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STRUCTURAL ANALYSIS AND VIBRATION TESTING OF THE TUMnanoSAT MICROSATELLITE

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Abstract. One of the important verification steps before the launch of the nanosatellite developed at Technical University of Moldova (TUMnanoSAT) was vibration testing of the real model. These tests were carried out according to the requirements submitted by the Japan Aerospace Exploration Agency (JAXA) in collaboration with which the launch of our nanosatellite was possible. Thus, in order to validate the structural integrity of CubeSat nanosatellites under launch loads, a 1U TestPod was designed and manufactured. This work presents hands-on experience of the vibration testing of the TUMnanoSAT microsatellite and simulation of static and dynamic loads. The dynamic behavior was analyzed by checking the harmonic oscillations (modal analysis and random vibrations) in order to avoid critical frequency (140 Hz). The testing facilities were provided by the Space Science Institute from Bucharest. The microsatellite was vibration tested in X, Y and Z axis directions according to special requirements. The numerical calculation model was developed in ANSYS Workbench. Comparison of the experimental results and numerical modal tests showed a good correlation within 10%.

Keywords: *CubeSat, modal survey, random vibration, static loads, simulation.*

Rezumat. Una dintre etapele importante de verificare înainte de lansarea nanosatelitului dezvoltat la Universitatea Tehnică a Moldovei (UTM) (TUMnanoSAT) a fost testarea la vibrații a modelului real. Aceste teste au fost efectuate în conformitate cu cerințele prezentate de Agenția Japoneză de Explorare Aerospațială (JAXA) în colaborare cu care a fost posibilă lansarea nanosatelitului nostru. Astfel, pentru a valida integritatea structurală a nanosatelitului de tip CubeSat sub sarcini de lansare, a fost proiectat și fabricat un TestPod 1U. Această lucrare prezintă experiența practică a testelor de vibrații a microsatelitului TUMnanoSAT și simularea sarcinilor statice și dinamice. Comportamentul dinamic a fost analizat prin verificarea oscilațiilor armonice (analiză modală și vibrații aleatorii) pentru a evita frecvența critică (140 Hz). Instalațiile de testare au fost puse la dispoziție de Institutul de Științe Spațiale din București. Microsatelitul a fost testat la vibrații în direcțiile axelor X, Y și Z în conformitate cu cerințele speciale. Modelul de calcul numeric a fost dezvoltat în

ANSYS Workbench. Comparația dintre rezultatele experimentale și testele modale numerice a arătat o bună corelație în limita a 10%.

Cuvinte cheie: *CubeSat, studiu modal, vibrații aleatorii, sarcini statice, simulare.*

1. Introduction

The CubeSat concept was first introduced in 1999 at Stanford University's Space Systems Development Laboratory and since then has gained widespread adoption across the globe. It was originally intended as an educational tool to allow students and researchers to design, build, and deploy small satellites at a fraction of the cost of traditional missions. Over time, CubeSats have become an important tool for commercial, governmental, and academic space missions. The current microsatellite launch project was achieved within the Cooperation Program for CubeSat Implementation of the International Space Station (ISS) from Japan, using the "KiboCUBE" experiment module. Such project is intended to provide the PhD and master students from Technical University of Moldova (TUM) the capacity to join the research for space technology and engages engineering students in a multi-disciplinary design process that will leverage their academic expertise across all backgrounds [1-3].

The standard CubeSat design is the 1-Unit (1U) CubeSat, which is a cube-shaped satellite measuring 100x100x113.3 mm and weighing up to 1.33 kg. CubeSats are typically launched as secondary payloads aboard larger rockets, often using deployers like the Small Satellites Orbital Deployer (SSOD), allowing reducing launch costs significantly.

Strict standards have been established for the structural integrity of CubeSats to withstand high static and dynamic loads during launch, while also ensuring the safety of nearby satellites. Like larger satellites, CubeSats must undergo rigorous testing to ensure they will function properly in the harsh space environment.

This includes thermal testing, vibration testing (to simulate launch conditions), and vacuum testing (to simulate the vacuum of space). The stiffness of structure must be designed so that its fundamental longitudinal and lateral frequencies meet the minimum values specified by the selected launcher. In addition to the necessary tests, thanks to the progress of computer technologies and numerical discretization methods, in the last decade various studies and simulations of the static and dynamic behavior of microsatellites have been carried out. Extensive recent research indicating methods for testing and analyzing the vibrations of satellites using ANSYS software are presented in the works [4–6]. Another interesting vibration analysis in COMSOL software and testing of a 6U CubeSat propulsion system is reported in the master thesis [7]. Aspects regarding the reduction of vibrations between the launcher and the satellite are presented in the master thesis [8] through the use of insulating materials.

A comprehensive approach to the design, analysis and optimization of a 2U Cubesat microsatellite using MSC Nastran software was performed by a team from University of Patras [9]. This work presents hands on experience of the vibration testing of the 1U TUMnanoSAT microsatellite, the simulation of the modal analysis and the correlation of the obtained results.

The testing facilities were provided by the Space Science Institute from Bucharest. The microsatellite was vibration-tested in the X, Y and Z axis directions. The numerical calculation model was elaborated in ANSYS Workbench 2021. Finally, the simulation results were validated with that of testing.

