limit the loads in the panel inserts.

5.3 Test results, modal correlation and conclusions

The test results have been post-processed by calculating the transfer functions between the

Table 2 Test-analysis MAC matrix. Frequency range from 25 Hz to53 Hz (note: test modes on the columns)

		Test Mode n°									
		3	4	5	6	7	8	9	10	11	12
Mode n°	Frequency [Hz]	25.07	30.46	32.01	36.13	39.85	45.13	46.45	49.37	51.27	52.83
2	25.13	**0.98**	0.00	0.01	0.00	0.00	0.01	0.04	0.00	0.02	0.01
3	30.18	0.02	**0.92**	0.00	0.01	0.02	0.01	0.01	0.00	0.01	0.01
4	33.32	0.00	0.01	**0.84**	0.17	0.00	0.00	0.00	0.00	0.01	0.00
5	37.31	0.00	0.00	0.00	**0.81**	0.11	0.01	0.01	0.00	0.01	0.00
6	38.06	0.00	0.00	0.05	0.03	**0.53**	0.00	0.00	0.00	0.00	0.02
7	41.94	0.04	0.00	0.01	0.00	0.00	**0.77**	0.21	0.01	0.00	0.01
8	42.68	0.04	0.00	0.01	0.02	0.01	0.00	**0.80**	0.00	0.00	0.04
9	48.18	0.04	0.01	0.00	0.01	0.01	0.02	0.10	0.10	**0.71**	0.00
10	48.55	0.02	0.00	0.00	0.07	0.00	0.01	0.00	0.00	0.28	0.09
11	50.84	0.00	0.00	0.00	0.00	0.01	0.00	0.03	**0.91**	0.07	0.01
12	52.82	0.00	0.02	0.00	0.00	0.00	0.07	0.01	0.00	0.05	**0.56**
13	52.92	0.00	0.03	0.00	0.00	0.00	0.04	0.01	0.00	0.06	**0.68**

Table 3 FEM/modal survey test natural frequency deviations; range 25-53 Hz

Test results		Correlated FEM		Delta frequency [%]	Mode description
Mode n°	Frequency [Hz]	Mode n°	Frequency [Hz]		
3	25.07	2	25.13	0.2	1st global mode
4	30.46	3	30.18	-0.9	2nd global mode
5	32.01	4	33.32	4.1	Bottom panel (bending mode)
6	36.13	5	37.31	3.3	Bottom/middle panels (bending mode)
7	39.85	6	38.06	-4.5	Minus Y (MY) wing
8	45.13	7	41.94	-7.1	Baffle
9	46.45	8	42.68	-8.1	Baffle
10	49.37	11	50.84	3.0	Bottom panel (bending mode)
11	51.27	9	48.18	-6.0	Bottom panel (bending mode)
12	52.83	13	52.92	0.2	Middle panel (bending mode)

measured accelerations and the excitation force, which was measured via load cell directly at the driving point. The modes have been initially located in the frequency domain by using mode indicator functions and then the modal identification has been performed with the phase separation method. A multi-degrees-of-freedom frequency domain curve fitting algorithm has been used for the evaluation of the modal parameters, i.e., natural frequencies, mode shapes and modal damping. The technique consisted of processing multiple response functions from a single reference location to obtain global least squares estimates of the modal properties. 33 modes have been identified up to 120 Hz.

Tables 2 and 3 summarize the main results of the modal survey test and subsequent correlation with the FE analysis results. In particular Table 2 reports the MAC matrix between the results of the FE modal analysis (after the correlation activity) and the modal survey test results for the frequency range 25-53 Hz. In the table the first column and last row both report the mode sequential number and the frequency value in Hertz. The columns refer to the test modes, while the rows to the analytical ones (note: the first two test modes are modes of the support table and not related to the test item).

The test modes number 3, 4, 5 and 6 correlate quite well since the MAC values are in the range 0.81-0.98. The MAC value for the 7th mode is only 0.53 however the visualization of the relevant mode shapes indicates that the mode of the "minus Y" (MY) wing is well identified. The 8th and 9th test modes correlate with MAC values in the range 0.77-0.80. Similarly the test modes 10, 11 and 12 (bending modes of the substrate panels) correlate with MAC values in the range 0.68-0.91.

The natural frequency deviations, between the values calculated by the FE analysis and the modal survey test results, are reported in Table 3 (frequency range 25-53 Hz).

In the frequency range 56-76 Hz the correlation of the bending modes is less accurate. Since the coupling (in and out of phases) between the panel modes is rather different, the MAC values are low, in the range 0.33-0.63. On the other hand the test modes are identifiable in the FEM and the dynamic behaviour of the SSH structure was considered sufficiently well characterized in the frequency range of interest (up to100 Hz), despite some minor discrepancies with respect to the correlation goals as reported in (ECSS-E-ST-32-11C 2008).

