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# VIBRATION ANALYSIS OF A MICROSATELLITE PANEL DURING THE SHAKER TESTING

**Claudiu Florinel BÎȘU[1,*], Dorel Florea ANANIA[2,*], Emilia BĂLAN[3], Cosmin GOGU[4], Andra Elena PENA[5]**

[1, 2, 3)] Assoc. Prof., PhD, Robots and Production Systems Department, National University of Science and Technology "Politehnica" Bucharest
[4)] PhD Student, Robots and Production Systems Department, National University of Science and Technology "Politehnica" Bucharest
[5)] Lecturer, PhD, Robots and Production Systems Department National University of Science and Technology "Politehnica" Bucharest

***Abstract:*** *Microsatellites are the subject of many research projects addressed today in universities. This paper presents the results of vibration tests on a microsatellite type CARDSAT which is a new concept designed for volume optimization and flexibility. A Cardsat is a thin panel-shaped satellite with low volume and weight. The concept optimizes the volume of the microsatellite and, by using more panel free or link between them, a complex configuration can be designed. Tests are made according with space standards for microsatellite launch requirements. Tests such as shock, random vibration, low-level sine-sweep and high-level sine are made on a CARDSAT 3U prototype by using a shaker device and data acquisition board. The dynamic behavior of a single, fully equipped panel is stable, without identifying defects after testing. The determination of the own frequencies is a necessary condition for compliance with the test conditions, to avoid the phenomenon of resonance on the test stand. For the tested CARDSAT panel the own frequencies were 15.8 Hz and 17.2 Hz. The main objectives of the tests are to validate the concept and prepare and check the set-up parameters of the testing stand in order to be used for more complex prototype.*

***Key words:*** *microsatellite CARDSAT, panel, vibration, shaker, tests.*

## 1. INTRODUCTION

A microsatellite is a complex product composed of many subsystems that interact with the supporting structure as well as with each other. Therefore, in the process of designing and developing a microsatellite, these subsystems must be considered as early as possible.

The design of complex, mechano-electronic mechanisms of microsatellites must take into account the state-of-the-art of scientific development strategies and, at the same time, identify possible directions for improvement by assessing trends and research gaps.

The aspects to be analyzed when designing complex mechanisms are:

- problem formulation,
- inter/multi/disciplinary modeling,
- analysis capabilities,
- implementation of tools and general applicability.

Simulations and analysis capabilities, as well as optimization of multidisciplinary design are often based on simplifications, while in some cases you may get calculation errors due to inadequate model integration.

Overall, a validation process can ensure the robustness and safety of the project and provide additional confidence in optimization.

* Corresponding author: Splaiul Independenței, 313, Sector 6, Bucharest, Romania,
Tel.: + 40 21-402 94 20;
E-mail addresses: *claudiu.bisu@upb.ro* (C.F. Bisu), *dorel.anania@upb.ro* (D.F. Anania), *emilia.balan@upb.ro* (E. Bălan), *cosmin.gogu@stud.fiir.upb.ro* (C. Gogu), *andra.pena@upb.ro* (A.E. Pena)

There are three possible methods of validating the results of the multidisciplinary microsatellite design optimization process: using high-fidelity simulations, testing physical prototypes, and using data from similar microsatellites.

The choice of validation technique is usually a compromise between the level of accuracy desired and the time required.

A series of recommendations for vibration testing of satellites and microsatellites are presented in scientific literature [1–8].

This paper presents the results of vibration tests on a microsatellite type CARDSAT which is a new concept designed for volume optimization and flexibility. They are structured as follows:

1. Introduction to vibration testing of microsatellites;
2. Plan of experiences, devices and tools needed;
3. Low-level sine-sweep testing, at low-level sine-sweep frequencies – LLSS – "low-level sine-sweep" testing (carried out at a low level of vibration in order to determine natural frequencies and damping);
4. High-amplitude forced vibration testing, sinusoidal impulse – SB – "sine-burst" testing (they are generated with the help of the exciter, at a frequency lower than the fundamental frequency);
5. Random vibration testing – RV – "random vibration" testing (performed on a frequency range, respectively 20–2000 Hz, with random amplitudes);
6. Imposed constraints (limitation of force by "reducing steep peaks");

7. Recommendations for the design of a microsatellite based on the analysis of vibration test results.

Adherence to these recommendations based on the analysis of the vibration tests results provides credibility in meeting the objectives related to the microsatellite flight demonstration, avoiding test failures, whether associated with a design deficiency or excessive loading during tests.

These recommendations apply primarily to satellites with mass between 22.7 kg and 227 kg CubeSats range. They can also be applied to larger satellites if they will be tested on a shaker (vibrating tables / dynamic exciter / vibration test system).

## 2. INTRODUCTION TO VIBRATION TESTING OF MICROSATELLITES

Most satellites weighing less than 227 kg are tested on vibrating tables / electrodynamic shakers in each of the three orthogonal directions *X*, *Y*, *Z* (Fig. 1). The test setup on a shaker consists of: the tie plate moves relative to the fixed base at an imposed acceleration and frequency or at a random acceleration and frequency.

Some larger satellites are also tested on shakers, depending on stakeholder preference.

For each test must be determined:

- the objectives (which must be clearly defined);
- the criteria to assess whether the test has met the objectives.

The reason for testing a microsatellite on a shaker is not because there is a requirement/recommendation to do so. There may be such a requirement, but the test won't mean much if that's the only reason it's done [10–12].

Most often, a vibration test is performed to determine whether the satellite can withstand the launch environment and whether it will operate afterwards. The process of establishing trust is called verification.

In the space industry, verification rarely brings proof, at least not when random variables such as those associated with launch environments are involved.

When random variables are involved, a combination of analysis and tests is used to establish confidence that the mission will succeed.