2. Numerical structural analysis of the microsatellite

2.1. Elaboration of the numerical calculation model

One of the stages of satellite design is the analysis of the behavior according to the operating conditions. This analysis consists of running virtual tests that may include the manufacturability test, an allowable stress analysis test, and the dynamic response analysis test. Carrying out such studies on the models leads to the optimization of the parts and increasing the ability to function in the desired environment. The virtual model of the satellite structure is tested several times, eliminating a good part of the real tests and achieving cost reduction. At the same time, the mass of the parts is also optimized, determining its minimum value to have an adequate structural strength.

Before conducting virtual satellite tests, it is necessary to prepare the appropriate geometry and establish the boundary conditions. For most spacecraft, including satellites, the greatest stresses occur during launch. These include g-acceleration (longitudinal and lateral) and random and harmonic vibration stress over different frequency ranges. The g-acceleration value is provided by the company that will provide the launch of the satellite. Once all the loads and launch characteristics are known, the structure can be modeled and tested using various modeling and simulation software (SolidWorks, Fusion 360, ANSYS, etc.). These applications provide various modules for manufacturability simulation and structural analysis of the created models. Manufacturability tests make it easy to determine the machining conditions of parts so that users can estimate the time, complexity and cost required to make them. Structural analysis tests facilitate the determination of the strength of the satellite assembly under specified launch and flight characteristics.

The geometry of the TUMnanoSAT satellite was developed in the SolidWorks 2020 software. The geometry was then imported into ANSYS Mechanical 2021 for finite element discretization and boundary condition imposition. All component elements were modeled with simplified geometries and equivalent masses were imposed to obtain the center of gravity approximately at the geometric center (Figure 1).

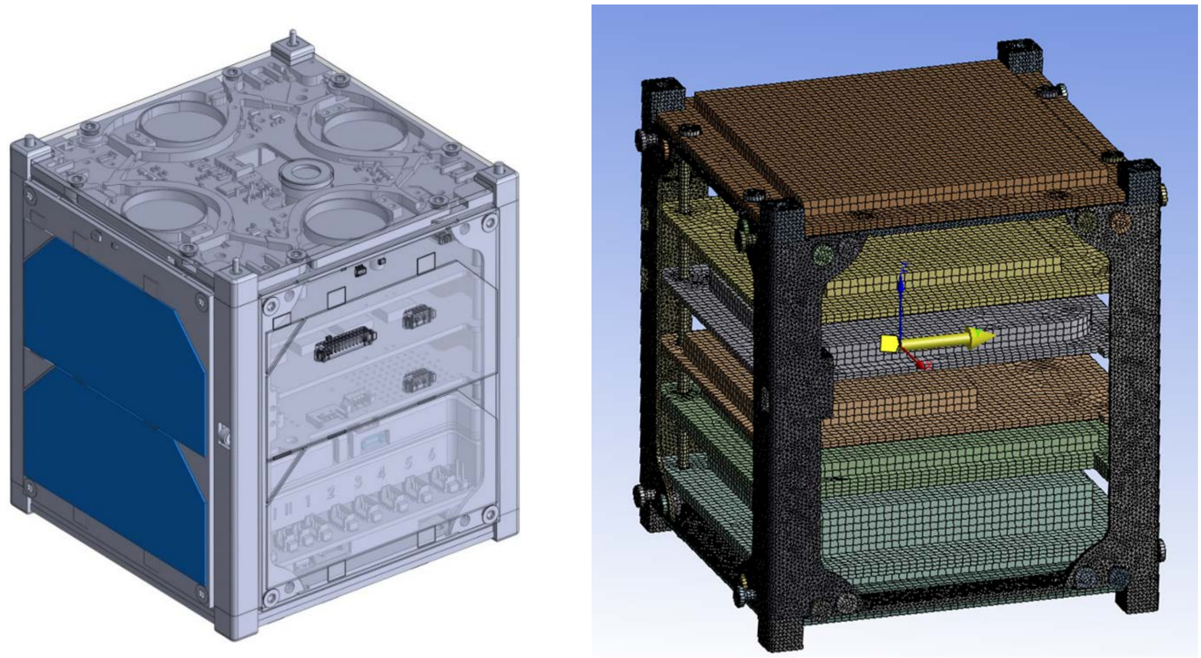


Figure 1. TUMnanoSAT 3D model and numerical calculation meshed model.

In order to perform the finite element analysis of the satellite in good conditions, the following simplifications were imposed:

- All internal components not on the main stress path have been replaced with a simulated point mass inside the structure. This mass is located at the center of the satellite or at the center of the simulated component and is connected to the main structure.
- The mass of external components outside the main structure, such as solar cells, has been included as a point mass fixed with the respective screws;
- Global bonded contact condition is used on fastener threads to eliminate errors created by bolts and complex geometry. The frictionless sliding contact condition is used at the component interface.
- Unnecessary threads and holes were suppressed from the structure parts;
- For the materials used, their real properties are applied;
- All fastening elements (screws) are pre-tensioned with axial forces equivalent to the admissible torque (Table 1).

In the result of the simulations, the following parameters of interest were analyzed: von Mises stresses, displacement, deformation and safety factor. After a series of simulations, the critical areas (where the safety factor is at the admissible limit) were detected and measures were taken to exclude them, such as changing the geometry or materials.

