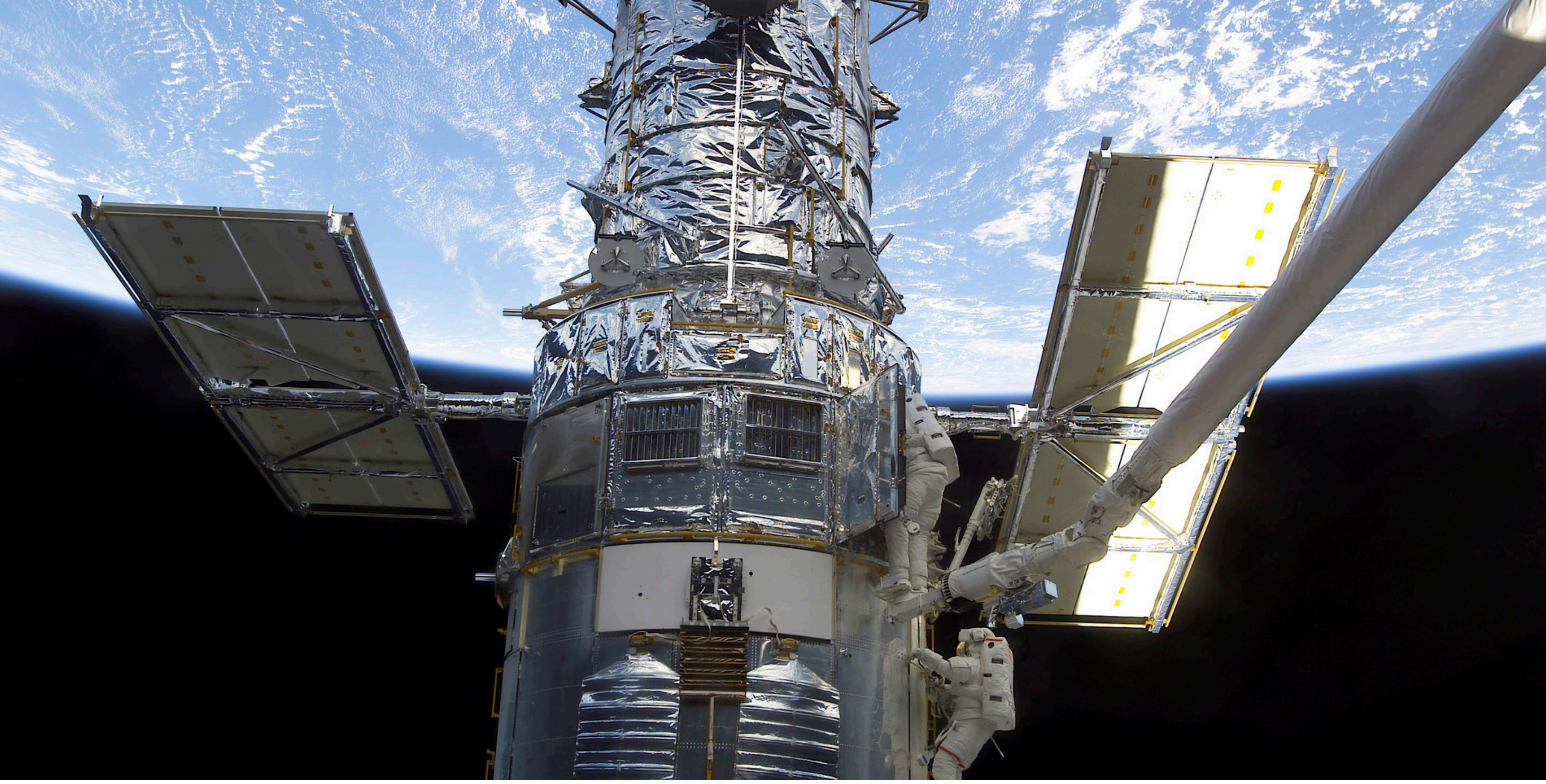

DIGITAL INDUSTRIES SOFTWARE

Space systems mechanical testing

Using Simcenter solutions for safe and efficient space hardware qualification testing

Executive summary

This white paper provides an overview and discussion of different space testing technologies, from mechanical qualification tests to modal survey and micro-vibration testing. Using a comprehensive digital twin to support de-risking and optimizing tests will also be addressed. Simcenter™ software provides a comprehensive solution for safe and efficient qualification testing of space hardware. Simcenter is a part of the Xcelerator™ portfolio, a comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software.

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Abstract

The space industry is experiencing an unprecedented era. The space race is shifting from a race between governments (and their space agencies) to a competition between companies. And business is booming. From CubeSats (of a few centimeters in size) to scientific missions of several meters, satellite manufacturers are competing for telecom constellations, cargo missions and human space missions.

These future space missions create many engineering challenges that will test current engineering development processes. Using traditional development and engineering processes creates significant risk. Organizations that have space ambitions need to be ready to question current development processes and tools to become successful.

In this white paper we focus on qualification and acceptance testing, which is required for all space hardware from component to full-spacecraft level assembly. The equipment should be capable of withstanding the maximum expected launch vehicle ground and flight environments, and this is verified by running mechanical qualification tests as mandated by the launcher vehicle authorities.

Organizations that have space ambitions need to be ready to question current development processes and tools to become successful.

Space industry in transistion

Technological and business model innovations have resulted in private companies competing to make space travel easier and more affordable.

Newcomers have defined new visions and energized the space industry. They have developed cheaper launch capabilities and revived manned space exploration (go back to the moon – go to Mars). Even space tourism with a short stay in orbit in a hotel in "a room with a view" may soon become reality, and furthermore, they are generating an explosion of Earth-based applications that require an orbital system to expand the capabilities of autonomous driving support.

These future space missions create many new engineering challenges for current engineering development processes. Using the traditional development and engineering processes creates a significant risk. The community of space engineers is very conservative when it comes to new test methods, new technology and new products. For example, the current testing standards remain the same as they were 40 years ago!

Organizations with space ambitions need to be ready to question current development processes and tools to become successful. A comprehensive digital twin approach for space hardware development and design verification through qualification testing can help businesses make decisions with full confidence. It allows them to investigate space HW physical behavior using computer-aided engineering (CAE), system and testing technologies.

Why vibration and acoustic testing in the space industry

Prior to launch, space systems must be tested against maximum expected launch vehicle ground and flight environments to verify spacecraft functionality under environmental conditions during launch and in orbit. The actual launch is an extremely harsh environment where the passenger/satellite experiences extreme levels of vibration. After lift-off and before deployment in orbit, there are also a series of violent shocks (stages separations, pyro-bolts and ultimately release to orbit) that place the satellite under significant structural stress. Once in orbit, life is much quieter.

To verify that a satellite can resist the launch, the launcher authorities provide a set of requirements that must be fulfilled and verified through mechanical testing. The flight profile of a launch vehicle and examples of the test requirements of the Soyuz launch vehicle (Soyuz user's manual) are shown in figure 1.