On the whole the modal survey test of the SSH has been considered successful and the goal of the correlation was substantially reached. The correlated model of the structure allowed the re-analysis of the SSH sine vibration test predictions and more accurate evaluations of the necessary notching for the subsequent base-shake qualification test.

6. Sunshield sine vibration test

6.1 Test objectives

The SSH vibration test campaign had the following objectives:

• To qualify the SSH structure with respect to the sine vibration environment. This qualification had to be reached by sinusoidal vibrations ("sine sweep") applied sequentially at the base of test item along the three reference axes.

• To qualify the strength of the SSH with respect to the specified "quasi static loads" (QSL), (ECSS-E-HB-32-26A 2013). This qualification had to be reached by sine-burst test (also called "quasi static load test") in case the QSL could not be reached during the sine sweep excitation.

• To verify the stiffness requirements of the overall SSH which are specified in terms of fundamental natural frequencies

6.2 Test setup and notching approach

The test article, having a mass of about 120 kg, was connected to the shaker through the vibration test adapter, MTA (see Fig. 9). The measurement locations were a subset of the ones used

Fig. 9 SSH on the shaker: (a) excitation in X direction and (b) in Z direction

for the SSH structure modal survey test. In total 125 channels/accelerometers were available.

A notching approach (ECSS-E-HB-32-26A 2013) was established and agreed in order to avoid possible overtesting of the structure. Threshold values in terms of test item I/F forces and accelerations have been considered during the design phases and applied during the test to activate both “manual” and automatic notches with respect to the specified sine vibration qualification levels (see Figs. 10 and 11). The implemented logic and procedure had to guarantee sufficient excitation for the qualification of the structure without jeopardising its integrity. For this reason it has been part of the procedure to ensure that positive margins of safety were estimated during all phases of the test.

For the primary notching the QSL values have been used as criterion to limit the forces at shaker interface. In practice, during the test, the target was to avoid any exceedance of the interface force values with respect to the design loads (ECSS-E-ST-32-10C 2009). The forces have been estimated by a “test-analysis hybrid evaluation”, i.e., by the triple product of the rigid body vectors, the FE model condensed mass matrix at the measured degrees of freedom and the measured accelerations.

The secondary notching was performed to avoid any structural damage to the SSH. In particular it was mainly applied to protect the inserts in the substrate panels. For this reason the sine input profiles have been limited such that during the test the margins of safety of the inserts at the interface between the substrate panels and the cleats remained greater than 0.10. In practice this was implemented and obtained by limiting the accelerations of the panels.

Of course a crucial aspect of the proposed notched levels, especially concerning the secondary notching approach and values, is that the applied input levels have to be accepted by the customer (ECSS-E-HB-32-26A 2013).

6.3 Test results and conclusions

The sine burst tests were performed to verify the ability of the SSH to withstand the quasi static