In other words, the main objective of vibration testing on a shaker is to verify compliance with certain structural strength and mechanical requirements, in particular to establish confidence that [9]:

- the spacecraft structure, payloads, equipment, and other assembly components can withstand and perform as required after exposure to the highest load during the mission (verification of strength and verification of maintenance of relative alignment of critical components or interfaces);
- spacecraft assemblies can withstand and perform as required after (and during, for any equipment required to function during launch) exposure to cyclic loads associated with launch vibration, and, to some extent, they can check the fatigue life of materials;
- electrical connectors will remain connected during the launch environment;
- the satellite will maintain its overall integrity, for example, no loosening of bolted joints due to loss of fastener preload, and no part will loosen or release from the fastening system;
- the satellite meets any specified natural frequency constraints (typically applied to the launch configuration to avoid dynamic coupling with the launch vehicle and subsequent high loads).

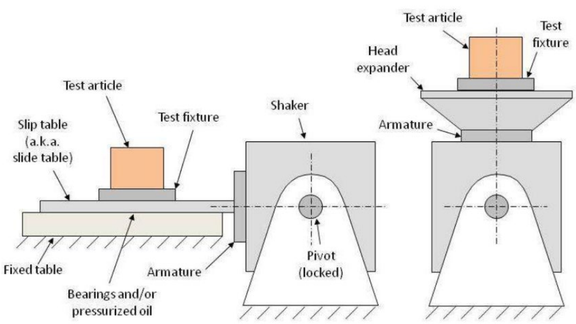



**Fig. 1**. Experimental setup [9].

An additional goal of vibration testing is often to obtain data to allow correlation of the FEM model for use in coupled load analysis and any other important analyses.

When planning and designing a test, always start with a clear definition of the test objectives. Then the test that satisfies the objectives is designed.

To simulate and take into account the effects of launch environments, small satellites are most frequently tested for sinusoidal pulse vibrations ("sine-burst" – SB) and random vibrations ("random vibration" – RV).

Periodic sinusoidal vibration testing (SV) is omitted for most small satellites because whatever sinusoidal vibrations conditions may apply, they are usually contained in a combination of sinusoidal pulse SB and random vibration RV.

For a small satellite, low-level sine-sweep (LLSS) vibration tests can be performed to characterize the dynamic behavior.

*Transmissibility*.To understand how a structure responds to vibrations introduced at its base, consider a mass placed on a spring (a single degree of freedom (SDOF) system), with a sinusoidal acceleration of 1 unit (1 *g*) introduced at the base of the spring. The transmissibility function, $T_R\,(f_{ratio})$, establishes the maximum value ("peak value") of the mass acceleration response characteristic as a function of $f_{ratio}$, which is the ratio between the input frequency $f$ and the natural frequency $f_n$ of the SDOF system:

$$T_R(f_{\text{ratio}}) = \sqrt{\frac{1+\left(2\zeta f_{\text{ratio}}\right)^2}{\left[1-f_{\text{ratio}}^2\right]^2+\left(2\zeta f_{\text{ratio}}\right)^2}} \tag{1}$$

where $\zeta$ is the damping ratio (damping factor divided by critical damping factor). Figure 2 shows the transmissibility function for several damping ratios.

*Resonance*, which occurs when a sinusoidal frequency of forced vibrations is the same as the natural frequency of the system, is an equilibrium condition in which the energy added by the next input cycle is balanced by energy lost through damping. Thus, at resonance, the maximum value of the response characteristic is limited by damping in the system.

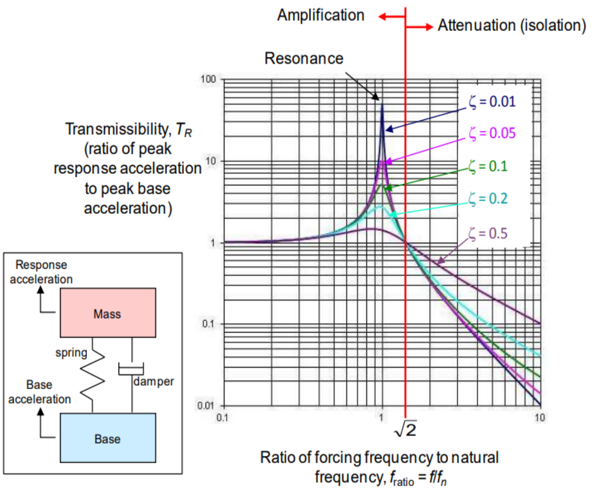



**Fig. 2.** Transmissibility $T_R$: ratio of the maximum value of the response characteristic of the vibrating mass acceleration to the maximum value of the response characteristic of the exciter base acceleration [9].

*The quality factor Q* is transmissibility to resonance and is expressed by:

$$Q \cong \frac{1}{2\zeta} \qquad (2)$$

At forced vibration frequencies below the system's natural frequency, the mass moves very closely-to the mounting base, with little dynamic amplification. If the frequency of forced vibrations exceeds approximately 1.41 times the natural frequency, the mass responds with less acceleration than that of the base, a situation called isolation.

Understanding transmissibility is the base to understand how a structural assembly responds to testing on a shaker, regardless of whether it provides sinusoidal acceleration at a single frequency (SB – sinusoidal impulse vibration testing, LLSS – low-level sine-sweep testing, SV – periodic sinusoidal vibration testing or stepwise sinusoidal signal (sine-dwell – SD) vibration testing) or at multiple frequencies, simultaneously, at amplitude and random phase (random vibration test RV).

The sinusoidal impulse vibration test SB is at low frequency, below the fundamental frequency of the test body to avoid dynamic response, and a random VR vibration test simultaneously excites all vibration modes within the test spectrum at random amplitudes. When damping is relatively low, under 10% of critical one - the response of any vibration mode, characterized by acceleration measured in a specific place, is sinusoidal just like the response of mass put on a spring.