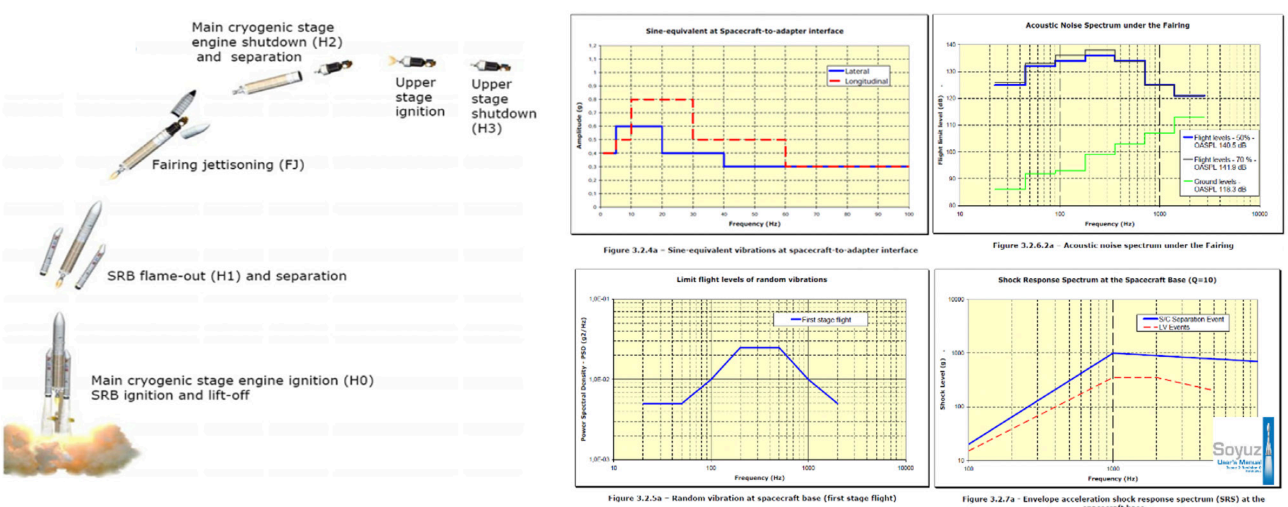


Figure 1. Left: Flight profile of launch vehicle. Right: Soyuz launch vehicle testing requirements.

Space HW mechanical testing covers a wide frequency range involving many different test types, such as sine, random vibration, acoustic and shock, and different test infrastructure (figure 2). Shakers, slip tables, reverberant rooms, speaker setups, drop tables and pyro shock test benches are tested, just to name a few. The nature of those tests is quite different. This presents, on one hand, challenges for the test team as they typically have to master as many tasks as possible. On the other hand, testing agencies are challenged to keep hardware and software investments under control as each setup has a specific set of requirements for data acquisition and analysis.

In addition to mechanical qualification testing, modal survey and micro-vibration testing are also a concern for space missions. Modal surveys help validate satellite or launcher finite element (FE) models for more accurate analysis. Micro-vibrations (caused by flywheels, etc.) can affect the functioning of extremely sensitive equipment such as optical devices or laser instruments. An overview of the different testing involved in space HW development is shown in figure 3. They will be discussed in further detail in upcoming chapters.

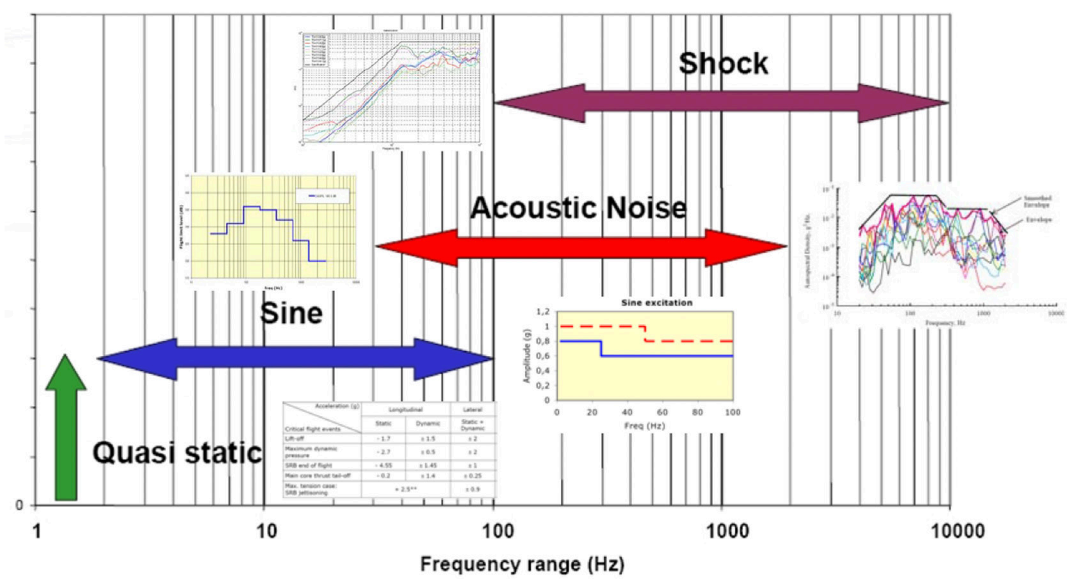


Figure 2. Vibration environments and corresponding frequency ranges.

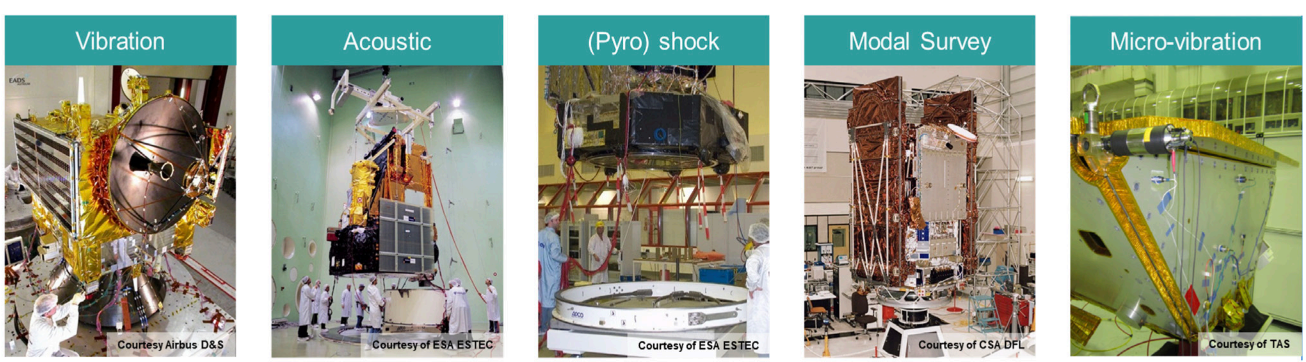


Figure 3. Space hardware validation involves different types of testing: mechanical qualification, modal survey and micro-vibration testing.

Vibration testing

A measurement system for mechanical qualification testing needs to respond to the most stringent, and at the same time flexible, requirements of space testing labs. On one hand, the control system during closed-loop vibration and acoustic testing has to reduce risks of incident to a minimum. On the other hand, the labs need to maximize the use (their investment) of the hardware to measure signals from different sensors, collect data in parallel on smaller systems, but also be able to face the challenging cases where hundreds of channels need to be acquired at the same time.

Challenges

Mechanical qualification tests happen on one of the very expensive mockups/prototypes or the actual spacecraft, presenting a significant risk of damaging the hardware. The integrity of the scarce and expensive engineering qualification model or the actual flight model should never be compromised. Any damage during testing can lead to missing the launch window's strict deadline and eventually heavy financial costs and penalties.

In addition, there is a trend of building larger and more complex spacecrafts that require higher channel count systems for additional protection of sensitive instruments and a better understanding of spacecraft dynamics. Such big test setups should still be conducted with the utmost safety, without compromising the control system.