Table 1

Axial load of fastener

Type	Nominal diameter, m	Initial torque, Nm	Axial load, N
M3	0.003	0.63	1050

The imposed constraint conditions are presented in the Table 2 and the values of the static loads acting on the nanosatellite structure are presented in the Table 3."

Table 2

Constraint condition

Natural Frequency Analysis	-Z face of rails	Fixed Geometry (no translations)
	+Z face of rails	Fixed Geometry (no translations)
	Surface of rails contacted with J-SSOD	No constraint
	Thread face / contacted material	Global bonded contact
	Boundary condition between other materials	Frictionless sliding contact
Static Load Analysis / Bolt Analysis	-Z face of rails	Fixed Geometry (no translations)
	+Z face of rails	No constraint
	Surface of rails contacted with J-SSOD	No constraint
	Thread face / contacted material	Global bonded contact
	Bolt head / contacted material	Global bonded contact
	Boundary condition between other materials	Frictionless sliding contact

Table 3

Loading condition

	Loading condition	Applied location	Value
Natural Frequency Analysis	No load	-	-
Static Load Analysis / Bolt Analysis	Force	+Z face of rails	46.6N (each rail)
	Gravity / pretension	-	9 G (direction is changed in each analysis cases)

2.2. Static loads analysis

The model of the TUMnanoSAT satellite was tested (virtually) on the stress conditions for the three directions of the coordinate system (denoted by the letters A, B and C). The 3D mesh model of the satellite with the imposed loads for one case is presented in Figure 2.

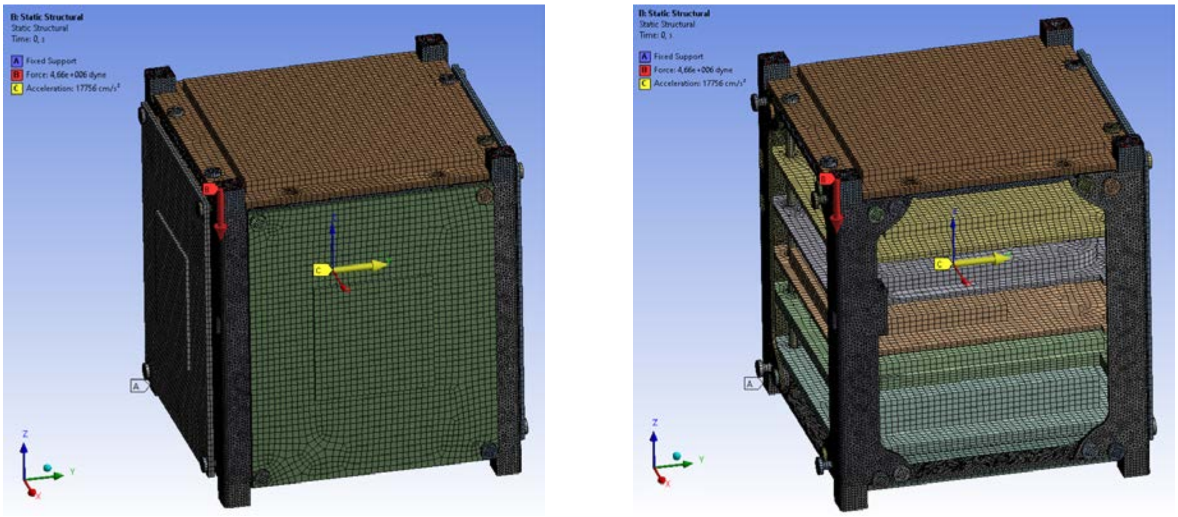


Figure 2. TUMnanoSAT 3D mesh model.

The analysis conditions are presented in Tables 4–6 and contain the following aspects:

a) Using the launcher's quasi-static acceleration levels, the model was subjected to a static load of 9G (88.3 $m \cdot s^{-2}$) in-plane with the launch axis (1G = 9.81 $m \cdot s^{-2}$);

b) An axial force of 46.6 N is applied to each rail;

c) Each rail is rigidly fixed at the base (-Z axis).

Table 4

Load applied on FEM (analysis A)

Load	X axis	Y axis	Z axis
Compressive Load	-	-	46.6 N
Static Load	9G	-	-

Table 5

Load applied on FEM (analysis B)

Load	X axis	Y axis	Z axis
Compressive Load	-	-	46.6 N
Static Load	-	9G	-

Table 6

Load applied on FEM (analysis C)

Load	X axis	Y axis	Z axis
Compressive Load	-	-	46.6 N
Static Load	-	-	9G

The results of the microsatellite model simulations are presented in Tables 7 – 9 for the three cases. After several trials and settings, the maximum von Mises stress values were obtained as 74 MPa, 67.6 MPa, and 10.3 MPa in analysis A, B, and C, respectively.

The margin of safety for the various frame components was calculated with the relationship below using a safety factor of 1.5 for the yield strength (F_{ty}) and 2.0 for the tensile strength (F_{tu}).

$$\mathrm{MS} = \frac{F_{tu}}{S_{max} \times FS} - 1 \geq 0. \tag{1}$$

The strength structure must also meet the following condition:

$$\frac{S_{max}}{F_{tu}} < 30\%, \tag{2}$$

where: S_{max} - maximum applied stress; F_{tu} - ultimate strength of the material.