## 3. DYNAMIC TESTING OF MICROSATELLITE STRUCTURES

The testing was carried out following the specific conditions imposed by NASA [11–14]. In order to meet the acceptance criteria imposed by satellite bodies, an experimental test set-up for microsatellite panels has been made.

A first action on vibration testing aimed to implement specific procedures and dynamically to test a CARDSAT panel as an element of microsatellite structure.

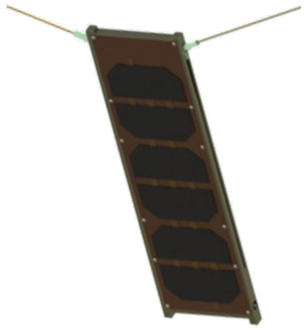


**Fig. 3.** CARDSAT 3U panel.

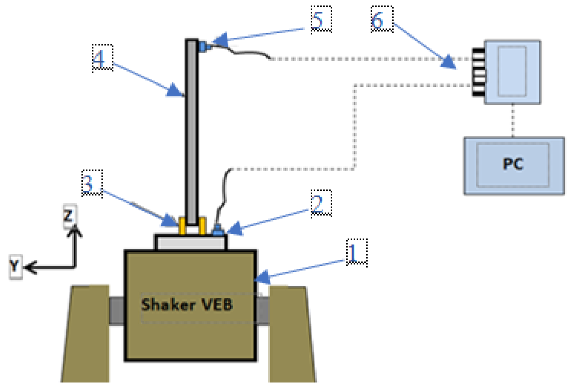



**Fig. 4.** Testing stands for CARDSAT panel: 1 – shaker; 2 – reference accelerometer; 3 – clamping system, 4 – CARDSAT panel; 5 – accelerometer; 6 – Data acquisition modulus USB4431 NI.

The CARDSAT is based on a patent application for an artificial satellite with small dimensions that demonstrates the novelty and originality of the constructive solutions and two applications for brands: for a new concept of satellite and for a family of Romanian satellites.

The dimensions of CARDSAT 3U version used for testing are: the dimensions of the folded microsatellite are $L = 340.5 \times H = 100 \times W = 10$ mm (Fig. 3).

The testing stand (Fig. 4) was designed by using equipment from National University of Science and Technology POLITEHNICA Bucharest, Department of Robots and Production Systems.

To apply dynamic force on the test CARDSAT panel, a VEB-RFT type 11075 vibrating bridge is used, with the possibility of controlling the frequency and amplitude parameters.

The CARDSAT panel is fixed with a clamping system. For data acquisition is used an accelerometer fixed on the CARDSAT panel in 3 orientations according with axis direction (Fig. 5).

A second accelerometer is mounting on the vibrating exciter in an axial direction in order to measure the input frequency and amplitude (Fig. 6). Different configurations of the accelerometer position are taking into account in order to highlight the vibration level and transmissibility effect to the panel.

A second set of tests were made for horizontal position of the panel (Fig. 7). These tests were necessary due to the *sheet* shape of the panel. The stiffness of the panel is non-uniform in all 3 directions.

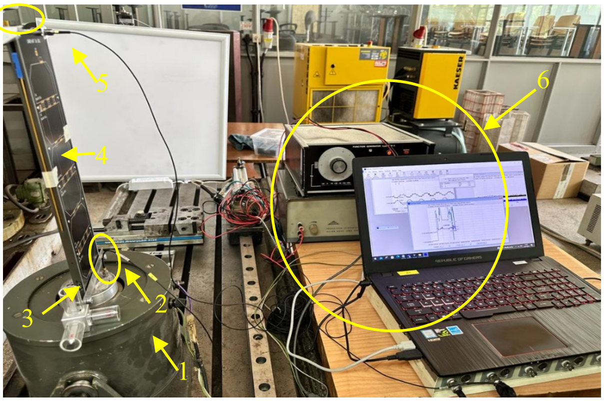
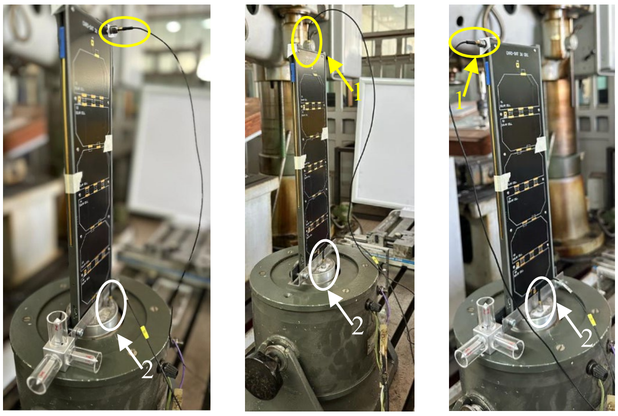



**Fig. 5.** Testing stand (vibrating exciter, CARDSAT panel, accelerometers, data acquisition system).



a. b. c.

**Fig. 6.** Direction of measuring: *a* – accelerometer on *X*; *a* – accelerometer on *Z*, *c* – accelerometer on *Y*.

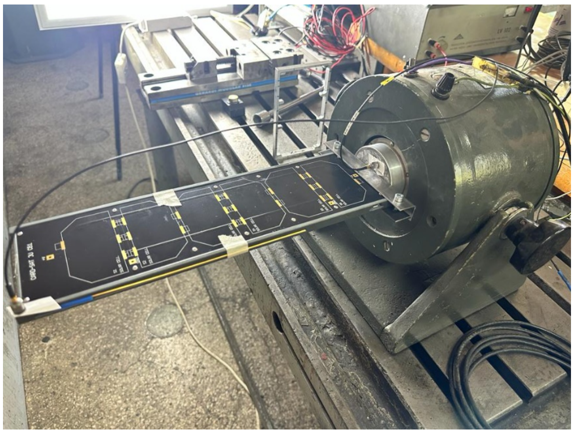


**Fig. 7.** Horizontal position of CRADSAT panel on testing stand (horizontal actuator).

## 4. VALIDATION TESTS PLAN

The measuring plan was designed according to ESA test.