For safe and efficient qualification testing it is also important to confidently monitor the test progress to watch the control accuracy, eventually remotely shutting down the test and quickly delivering qualification test results to the analysis team for data validation and processing.

The next section will discuss technologies and solutions to overcome these challenges and enable an efficient, safe, flexible and advanced qualification testing solution for the aerospace industry.

Vibration testing with full confidence

A satellite vibration test (sine or random) consists of reproducing the vibration levels described in the launch vehicle manual on a shaker. The control system drives this installation, taking the levels at the interface points (control channels) into account and closing the loop in real time. At the same time, response levels (notch channels) are being monitored and checked against auxiliary not-to-exceed levels. If those responses are exceeding the prescribed level, the control system will reduce the drive level to protect the instruments. Figure 4 shows a typical setup for a vibration control test.

State-of-the-art control systems incorporate a wide range of safety parameters to ensure specimen protection. This includes functions such as self-check, notching and abort limits. The following sections discuss the main safety implementations of a control system as implemented in the Simcenter test solution for space hardware validation.

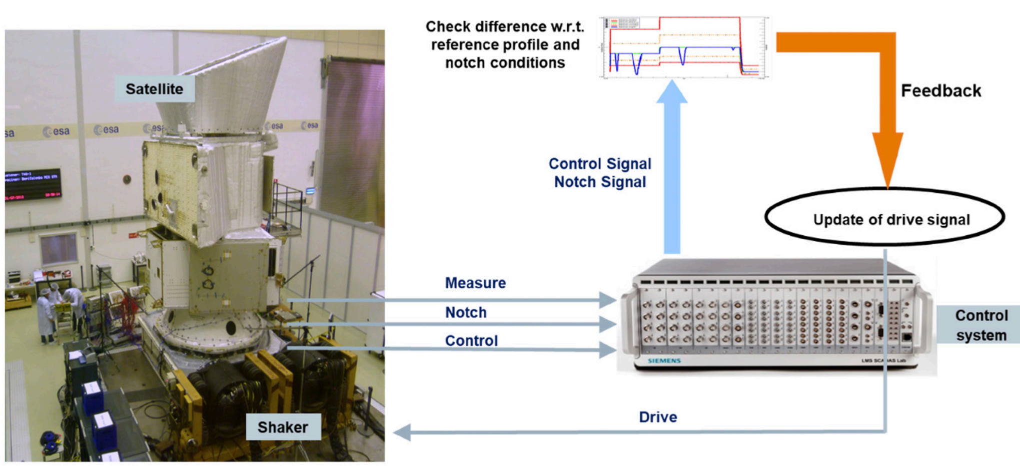


Figure 4: Preparing the BepiColombo for vibration testing ensuring the spacecraft will survive the rough start of its journey atop the Ariane 5 launch vehicle (courtesy ESA).

Self-check to verify setup consistency and completeness

An essential part of a complete vibration control test is the self-check procedure to verify the actual vibration measurement setup. It must be successfully accomplished before a test can be carried out. During this self-check, a low-level drive will be sent to the shaker to verify loop closure. During this low-level excitation, the system measures frequency response functions on all channels and verifies that all instrumentation is properly connected and working. It also extrapolates the low-level excitation to the full-level test, simulating the test run and verifying that all signals are in acceptable ranges. The process as implemented in Simcenter Testlab™ software is illustrated in figure 5.

Notching for real-time spacecraft protection

During a sine or random control shaker test, structural resonances can cause the vibration at certain locations to become too high. This can potentially cause damage to sensitive or expensive instrumentation on the satellite. Notching can help protect test objects by limiting the vibration levels at designated locations on the test item or on the shaker system by reducing the drive signal at the offending frequencies as shown in figure 6.

Notch levels do not need to be expressed in acceleration but can also be specified in terms of force, moment or any other quantity being measured during the test. Force and moment limiting are very important to avoid overturning the satellite when the test object's center of gravity is not exactly aligned with the shaker support interface. It is also very useful in ensuring that the test levels required by the launcher authorities were strictly applied. Force measurement devices (FMDs) are typically used to directly measure the forces and moments at the spacecraft/launch-vehicle interface.

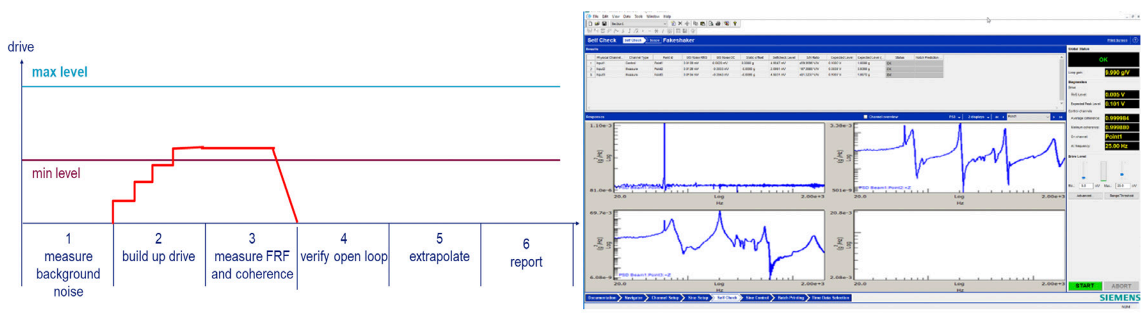


Figure 5. Left: Self-check procedure. Right: Simcenter Testlab self-check implementation.

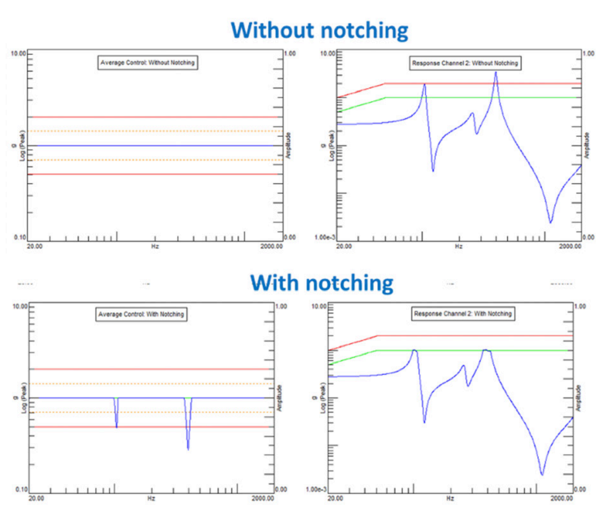


Figure 6. Measurement without (top) and with notching (bottom) active.

High channel-count dynamic measurements without jeopardizing the control system

Spacecrafts are getting larger and more complex. This triggers the need for higher channel count systems for extra protection – and better understanding of the spacecraft's dynamics. However, such large channel count systems should not impact the control system's performance or the efficiency of processing and reporting data after the test.

To allow large configurations without overloading the control system, reduction systems have been developed. Those are extensions to the control system that are fully synchronized to the control system. They acquire and store the raw-time data, but in parallel also process the data in real time to spectra and frequency response functions. A schematic representation of a measurement setup using Simcenter SCADAS™ hardware control and reduction systems is shown in figure 7.

This processing is controlled by the synchronization channels generated by the control system. This setup allows the control system to focus on the safety-critical control and notching task, while the reduction system measures and processes the response channels in parallel. This allows the control system to dispatch the analysis results promptly after shaker shutdown so that the test team can immediately start preparing the next test run while the analysis team reviews the data. This leads to more efficient testing and shorter test campaigns.