Table 7

Satellite parts stresses and margin of safety (analysis A)

Part	Material	Max. Stress (S_{max}) (MPa)	Yield Strength Fty (MPa)	Ultimate Strength, Ftu(MPa)	MS*1 ≥0 (yield) FS*2=1.5	MS*1 ≥0 (Ultim.) FS*2=2	Smax/Ftu <30[%]
Main structure frame	Al 6061	74	275	310	1.48	1.09	23.9
Stacking rod	Al 6061	26.4	275	310	5.94	4.87	8.5

*1: Margin of safety, *2: Factor of safety

Table 8

Satellite parts stresses and margin of safety (analysis B)

Part	Material	Max. Stress (Smax) (MPa)	Yield Strength F_{ty} (MPa)	Ultimate Strength, F_{tu}(MPa)	MS*1 ≥0 (yield) FS*2=1.5	MS*1 ≥0 (Ultim.) FS*2=2	Smax/F_{tu} <30[%]
Main structure frame	Al 6061	67.6	275	310	1.71	1.29	21.8
Stacking rod	Al 6061	24.2	275	310	6.58	5.40	7.8

Table 9

Satellite parts stresses and margin of safety (analysis C)

Part	Material	Max. Stress (Smax) (MPa)	Yield Strength F_{ty} (MPa)	Ultimate Strength, F_{tu}(MPa)	MS*1 ≥0 (yield) FS*2=1.5	MS*1 ≥0 (Ultim.) FS*2=2	Smax/F_{tu} <30[%]
Main structure frame	Al 6061	10.3	275	310	16.80	14.05	3.3
Stacking rod	Al 6061	7.1	275	310	24.82	20.83	2.3

For example, in Figure 3, selective views of the constraint conditions and the distribution of equivalent stresses on the elements of the satellite structure for the Z direction load case are presented.

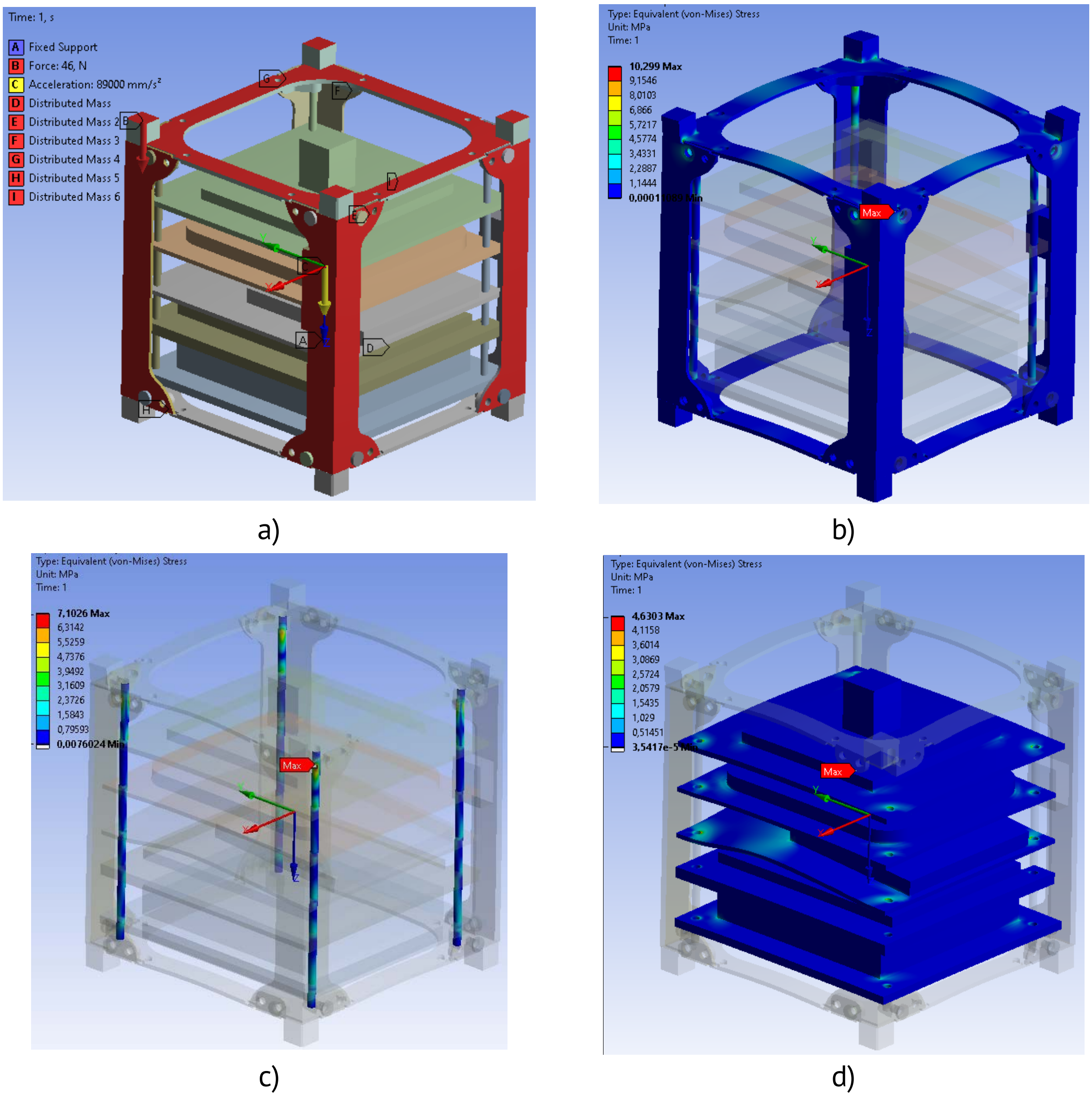
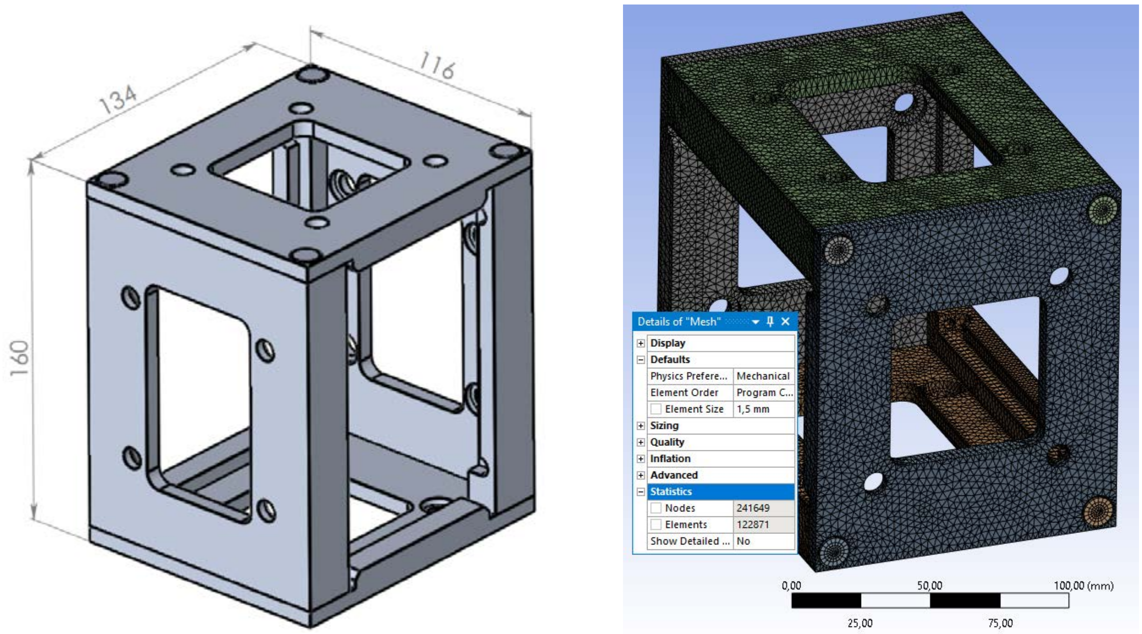