For two positions of CARDSAT panel on the shaker, vertical and horizontal the following test were made:

1. Impact test (Bump test).
2. Low level sinusoidal impulse vibrations.
3. High level sine-sweep vibration.
4. Random vibration.
5. Shock vibration.

One of the most information to perform the test on the vibration shaker is to identify the natural frequency. Regarding this scope, the determination is based of two types of test: impact test and excitation test. Ussuly for natural frequency determination one of the test is sufficient. To understand more deeply the fixing influence of the micorsatelite structure, the impact test validates the frequency identification.

The purpose of measuring own frequencies (Figs. 8 and 9) at impact is to verify the excitation frequencies generated by the exciter.

During the vibration test on the shaker (Fig. 10 and Fig. 11) fundamental frequency of the microstallite is 15.7 Hz in relation with 15.87 Hz.

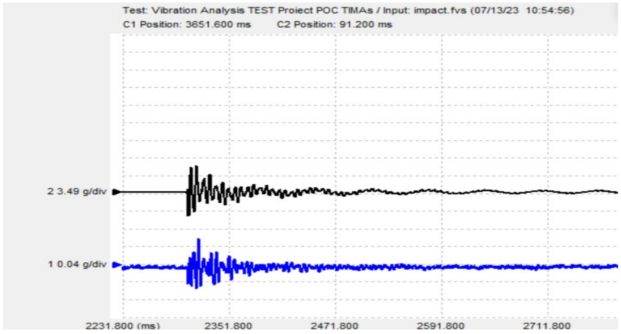



**Fig. 8.** Waveform on impact.

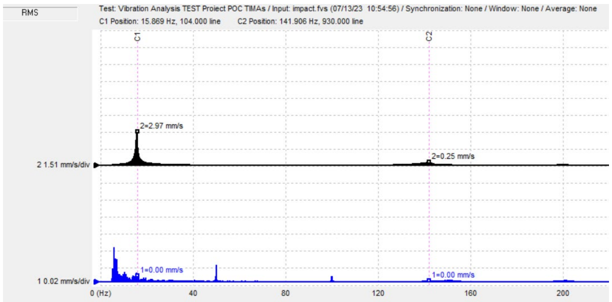



**Fig. 9.** Frequency spectrum for impact test.

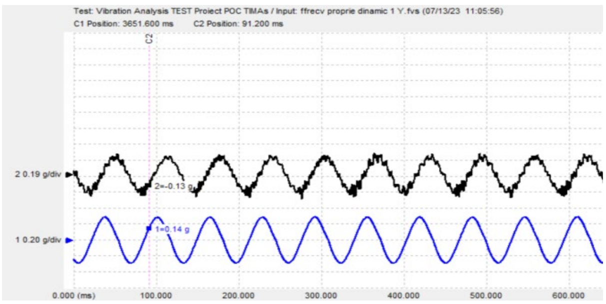



**Fig. 10.** Waveform for dynamic test.

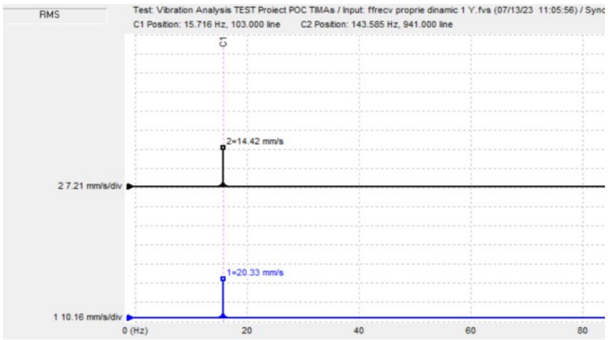



**Fig. 11.** Own frequency measured in dynamic test.

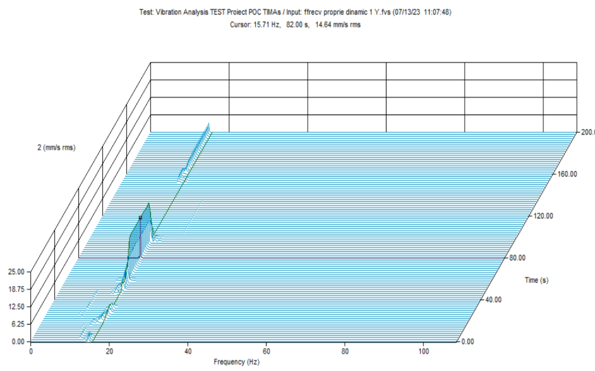


**Fig. 12.** Waterfall diagram following forced excitation to determine own frequency.

Also in the Fig. 12, the natural frequency is highlighted without other frequency components.

One can observe the similarity between the natural frequency determined at impact and those determined by the excitation induced by the exciter. For one panel in standard configuration the natural frequency is 15.7 Hz.

Knowing the fundamental frequency, specific tests related to testing can be performed in accordance with the ESA requirements.

The next test to be performed is the low level sinusoidal impulse.

The test provides a low level and allows us to reliably assess the natural frequencies of the system to avoid excessive damage due to non-linear responses.

In Fig. 13, the two waveform signals are presented: the generating or excitation signal (no. 1) and the vibration signal of the panel, respectively the response signal, signal no. 2.

The wtarefal diagram (Fig. 14) shows the frequeny distribution according with generated excitation. The damping of the panel is important and the vibration level is much smaller than the exciter vibration level.