Instant access to test results for all teams

The qualification procedure doesn't end when the test is completed. The importance of fast and efficient reporting is sometimes underestimated but plays an important part in a successful test run. Quickly sharing the results from a qualification test allows the engineering team to immediately examine the test's status and enable the analysis team to validate the physical design and understand the physics behind the test.

Coupled loads analysis

Coupled loads analysis (CLA) is performed to understand how a payload, such as a satellite or spacecraft, interacts dynamically with the launch vehicle during launch and ascent. The loads and responses derived from this analysis are used to qualify the payload for launch aboard a given platform. Laboratory vibration tests on (large spacecraft) structures essentially serve two goals: qualification of the structure by subjecting it to vibration environments, which are representative for the operational conditions; and validation of the FE model for a reliable simulation of the coupling of the structure with the launcher.

The industry-standard Simcenter NASTRAN® software dynamic analysis solution has a wide customer base in the aerospace and defense industry for CLA. It allows for the study of the dynamic response under different operating conditions of assemblies, such as the study of the dynamic behavior of the satellite and solar panels at launch and deployment. Unique to Simcenter NASTRAN is the ability to create external super elements with mode acceleration, output transformation matrices that are required for CLA.

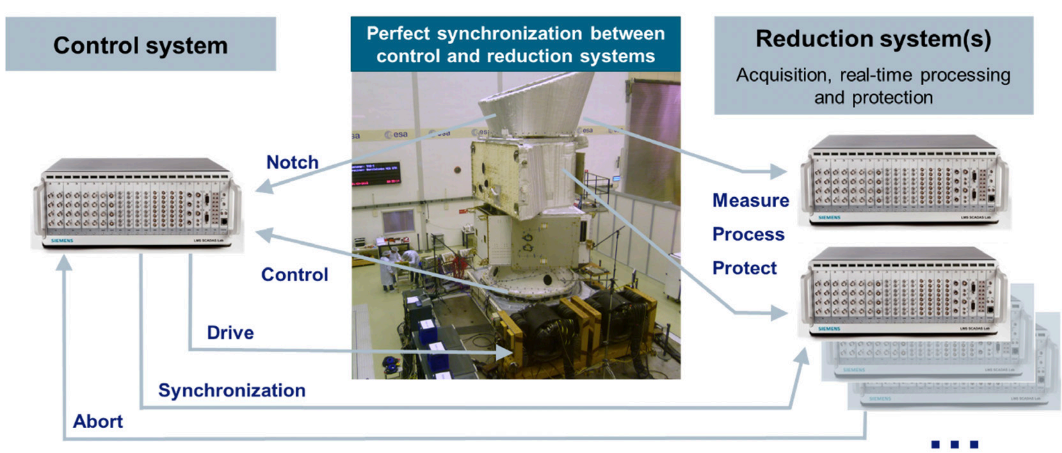


Figure 7. Set up with control and reduction system.

Virtual shaker approach

In the field of vibration testing the interaction between the spacecraft being tested and the shaker used to perform the test is a critical issue because the dynamics of the shaker (testing facility) often couples with that of the test object in the frequency range of interest, making its behavior during the physical tests unpredictable. Especially when the product being tested is as heavy as the shaker, it forms a new product-shaker coupled system with unknown dynamic properties. This holds a high risk of overtesting that might damage the satellite or expensive instruments on the satellite[10].

Therefore, simulation methods such as virtual shaker testing are being developed to foresee these testing difficulties and take countermeasures before running the actual program. The virtual shaker testing approach requires the integration of three simulation blocks (figure 8):

- The vibration control system model (A)
- The test facility and shaker model (B)
- The structural model of unit under test (C)

By carrying out such a virtual shaker test, the test engineer can evaluate the test performance of the mentioned system prior to actually putting things in operation. This helps define the proper selection of all parameters involved in the experiment (location of control, measurement and notching sensors, controller settings such as sweep rate, number of periods and compression factor) and accounts for a smoother test deployment. Also, sensitivity studies can be performed to quantify the importance of shaker-structure interaction and its effect on the controller. Finally, this process can lead to the correlation of mathematical models with experimental results, offering deeper insight about overall system physics.

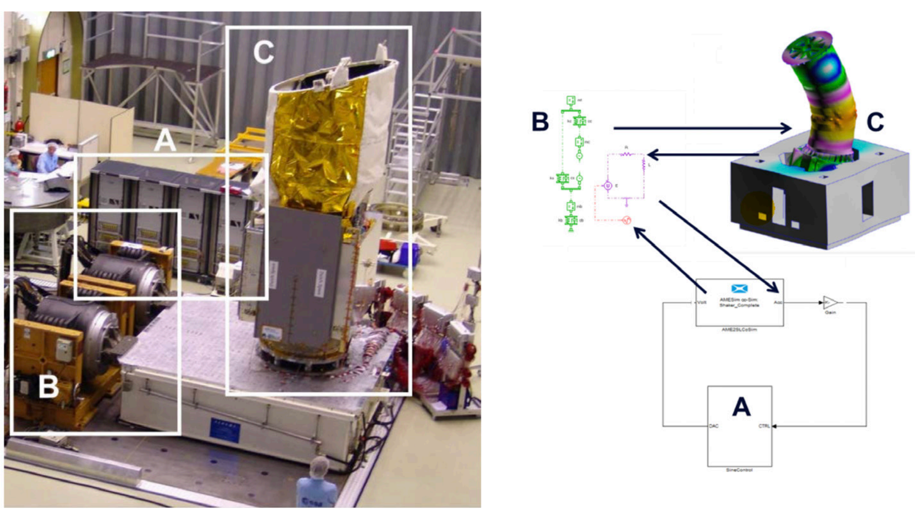


Figure 8. Vibration test facility (left) physical and (right) virtual representation. The different blocks are also marked: (A) Closed-loop vibration controller; (B) Vibration exciter(s); (C) Unit under test.

Acoustic testing

The noise levels generated at launch can reach levels up to 146 decibels (dB) or higher inside the fairing and cause structural damage and jeopardize the functionality of instruments and subsystems. Therefore, launcher authorities also require spacecrafts to be qualified for acoustic loading. So, before the spacecraft launch, both the space vehicle and major subsystems such as solar panels, antenna and reflectors are tested and exposed to acoustic pressures expected during lift-off and subsequent mission phases.

Satellite acoustic testing is traditionally performed in acoustic reverberant rooms, but it is costly and time-consuming. Therefore, new testing methods have been investigated that offer a more economical and flexible alternative. The traditional as well as the new testing methods will be discussed in more detail in the next paragraphs.

Reverberant field acoustic excitation: traditional method

Satellite acoustic testing is traditionally performed in acoustic reverberant rooms, ensuring a uniform sound field around the test object. In most cases, these large facilities are filled with gaseous nitrogen, while some also use dried oxygen. The goal is to keep the air as clean as possible and minimize sound absorption. The noise is generated by a set of acoustic modulators connected to horns, which together can produce noise levels that can reach over 150 dB.

A schematic representation of an acoustic control system based on Simcenter SCADAS hardware and Simcenter Testlab software is shown in figure 10. First a target sound pressure level profile (corresponding to a launcher) is defined. The room model characterized by the reverberation time per one-third octave band (T60)

Figure 9. Reverberant field acoustic excitation test at the European Space Agency (ESA).

is an important parameter for the control that also needs to be specified. Once the test is started, the control algorithm will generate the drive signal. This drive signal can be split by crossover filters and streamed through the desired amount of digital-to-analog converter (DAC) outputs of the frontend to feed a number of modulator-horn and or amplifier-speaker sources, which will produce the diffuse sound field in the room.