Figure 3. Result for analysis C (Z direction acceleration): a) load location; b) distribution of equivalent stress in main structure frame; c) – in stacking rod; d) – in internal components.

2.3. Dynamic loads analysis

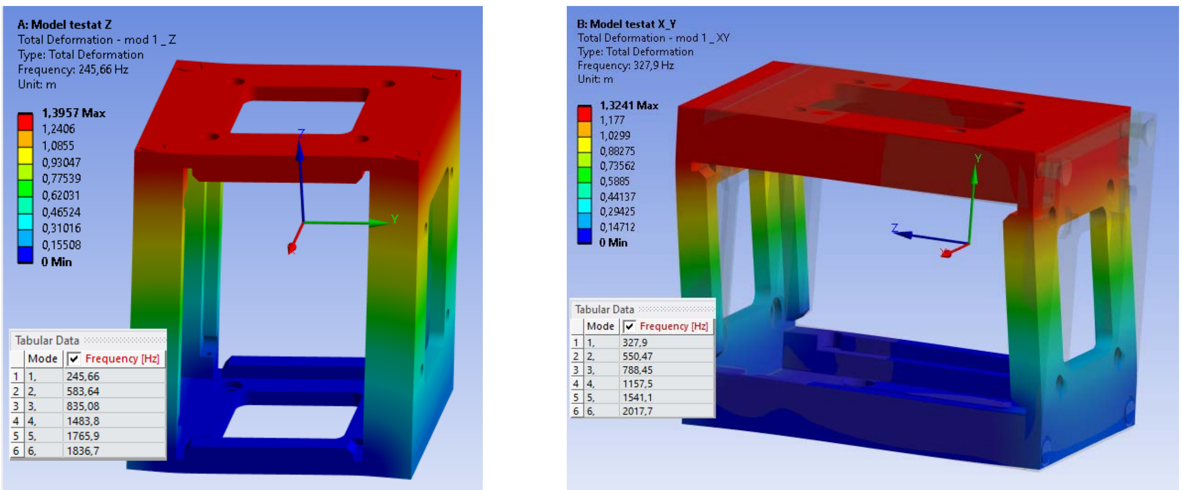
The dynamic behavior of the satellite is analyzed by checking the harmonic oscillations (eigenfrequencies). These checks are necessary to detect the occurrence of the resonance phenomenon. The checking of the harmonic oscillation shapes and eigenfrequencies was performed using the ANSYS Modal Analysis application in the Workbench platform. The simulations were performed separately for TestPod and microsatellite. The 3D model of the TestPod was developed in the SolidWoks 2020 application, Figure 4a. The numerical calculation model was elaborated in ANSYS Workbench after the geometry was imported. The model was discretized into more than 122800 finite elements, Figure 4b.



a) b)

Figure 4. TestPod modal analysis calculation model: a) geometry; b) discretized model.