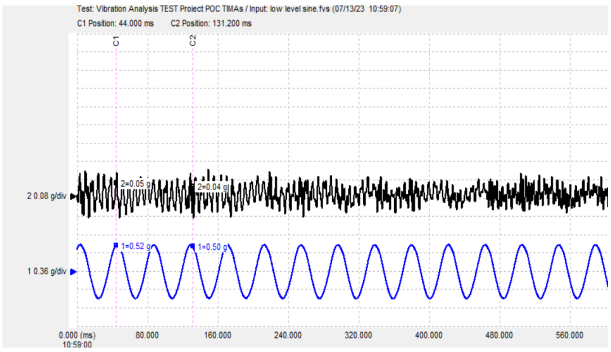


**Fig. 13.** Waveform at low level sine vibration.

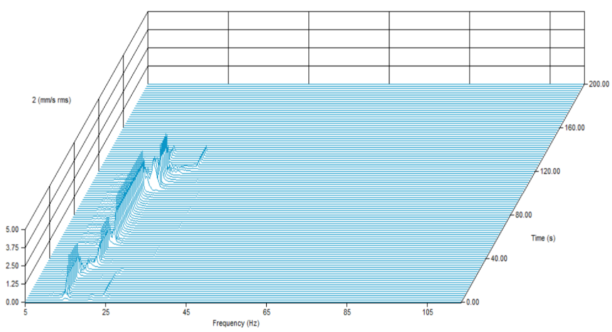


**Fig. 14.** Waterfall Low Level Self Chart.

After low level sin test, the next test is the high level sine-sweep. Similar to the low-level sine test, during this test the target is subjected to a uniaxial sinusoidal motion of increasing frequency.

In Fig. 15, one can observe the variation of the frequency of generating vibration, passing from low to high frequencies.

The resulting vibration amplitude of the target is smaller and shows low frequencies without response to high frequencies, show in Fig. 16.

For an overall level between the two signals, you can see in Fig. 17, the trend with the amplitude difference between the exciter vibration and microsatellite vibration.

When the frequency is varied (Fig. 18), the excitation with the most important amplitude is around the natural frequency. In this way, the Fig. 19 shows the natural frequency excited during the shaker vibration.

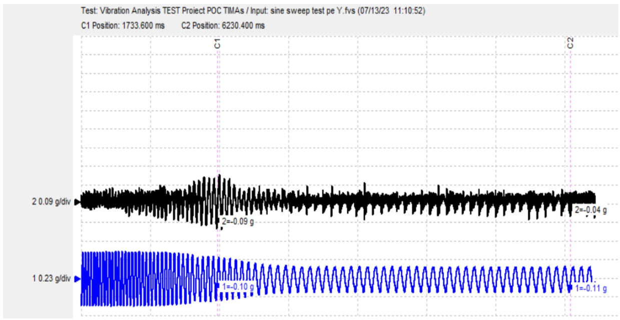


**Fig. 15.** Waveform for Sine Sweep test.

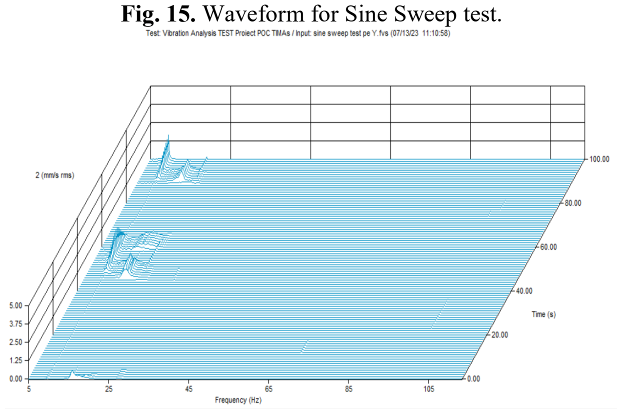


**Fig. 16.** Sine Sweep Waterfall chart.

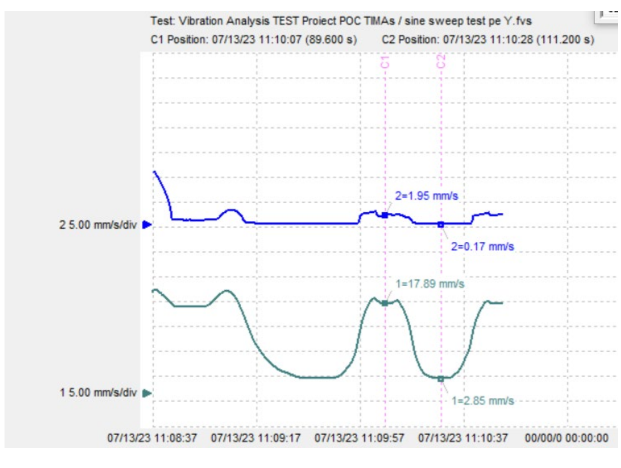



**Fig. 17.** Trend chart for Sine Sweep test – measurement direction *Y* (vertical configuration).

To analyze the influence of vibrations on the microsatellite panel in the different fixing positions, horizontally and vertically, the vibration evolution is shown in Figs. 20 and 21. In the case of the horizontal position (Fig. 21), the panel reaches amplitude up to 20 mm/s·rms.