A number of microphones suspended in the room are used to control and monitor the sound field. The control algorithm computes a control signal from all the microphones (spatial average) to adapt the drive signal to meet the defined target. Extra vibration channels can be configured to monitor power spectral density (PSD) levels on the test object's structure with the possibility to trigger aborts.

To prepare and optimize a reverberant acoustic test, the aerospace industry also uses simulation tools to avoid overtesting the spacecraft. Simcenter 3D software makes it possible to create diffuse fields as a combination of random plane waves and use this excitation to calculate the pressure load on the spacecraft.

Although reverberant field acoustic excitation (RFAX) is a well-established method, the overall operating complexity and running cost of reverberant rooms, together with the geographical spread of the facilities, makes it a real challenge for spacecraft owners to get their products tested.

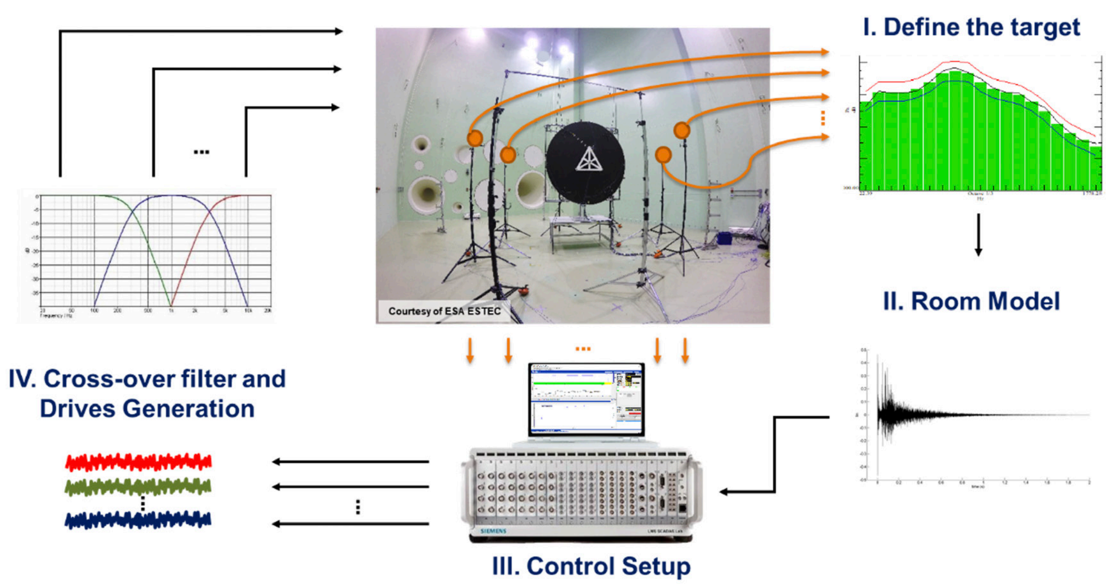


Figure 10. Schematic representation of an acoustic control system.

Direct-field acoustic noise: alternative method

Satellite original equipment manufacturers (OEMs) are showing an increasing interest in finding alternative testing methods to the standard acoustic test in reverberant rooms that offer a more economical option as well as more flexibility to perform the tests away from sparse and costly-to-operate facilities. A direct-field acoustic noise test (DFAN) is an alternative method that has attracted a lot of attention in recent years.

To replicate the acoustic loads, DFAN technology does not require a dedicated reverberant facility, but it can be realized with commercial loudspeakers and amplifiers in acoustically ordinary rooms. The test specimen is placed in the middle of a loudspeaker circle and gets excited by a direct acoustic field. A closed loop multiple input multiple output (MIMO) random control algorithm is used to achieve the correct environment in terms of data uniformity and diffuse field requirements.

A test arrangement on a reflector shell of an antenna subsystem at Thales Alenia Space is shown in figure 11. The setup is comprised of 96 loudspeakers stacked in 12 columns and adequately positioned in a circular configuration, and 96 amplifiers that deliver the required power to generate a 147dB sound field. The setup uses Simcenter SCADAS fitted with a MIMO controller combined with Simcenter Testlab. Sixteen microphones around the test specimen are used to measure the sound field and generate corrected drive values to create a homogenous acoustic field[4].

To improve test controls and uniformity of the acoustic field, many MIMO closed-loop control strategies have been investigated. Simcenter Testlab MIMO acoustic control software uses projection and optimization algorithms for a proper definition of test references for the MIMO random control process and an optimal selection of control sensors for the acoustic field uniformity. More details of this unique technology can be found in reference[5].

Space agencies and launch vehicle producers are also creating the necessary guidelines for the industry to correctly conduct a DFAN test. At the moment, NASA is the only one who has developed a technical handbook (NASA-HDBK-7010).

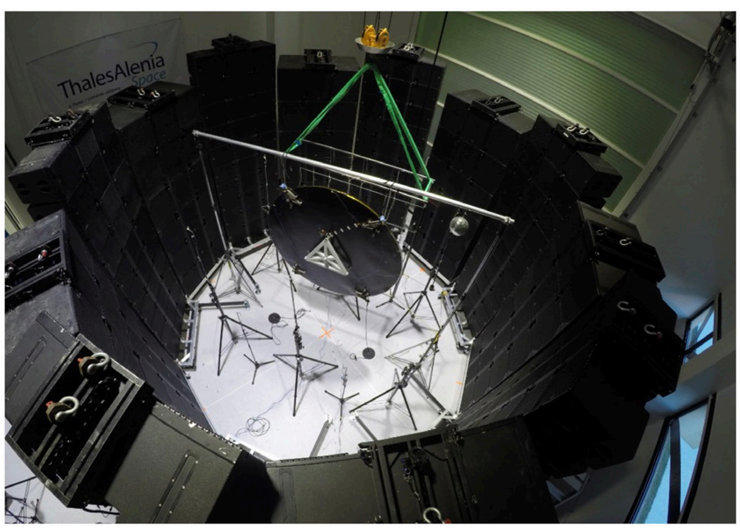


Figure 11. Direct field acoustic noise (DFAN) test on a Thales Alenia Space reflector.

Virtual direct field acoustic testing: comprehensive digital twin for de-risking the test

In preparation for DFAN tests, a comprehensive digital twin can be used to design and optimize the setup for a more efficient test. The comprehensive digital twin can help define the number and type of speakers needed to provide the required acoustic energy to reach the desired sound level. It can be used to determine the position of the speakers as well as the number and position of the control mics to improve the uniformity of the acoustic field. To overcome overtesting the actual test can be simulated to calculate the structural responses on the test item itself to ensure levels will not be exceeded and allow for the anticipation of response limiting.

An example of a pretest simulation using a comprehensive digital twin for a DFAN test on a reflector of an antenna is shown in figure 12. In preparation for this test, the setup was designed in Simcenter 3D, including the arrangement of the speakers and the position of the microphones and test item. Then the performance was predicted, including the uniformity check of the acoustic field. Finally, a complete test was simulated all the way down to calculating the acoustically induced loads on the test item itself.