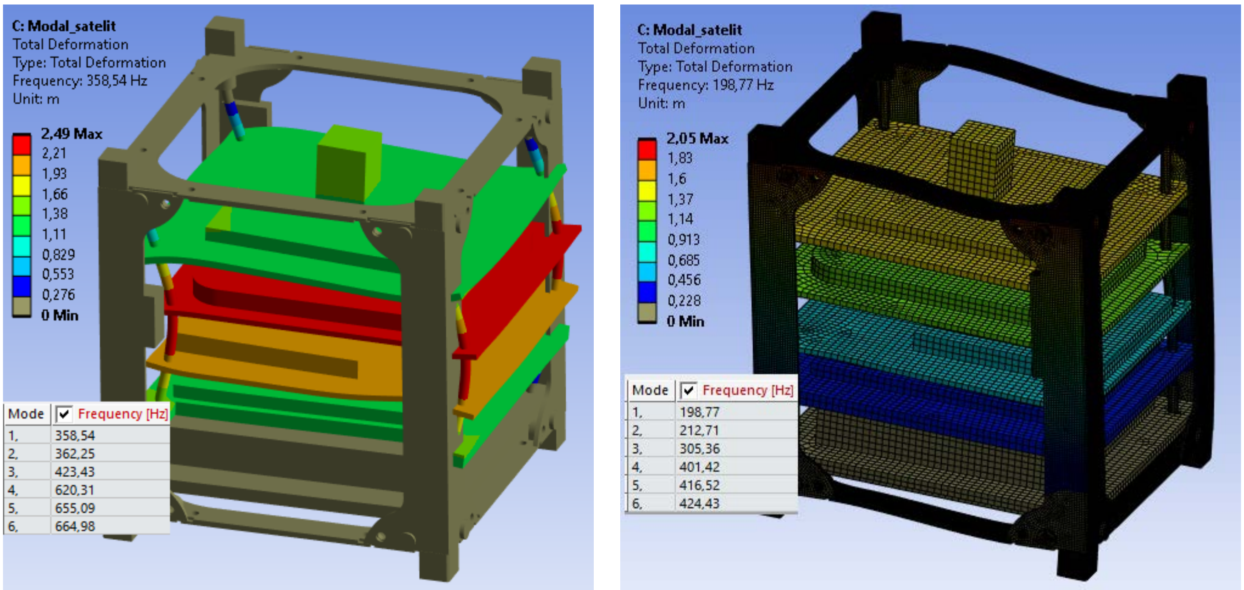
In order to cover the frequency range 20-2000 Hz in which the vibration tests take place, it was sufficient to set six natural frequency modes. The first principal mode of the TestPod deformation for the axis Y and Z is presented in Figure 5.



a) b)

Figure 5. TestPod first eigenform: a) Y axis; b) Z axis.

The microsatellite modal analysis simulation took place according to JAXA recommendations. Thus, to simplify the computational model of the microsatellite, the PV cells on the 6 faces were replaced by equivalent masses. In order to emulate the microsatellite mounting conditions in TestPod, the four rails of the satellite structure were fixed at both ends, similar to the boundary conditions presented in [10]. The numerical calculation model is the same as in the static analysis (Figure 1). The modal analysis is a general one and has not been done distinctly on the 3 axes due to software limitations. On the other hand, validating the results of the simulations is more difficult because during the vibration tests the measurements are made only on the TestPod body. The first eigenform of the microsatellite vibration and 6 natural frequency range are illustrated in Figure 6*a*. For comparison, a simulation was performed under the conditions of fixing only one end of the rails of the satellite structure. The results are presented in Figure 6b.



a) b)

Figure 6. Microsatellite first eigenform: a) 4 rails both fixed end; b) 4 rails one fixed end.

3. Experimental vibration testing

2.1. Equipment and work steps

The microsatellite vibration test methodology foresees the following verification: the presence of fractures in the main structure; the main structure must satisfy the specified natural frequency (>140 Hz); the natural frequency before and after testing must remain unchanged; fracture of glass elements such as photovoltaic cells; loosening of fasteners.

Vibration tests were performed along the X, Y and Z axes and according CubeSat general testing flow diagram [11]. These include low level sinusoidal scanning (modal survey) and random vibration [12]. Low-level sinusoidal scanning is suitable for model checking of simple structures with relatively rigid components whose flexibility is limited to mounting brackets or frequency isolation devices.

Before the nanosatellite test, according to the requirements, the empty TestPod was tested on the Y and Z axes (for the X axis the nanosatellite can be repositioned inside the Pod). The TestPod was designed and manufactured at TUM FabLab facilities according 1U CubeSat standard and available testing facilities requirements at Bucharest Space Science Institute.