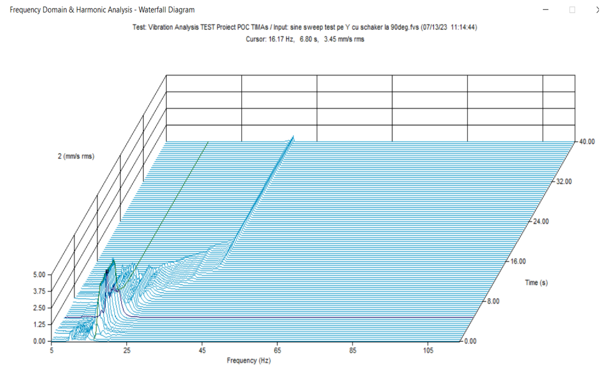



**Fig. 18**. Waterfall chart in case of Sine Sweep test on CARDSAT panel – horizontal position.

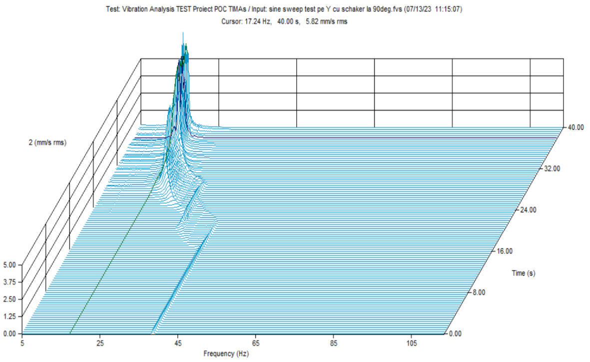



**Fig. 19.** Waterfall diagram for Sine Sweep test in horizontal direction, highlighting the own frequency of 17.2 Hz.

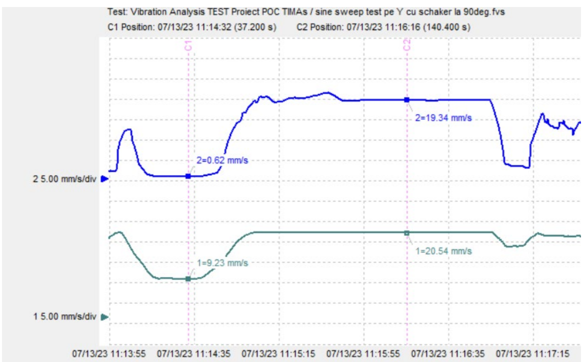



**Fig. 20.** Trend chart for Sine Sweep test, in case of horizontal panel position.

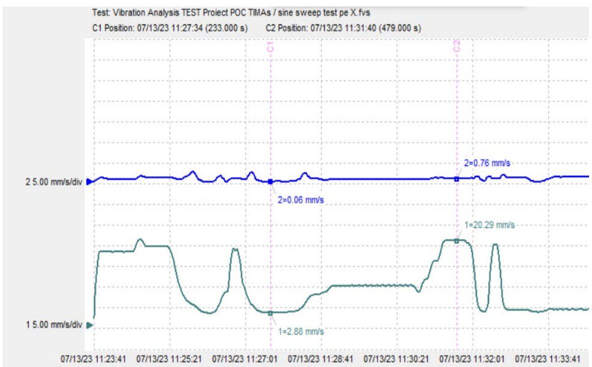



**Fig. 21.** Trend chart for Sine Sweep test – *X* direction of measurement (vertical position).

The same test is made on the *Z* direction, obtaining a high frequency response (Fig. 22). In the case of vertical position of the panel the vibration level is amplified on the *Z* direction, reaching 2.95 mm/s·rms (Fig. 23).

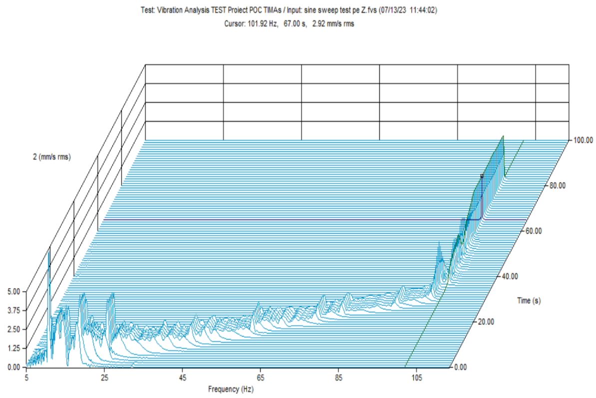



**Fig. 22.** Waterfall diagram for *Z*-direction Sine Sweep test (vertical configuration).

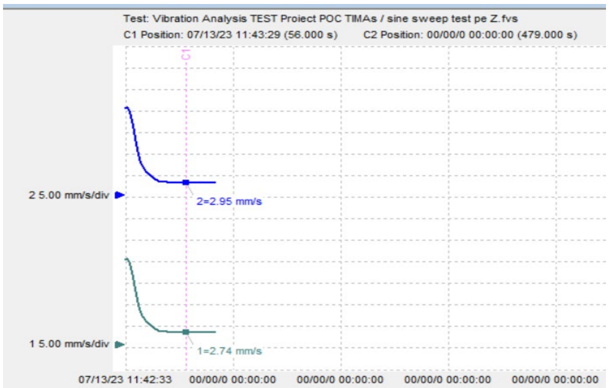



**Fig. 23.** *Z*-direction Sine Sweep trend chart.

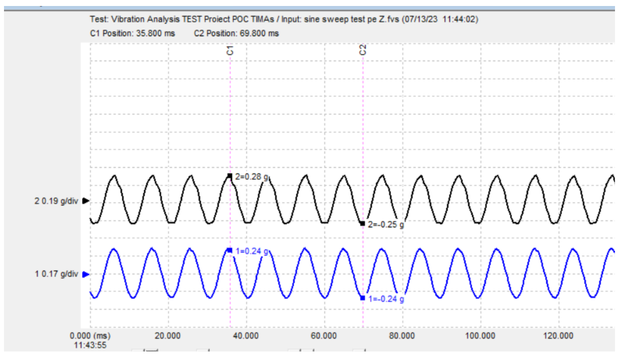



**Fig. 24.** Waveform in the case of the Sine Sweep test on *Z* direction.

The vibration waveform between the 2 signals present a very good precision in phase which shows a proper transmibility between shaker and panel (Fig. 24). Concerning the *Z* direction the vibration level increases at the 102 Hz, and represent an important frequency excitation (Fig. 25).

In order to know the global behavior of the panel, the testing is also carried out under high level sine sweep vibration. In *Z* direction (Fig. 26) the amplitude of acceleration is 0.56 g·rms with a higher amplification than the exciter vibration.