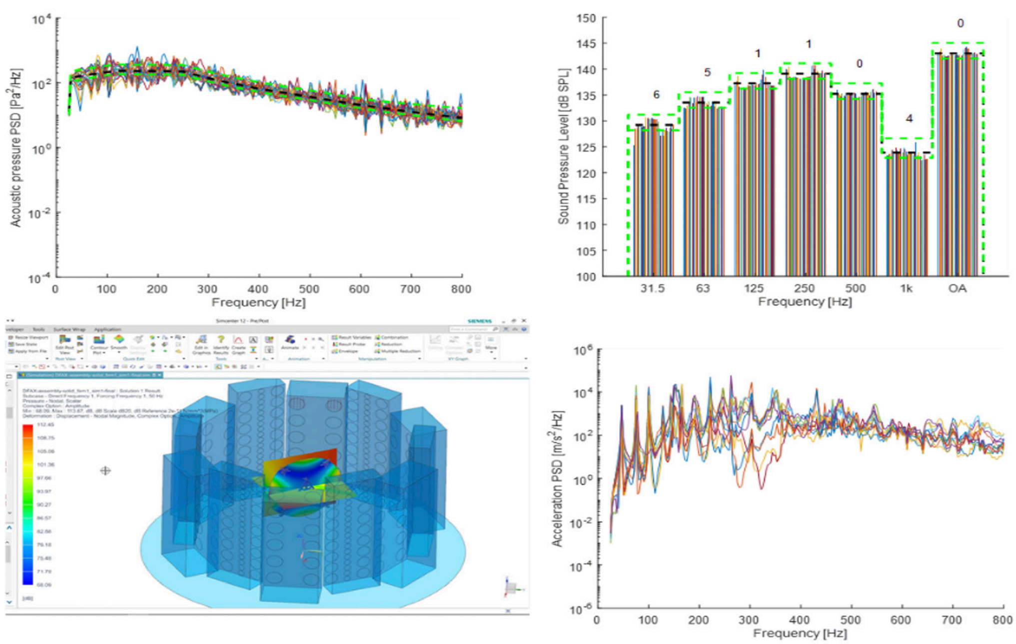


Figure 12: Simcenter 3D simulation used to design and optimize the DFAN test setup. Left-top: acoustic field uniformity check in narrow-band. Right-top: acoustic field uniformity check in octave-bands. Left-bottom: predicted acoustically induced loads. Right-bottom: predicted specimen vibration response.

Shock testing

During the launch and deployment operations, the spacecraft is subjected to several high energetic shock events introduced by pyrotechnic devices: launcher stages separation, fairing jettisoning, separation of the satellite from the launcher (for example, clamp-band release) and deployment of appendages such as solar arrays, antennas or scientific instruments on deployable booms.

These shocks propagate through the entire spacecraft and may cause damage to the payload's electronics and compromise the functionality of mechanical parts. Because of their high accelerations and frequency content, many hardware elements and small components are susceptible to pyro shock failure while resistant to a variety of lower frequency environments, including random vibration.

Verifying by test that spaceflight hardware can withstand the anticipated shock environment is essential to mission success. Shocks testing may be conducted by using a pyrotechnic device, a mechanical impact device or a shaker. Using pyrotechnic devices produce the most accurate simulation. However, for cost reasons or early proto-flight testing of potentially susceptible hardware, the alternative test methods may be more attractive. Figure 13 shows some setups for pyro shock testing.

To study the impact of the shock on the instruments onboard the spacecraft hundreds of vibration and strain responses are measured. The typical analysis result is a shock response spectrum (SRS) for each measurement location. The maximax SRS is the one most commonly used for pyro shock testing as the absolute maximum value is of greatest interest, regardless of whether it occurred in the primary (during excitation) or residual instant (after excitation) of the response.

Simcenter SCADAS and Simcenter Testlab allow engineers to acquire the specimen response at high speed to analyze the effect of pyro shock events on the space system. It also allows a safe reproduction of a wide range of shock tests (such as half sine pulse shocks or synthesized shocks) on shakers and provides all necessary processing capabilities such as online calculation of shock response synthesis (SRS) and SRS limiting for specimen protection.

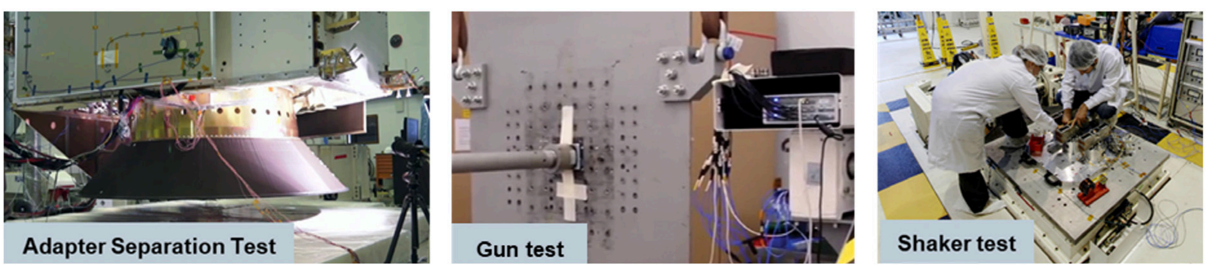


Figure13: Spacecraft separation test using pyro devices (left), shock test using mechanical devices (mid) and shock test using electrodynamic shaker (right).

Statistical energy analysis: prediction of payload shock response

As testing environments differ from the actual flight environments, simulation is used to validate test environments to ensure proper payload qualification. Statistical energy analysis (SEA) methods can be used to predict shock response spectra for shock qualification testing. Simcenter 3D SEA allows spacecraft separation simulation to predict a proper qualification SRS that is an envelope of various shock events.

Figure 14 shows the results of a benchmark test conducted for ESA of SEA-shock, a specific SEA technique for SRS prediction, applied to a fairing separation test of the VEGA upper part[11].

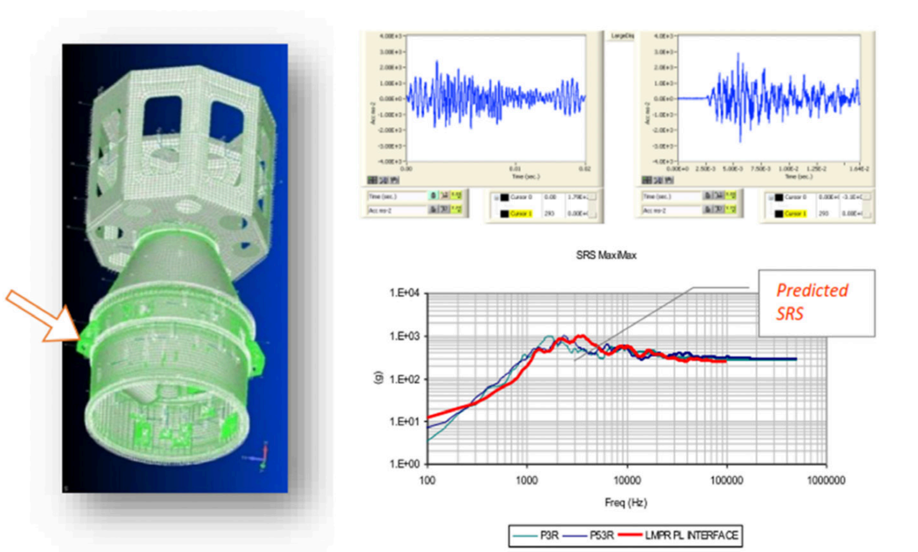


Figure 14. SEA prediction of VEGA launch vehicle upper part. Top-left: predicted and measured acceleration time history on payload interface. Bottom: predicted and measured SRS on payload interface.