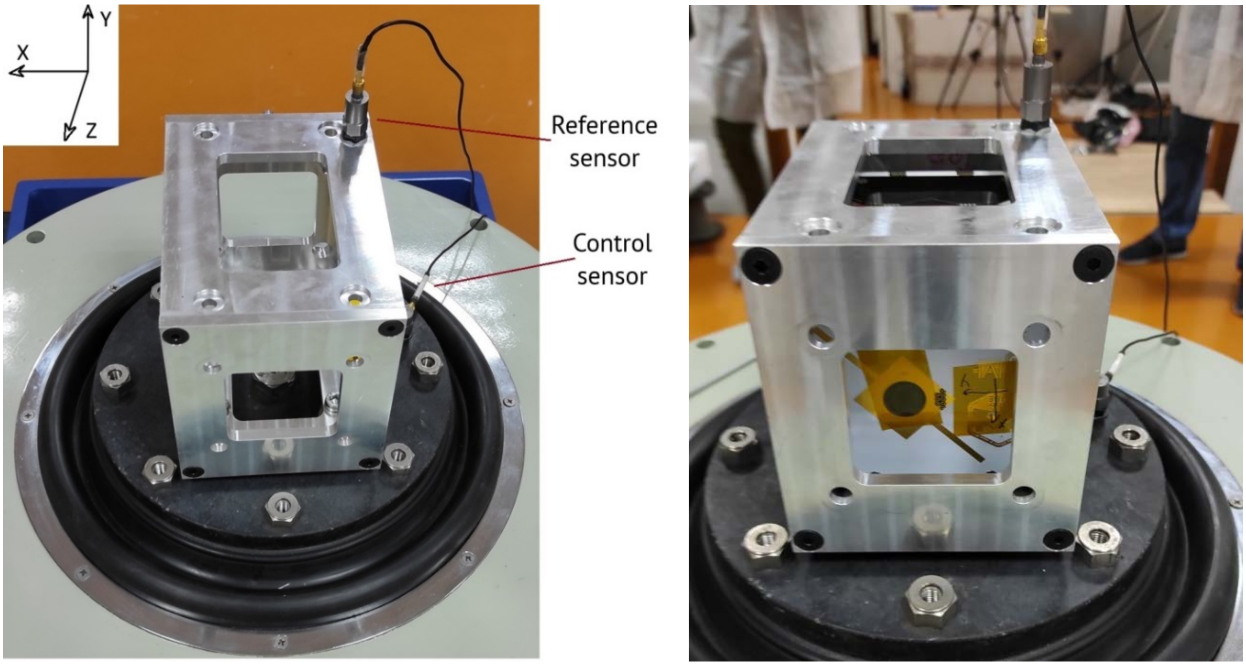
According to JEM Small Satellites Orbital Deployer the following test sequences should be performed, Table 10.

Table 10

Test sequence

Sequence	Test Contents
Before vibration test	Visual inspection of satellite
X, Y, Z – axis test*	Random vibration test (without satellite) Satellite setup Modal survey Random vibration test Modal survey
After vibration test	Visual inspection of satellite Function test of satellite

The TestPod mounted on the test Jig is presented in Figure 7a and with nanosatellite inside - Figure 7b. The attached accelerometer generates a voltage signal that corresponds to the amount of vibration and the frequency of vibration the machine is producing.



a) b)

Figure 7. CubeSat test configuration: a) empty TestPod; b) TestPod with satellite.

The characterization of random vibration typically results in a frequency spectrum of Power Spectral Density (PSD) or acceleration response over frequency domain (ASD) which designates the mean square value of some magnitude passed by a filter, divided by the bandwidth of the filter.

This parameter is measured in g^2/Hz. The random vibrations are generated by the operation of the space launcher propulsion system and by the vibro-acoustic response of the adjacent structure, [13]. Vibration test level is presented in the Table 11.

The random vibration test control sensor response for the axis X is presented in Figures 8a (empty TestPod) and 8b (with Satellite). For the other axes the diagrams do not show significant differences.

Table 11

Random vibration test level

Freq. [Hz]	PSD [G^2/Hz]
20	0.02
40	0.02
80	0.04
500	0.04
2000	0.01
Overall	6.79 Grms
Duration	1 min/axis
Direction	3 axes each

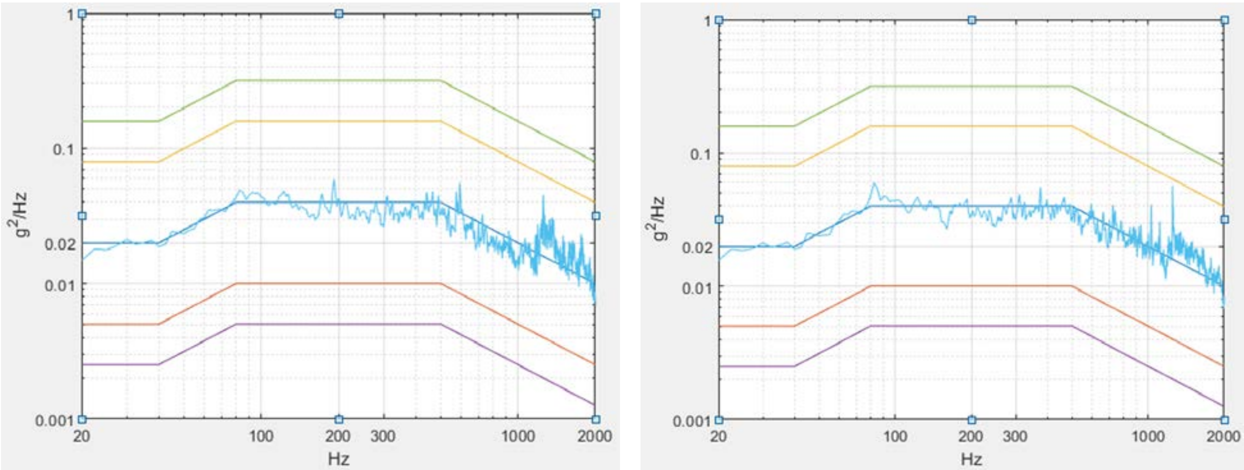
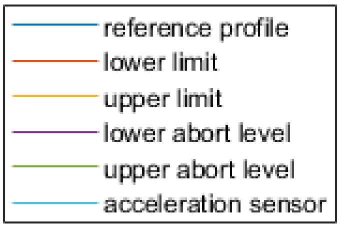