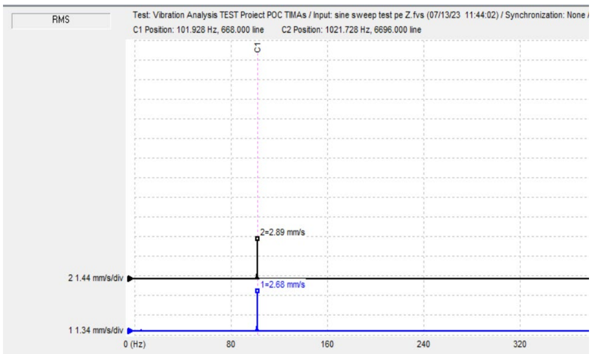



**Fig. 25.** Frequency spectrum in case of vertical configuration, *Z*-direction.

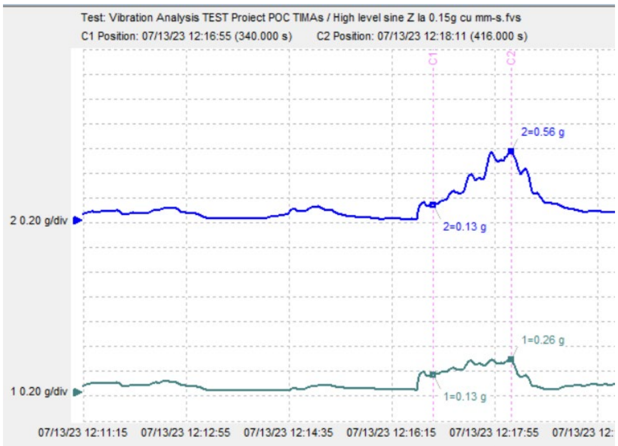



**Fig. 26**. Trend chart for High Level Sine Sweep vibration – *Z*-direction of measurement.

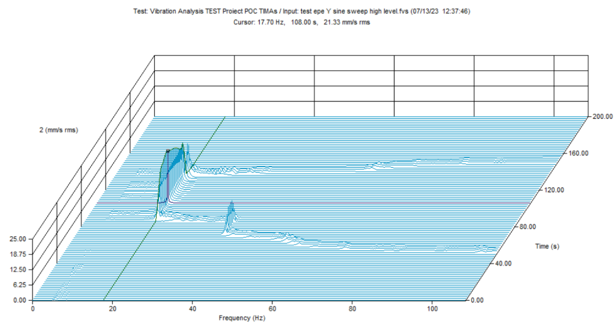



**Fig. 27.** Waterfall diagram for the High Level Sine Sweep vibration test in the *Y* direction (vertical configuration).

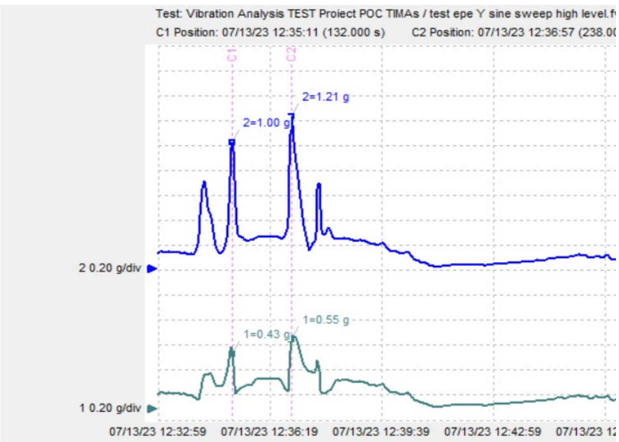



**Fig. 28.** Trend chart for the High Level Sine test – *Y* direction (vertical position).

During the hig level sine test the vibration of the panel reach the acceleration to 1.2 g·rms (Fig. 28) wich is very important because it allows analyzing the condition of the panel.

The ESA test also proposes testing for shock and random vibrations. The tests of shock need an external source of vibration to ensure a high energy peack. During the shocks test the vibration level of the shaker reach the maximum amplitude around 68 mm/s·rms and the vibration level of the panel reaches the values of 13.5 mm/s·rms.

For a qualitative analysis the vibration of the waveforme is analyzed both in time (Fig. 30) and frequency domain (Fig. 31). The vibration energy shows a frequency pick at 38.9 Hz but very damped.