Modal survey

To really understand the structural dynamics of a spacecraft, the program sometimes requires a modal survey test. This test aims at test validating the space-craft's FE structural dynamics model. This model is necessary for the launcher CLA process, which assesses the risk of launch load damage. The same model can also be used to perform de-risk qualification testing and predict spacecraft response to the loads injected during this test, as explained above in the virtual shaker approach paragraph.

A modal survey test consists of injecting forces, using electrodynamic shakers at a number of carefully chosen inputs. Burst random excitation is usually used because it is fast and efficient. When higher excitation levels are required, or for the assessment of nonlinear characteristics, stepped sine techniques are used. The forces are measured during the test, along with the response accelerations at a large number of locations throughout the structure. During this test, the satellite is mounted in well-known boundary conditions, clamped or free-free, or a combination thereof. During the excitation, FRFs are measured.

After the test, modal curve-fitting technology is applied to extract modal information: resonance frequencies, damping values and mode shapes. The test results are used for the purpose of validating the entire FEM and correlating frequencies, mode shapes and damping assumptions. The significant mode shapes and frequencies are those that are primary contributors to launcher/spacecraft interface loads and internal loads[13].

An example of a program where a modal survey test was recommended is Radarsat, a Canadian Space Agency project (figure 15). The CLA (forced response calculation of launch loads on the combined dynamic spacecraft and launcher model) for this particular program revealed that damage during launch could occur on the synthetic aperture radar (SAR) panels. Those four panels have an almost identical geometry and are stacked closely together in launch configuration.

An in-depth and accurate identification of the reso-nance frequencies was required to calibrate the FE models. As a result of the high modal density, the test required five simultaneous shakers and a total of 240 responses. Simcenter Testlab Modal Analysis was used to accurately isolate the closely spaced modes between 49Hz and 61Hz.

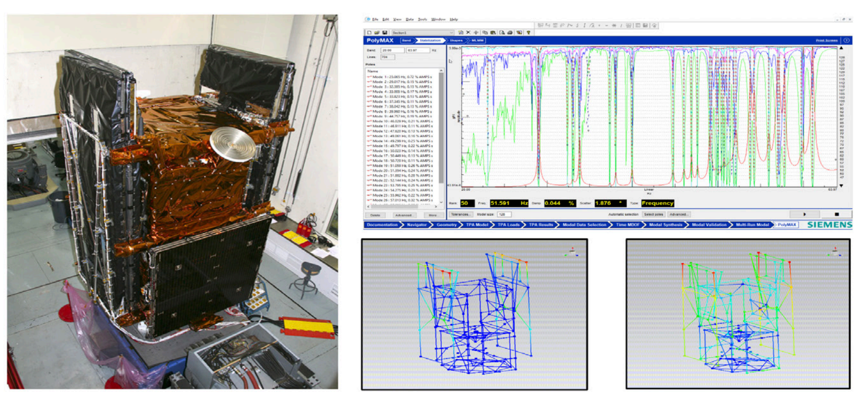


Figure 15: Modal survey test conducted during Canadian Space Agency project Radarsat (left).
Mode shape results after applying Simcenter Testlab Polymax modal curve fitting algorithm (right).

Operational modal analysis: Gaining more engineering insights

During qualification tests of entire spacecrafts and subassemblies or large components, the instrumen-ta-tion typically includes, in addition to control and limiting channels, a large number of sensors (such as accelerometers and strain gauges) for measuring the structural response. Traditionally, these accelerometer and strain signals are processed towards PSDs to get an idea about the induced loads. However, advanced techniques such as operational modal analysis can provide even more insight into the dynamics of the structure based on this data.

An application where operational modal analysis has been applied to characterize the structural dynamics of an antenna reflector (provided by Thales Alenia Space Toulouse) during a DFAN test is shown in figure 16. In addition to the microphones used for feedback control, structural vibrations of the specimen were monitored using accelerometers. Even insights in the non-linear behavior can be studied by analyzing data at multiple sound pressure levels. The data was acquired using Simcenter SCADAS and Simcenter Testlab MIMO random control software. The analysis was conducted using Simcenter Testlab operational modal analysis[8].

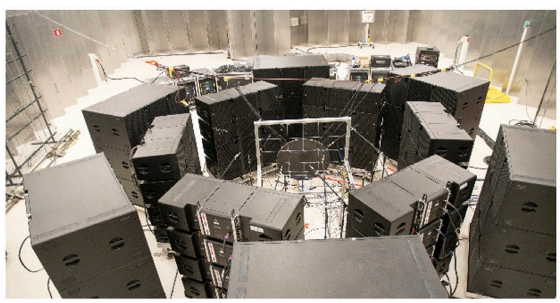
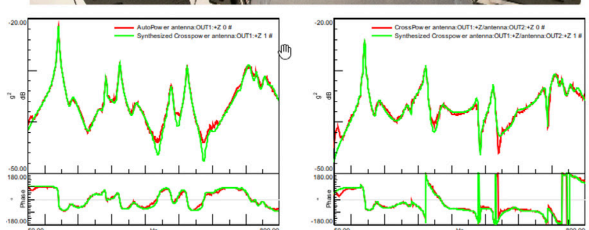


Table 1. Eigenfrequency and damping ratio estimates for the 9 disk structural deformation modes.

Mode #	Impact PolyMAX		Closed-loop (12) 110dB Op. PolyMAX		Open-loop (12) 0.45V Op. PolyMAX	
	f [Hz]	xi [%]	f [Hz]	xi [%]	f [Hz]	xi [%]
1	127.9	1.7%	130.9	0.7%	128.7	0.8%
2	140.4	2.6%	141.0	0.5%	138.6	1.0%
3	279.8	1.0%	283.0	0.4%	279.4	0.6%
4	319.1	2.1%	324.2	0.7%	317.8	1.4%
5	478.5	1.8%	478.7	0.7%	480.2	1.9%
6	525.1	2.0%	525.8	0.5%	523.9	0.8%
7	687.4	1.7%	682.2	0.9%	689.5	1.4%
8	707.6	1.8%	710.4	1.1%	718.0	1.3%
9	773.7	3.3%	775.9	1.4%	773.4	1.9%



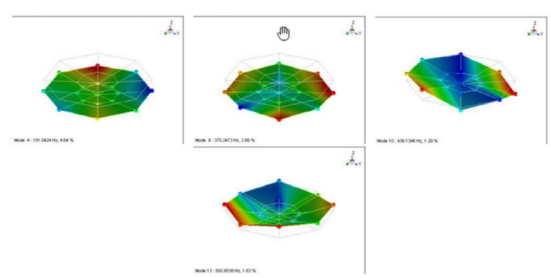


Figure 16. Left-top: DFAN test setup with antenna reflector surrounded by loudspeakers. Right-top: comparison of identified eigenfrequencies and damping values with impact and OMA techniques. Left-bottom: Curve-fitting quality check: measured spectra compared to synthesized spectra. Right-bottom: Some OMA identified mode shapes.

Micro-vibrations

High-end optical imaging sensors and lasers are increasingly used in satellites. These sensors have lofty requirements in terms of stability to provide high-quality images. However, mechanical devices on the spacecraft such as reaction wheels for attitude control can cause micro-vibrations (in the order of micro-g) leading to the blurring of images (figure 17). Therefore, scientific and earth observation missions call for stringent requirements with regard to the micro-vibration environment onboard a spacecraft.