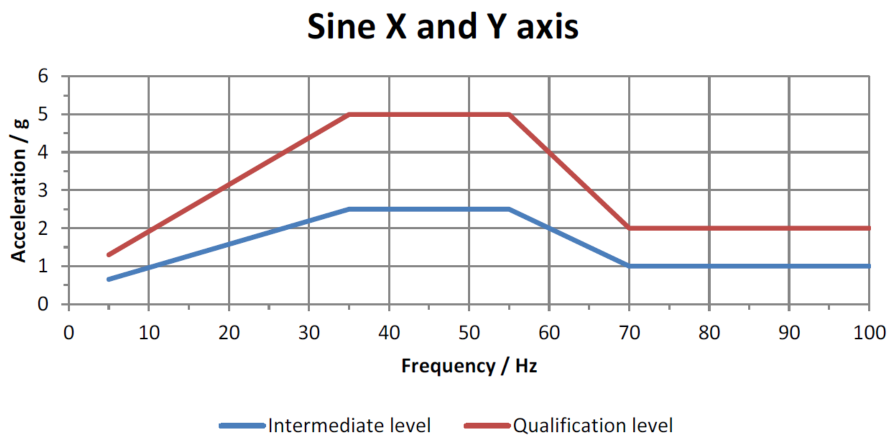


Fig. 10 SSH Sine test levels in lateral directions

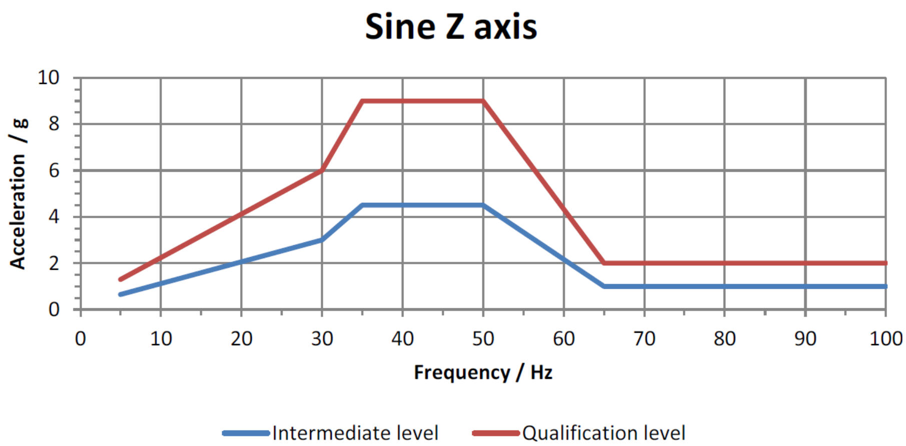


Fig. 11 SSH Sine test levels in longitudinal direction

Z-Direction

Frequency in Hz	Load in g
14.75	0.5
16 - 16.125	11 *)
17.375	0.5
Sweep Rate 0.4 Hz/sec	

Duration: 6.563 Sec

*) max shaker capability

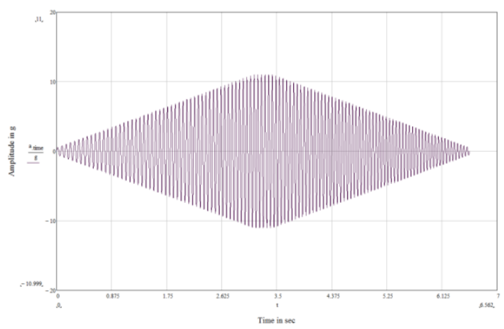


Fig. 12 Quasi-static test in Z direction (theoretical input in the time domain)