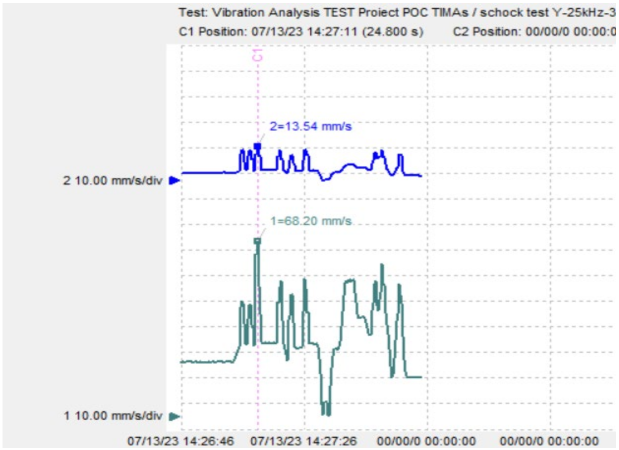



**Fig. 29.** Trend in dynamic shock test.

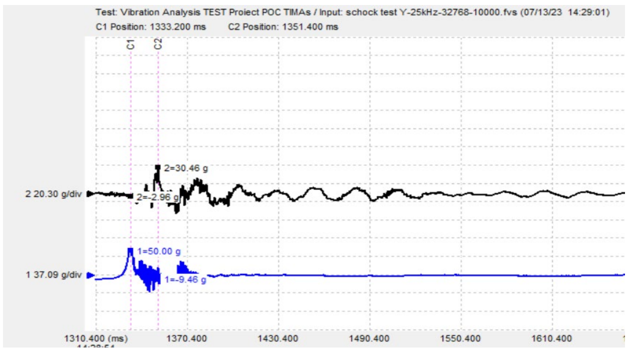



**Fig. 30.** Shock test waveform.

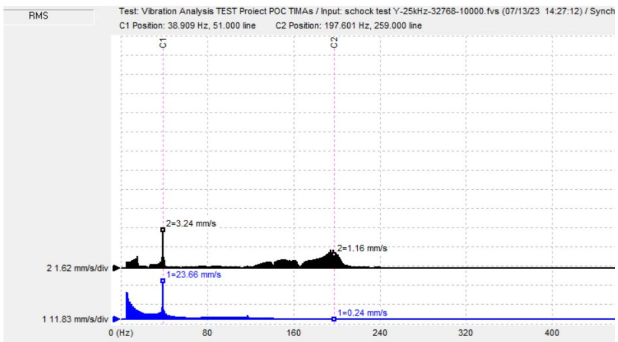



**Fig. 31.** Spectrum of vibration speed in the case of shock test.

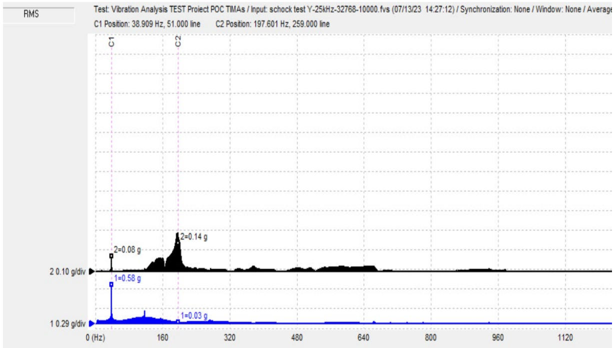



**Fig. 32.** Spectrum in the shock test.

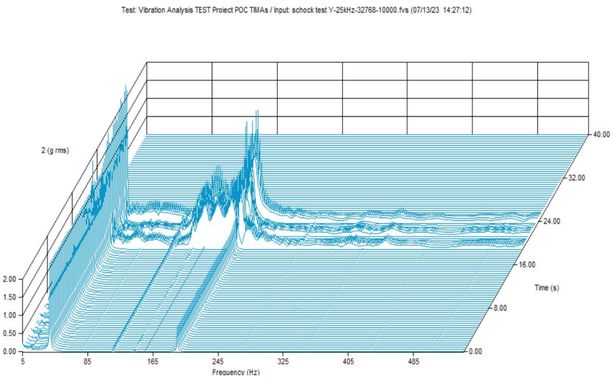



**Fig. 33.** Shock test Waterfall chart.

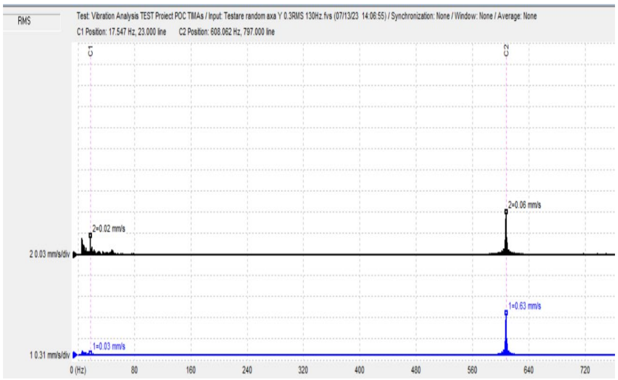



**Fig. 34.** Frequency spectrum in random vibration test.

Considering that the multiple constraints have as a source of vibrations the shocks during the launch, the vibration analysis is also focused on the accelerations (Fig. 32 and Fig. 33). The amplitude of the acceleration shock reaches 2.2 g·rms on the microsatellite panel, Fig. 33.

Another important condition of mechanical stress is generated by random vibrations.

Random vibration analysis provides testing in several generator vibration configurations, respectively 20 Hz, 130 Hz, 800 Hz and 2000 Hz. Figure 34 shows the random vibrations up to 600 Hz, where the most important amplitude is located at 200 Hz.

As a result of the testing, it was possible to inspect the state of the panel, both from a mechanical point of view: loosening of screws, deformations or cracks, as well as electronically: weakening of electronic components or broken circuits. Based of this inspection, it was found that the microsatellite panel is in its original condition, showing the integrity of all components as well as the mechanical integrity of the structure.

## 5. CONCLUSIONS

The testing was carried out for a single CARDSAT panel according with NASA specific test conditions. The first tests were aimed at highlighting the necessary parameters in order to establish the vibration conditions to which the structure will be subjected.

In order to obtain specific test conditions, a first testing protocol was carried out, using existing equipment within UNSTPB, RSP department.

In this context, a test stand was designed and built so that it would be possible to perform specific tests on a microsatellite panel.

Following the specific vibration tests to which the panel was tested, the integrity of the panel and electronic circuits could be observed by visual inspection. Following the inspection, cracks, loosenings or detachments of the electronic circuits were not observed.

One goal of this test was to identify and set-up the right parameters for measuring devices in order to be used on final CARDSAT prototype tests.

In conclusion, the dynamic behavior of a single, fully equipped panel is stable, without identifying defects after testing.

The determination of the own frequencies is a necessary condition for compliance with the test conditions, so as to avoid the phenomenon of resonance on the test stand.

For the tested CARDSAT panel the own frequencies were 15.8 Hz and 17.2 Hz.

Knowledge of the dynamic test rig is also a prerequisite to be fulfilled before the tests are carried out, so that the dynamic signature of the stand can be distinguished from the actual behaviour of the CARDSAT microsatellite tests.

Compliance with repeatability requirements for tests should be another requirement to be respect.

The first 3U CARDSAT microsatellite prototype tests, in according with NASA standards, prove the fiability of the prototype as a complex product with many components mechanical and electronics.

This first test provides the validation premises for further research and testing in a multi-panel configuration, respectively a complete multi-panel microsatellite structure.

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