For the experimental verification of the compliance to such requirements, dedicated test rigs are being built to characterize the micro-vibrations. A setup made at ESA-ESTEC is shown in figure18. Given the low levels that need to be measured (down to 10mN force and 2mNm moment in a frequency between 5Hz to 1kHz) the test-rig is isolated from the environmental ground vibrations using a large seismic block of marble supported by pneumatic isolators[9].

Simcenter SCADAS has been extended with the SCL-VCF4, a dedicated input module with ultra-low-noise charge input, very suitable for accurate measurement of extremely low force levels as encountered in micro-vibration testing.

The data obtained from the tests can be used for detailed investigation of the contribution of the unit dynamic behavior to subsystem or system-level performance as well as enabling identification of the key micro-vibration sources within the wheels.

For a better interpretation of the results, it is important to know the resonance frequency of the combined setup of test rig and test specimen to differentiate between responses from the reaction wheel and the combined setup. Figure 18 shows a configuration where a Simcenter QSources™ hardware shaker is used to determine the resonance frequency of the combined setup.

The source-transfer-receiver model, very popular in the automotive industry for understanding vibration transmission paths, can also be used in this context to understand how the energy from the vibrating source is transmitted to the high-end equipment and optimize its location and mounting system. The required structural FRF data for such an analysis can be obtained using an impact hammer or shaker such as the Simcenter QSources shaker.

The Simcenter platform offers a complete TPA (Transfer Path Analysis) solution, implementing the process described in chapter 13 in the ECSS-E-HB-32-26A handbook. Micro-vibration studies can be performed using CAE models and can be validated by tests. The unique "hybrid TPA" capability in Simcenter even allows to combine both worlds, feeding test data into simulation models or building assemblies of test-based models with purely numerical models.

Non-linearities

To suppress micro-vibrations satellite manufacturers often use mounting systems with a soft interface between the fixed and mobile parts such as elastomer bushings. The wheel elastomer mounting system

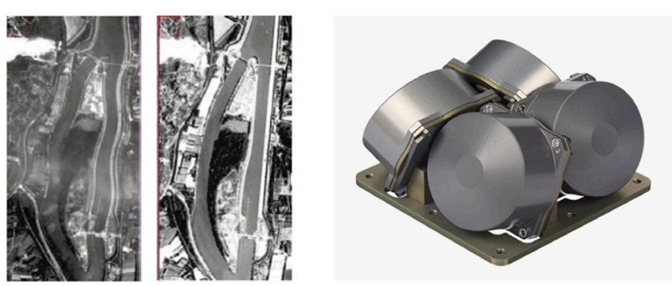


Figure 17. Left: Image distortion caused by micro-vibrations[12].
Right: Reaction wheels for attitude control.

(WEMS), a vibration isolation system of the SmallSat spacecraft developed by EADS-Astrium, is such a mechanical device designed to mitigate in-orbit vibrations and protect the reaction wheel during the launch. The bushings are soft with low vibration levels but hard above a certain level, implementing mechanical stops and giving rise to nonlinear dynamic phenomena.

Traditional spectral interpretation of qualification test results of this type of non-linear structures leads to time-consuming discussions since response levels differ from sweep to sweep and are heavily distorted at high input level sweeps. To develop more insights on how to deal with non-linearities, ESA sponsored a research project to study non-linear response of spacecraft mounted systems during the qualification test. This work led to an update in the ESA handbook on the ECSS-E-HB-32-26A spacecraft mechanical loads analysis handbook, adding a chapter on how to deal with non-linearities[12].

For this project Simcenter SCADAS and Simcenter Testlab were used to run a qualification campaign on a structural model of a satellite (SmallSat) with a WEMS-mounted dummy reaction wheel. Sine sweep tests from five to 80Hz and for different target control levels have been conducted to investigate the non-linearity[7]. Test set up and some results are shown in figure 19.

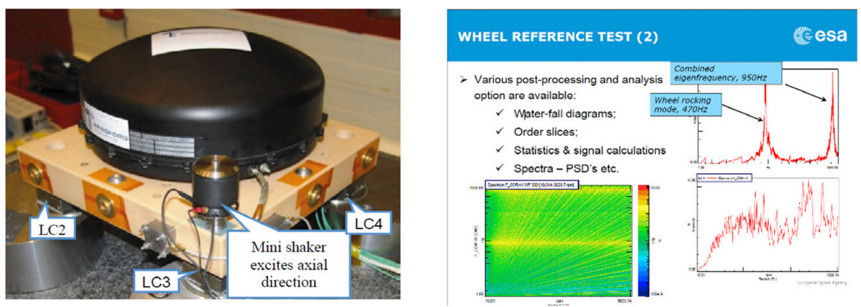


Figure 18. Left: ESA-ESTEC test rig for micro-vibration characterization with reaction wheel assembly and Simcenter Qsources shaker. Right: Some Simcenter Testlab analysis results with waterfall plot, peak hold spectrum plot and force spectrum plot at specific rotational speeds (ESA report).

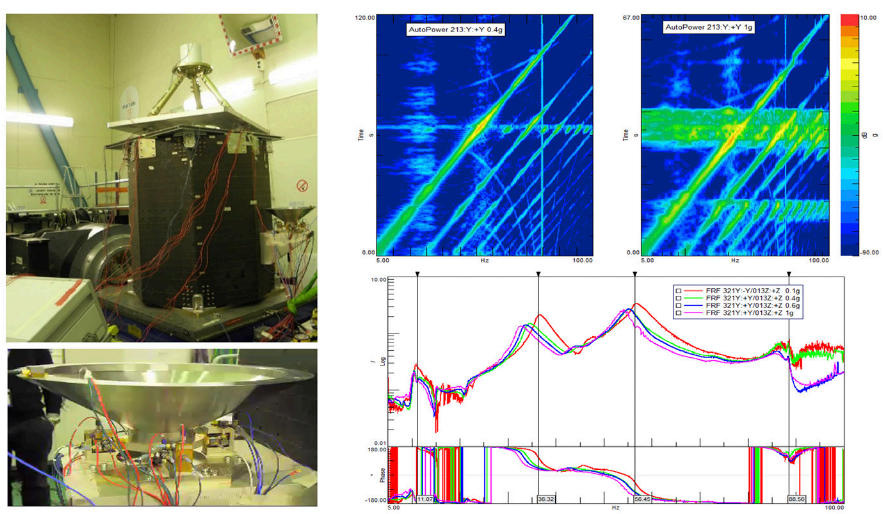


Figure 19. Left-top: SmallSat spacecraft test setup. Left-bottom: Wheel elastomer mounting systems WEMS with dummy structure on top. Right-top: Simcenter Testlab color map displays comparing 0.4g and 1g sweeps. On both non-linear distortions (harmonics) can be observed. On the 1g sweep also a wide band spectrum distortion due to the mechanical stops is present. Right-bottom: Simcenter Testlab bode plot showing resonance frequencies shift for increasing loading conditions.

Conclusion

The primary goal of the various types of dynamic tests (acoustic, vibration, shock) is to expose the space hardware to the dynamic launch environment and verify that it performs as expected after being exposed to the harsh environment. A critical concern is to protect the spacecraft structure and hardware from exceeding design-strength capabilities and conduct the tests in a safe manner.

On the other hand, vibration qualification tests are more demanding today than they used to be. Test laboratories around the world must reduce costs and test teams must keep set up and testing time as short as possible.

Simcenter solutions have been discussed to address these challenges. The various mechanical qualification tests are explained, as well as modal research and micro-vibration tests. A comprehensive digital twin in support of de-risking and optimizing tests has also been addressed.

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