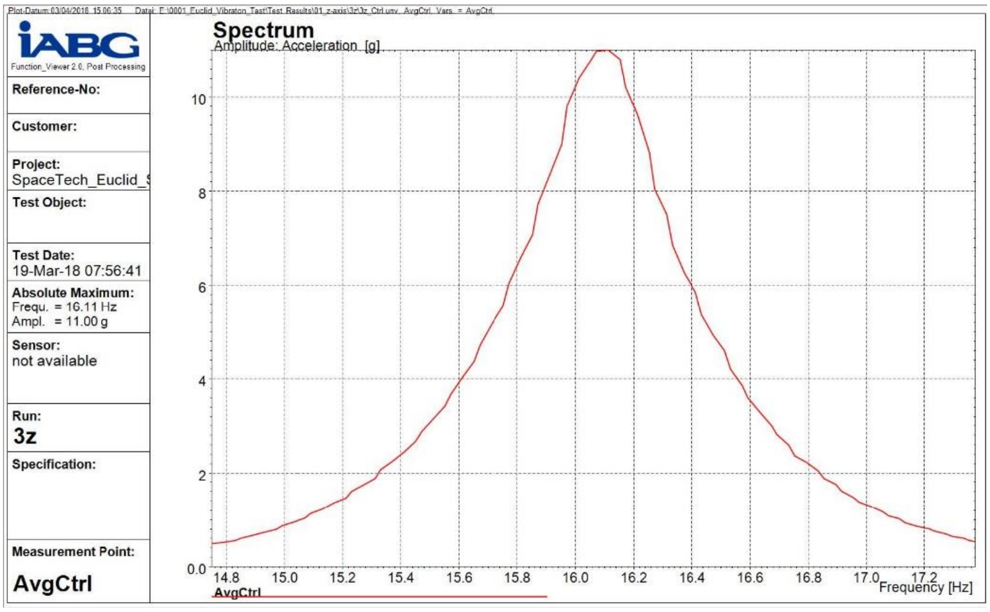


Fig. 13 Quasi-Static Test in Z direction: average input

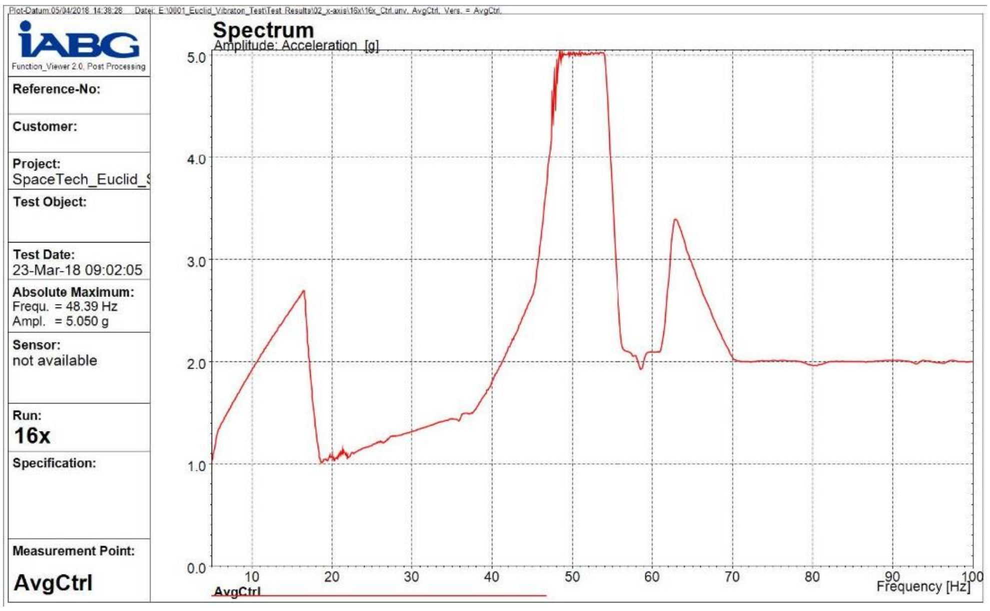


Fig. 14 Quasi-Static Test in Z direction: average input

loads and the maximum interface loads to the S/C. The target accelerations at the centre of gravity of the test item were achieved, specifically:

- 10 g in X and Y directions (lateral axes)
- 11 g in Z direction (longitudinal axis). This value was limited by the shaker capability

The sine burst tests were performed in line with the applicable procedure. For example, in Z direction the SSH was loaded by means of a narrow band sine sweep around 16 Hz as per the input profiles reported in Figs. 12 and 13. It can be noted that the input reached 11 g, however due to a small dynamic amplification, the structure could reach an equivalent load at the centre of gravity of about 11.8 g. This was estimated by means of the interface forces between the test article and the shaker.

The SSH sine vibration qualification runs involved a rather complex evaluation of the notched input profiles. For example, Fig. 14 reports the sine test input which was applied in X direction. It should be noted that the test profile, "as applied", is substantially different from the specified sine vibration levels, which resulted to be substantially "notched out". This kind of situations are not unusual. In fact the test specifications of sub-systems and equipment are normally prepared in the early phases of the spacecraft development (e.g., System Requirements Review, SRR) and it is normal practice to generate the test levels by enveloping the results of "coupled loads analysis" which consider higher levels of mechanical assembly, typically at spacecraft level. At the time of the sub-systems qualification, the spacecraft hardware is partially or totally manufactured and more reliable "coupled analyses" are usually available. In this context the notching of the sine vibration levels can be more easily negotiated and agreed among the relevant parties. In the specific case of the SSH sine vibration tests, the notching was agreed mainly on the basis of the results of the sine vibration test predictions at spacecraft level. More information on the logic and criteria usually applied for notching justification can be found in (ECSS-E-HB-32-26A 2013).

On the whole the SSH vibration test campaign was considered successful. In fact all planned test cases were properly performed and the structure withstood the qualification loads without any failure or degradation. However, due to a non-compliance of the first fundamental mode in X direction, detected at about 20.5 Hz versus a required value of 22 Hz, some design changes of the SSH structure have been proposed, agreed and implemented. A "delta-test" in X direction has been then successfully performed.

7. Conclusions

This paper addressed the mechanical system of the Euclid spacecraft and the mechanical verification philosophy which is based on the Structure and Thermal Model (STM), built at flight standard for structural and thermal qualification and the Proto Flight Model (PFM), used to complete the qualification programme. The PFM will be submitted to a proto-flight test approach and it will be suitable for launch and flight operations.

The decision to manufacture and testing the STMs of the spacecraft was taken by ESA at the earliest phases of the programme, mainly to reduce the development risks associated with the challenging design of the Euclid spacecraft. In particular the high performances required to the telescope and the high accuracy of the scientific data to be provided by the instruments, had imposed stringent requirements to the thermo-mechanical system.

The overall verification logic of the mechanical system, as well as the mechanical tests plan, have been illustrated. Within the overall verification approach some crucial mechanical tests have been successfully performed in 2018. In particular this paper reported the objectives and the main results of the:

- SVM platform static load test
- SSH structure modal survey test
- SSH sine vibration qualification test

The above tests have been successful. Following also the successful qualification of the PLM STM in April 2019, the qualification of the spacecraft STM has been completed in October 2019.

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