Figure 8. Random vibration test control sensor response for the axis X; *a)* and *b)* random vibration test control sensor response.

As can be seen on the diagram, different colored profiles are drawn to indicate the limits of permissible and critical vibration level, Table 12.

Table 12

Admissible and critical limits of the vibration level

	*Reference profile:* a baseline or target vibration level that the system is expected to achieve under normal operating conditions. *Lower limit*: the minimum acceptable level of vibration. Any reading below this line may indicate a problem, such as insufficient excitation or sensor failure. *Upper limit*: the maximum allowable level of vibration under normal operating conditions. Exceeding this limit may suggest potential component damage or wear. *Lower and Upper abort level*: This is a critical threshold. If the measured vibration level exceeds this limit, the system should be shut down immediately to prevent further damage. *Acceleration sensor*: This line represents the actual measured vibration levels obtained from the acceleration sensor (real-time data).

The test level in the modal study is shown in Table 13. Acceleration data measured by modal survey are illustrated in Figure 9. The blue line graph shows the response of the acceleration sensor.

Table 13

Modal survey vibration environment

Measurement axis	Frequency, Hz	Amplitude, G	Sweep Rate, Oct/min	Sweep Direction
Each axis	20~2000	0.5	1	Sweep up/Once

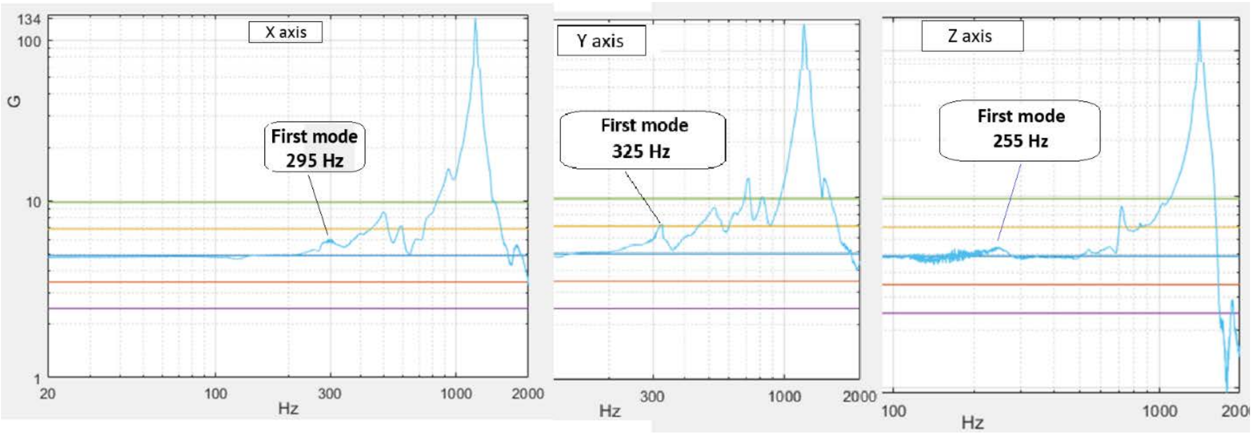


Figure 9. Modal testing results.

3. Results and discussions

No distortion or damage to the TUMnanoSAT microsatellite and solar battery was observed during and after vibration tests. Also, by visual inspection, no loosening of the main structure fasteners and no damage to the glass elements (camera lens and PV cells) were found. The natural frequency at the lowest order of TUMnanoSAT was above 140 Hz, which satisfies the stiffness requirements specified by JAXA.

Static load analysis shows the following results. The value of minimum margin of safety obtained for yield strength is 1.48 and for ultimate strength is 1.09 satisfying the condition (1). Another resistance condition (2) calculated with the ratio of maximum applied stress and ultimate strength of the material <30% is also satisfies (the maximum value obtained ≈24%). The maximum equivalent stress (74 MPa) occurred in main structure frame made from Al 6061. For the comparison, in the research carried on 3U CubeSat structure analysis [14] made from Aluminum alloy 6061 and 6082 with very close properties, the maximum stress was 76.2 MPa and occurred in the C-rib of the middle stack.

Vibration tests also validate the computational model and simulations of the dynamic stresses of the microsatellite within acceptable limits. The natural frequencies of the first modes obtained in the simulations and experiments are included in Table 14.

Table 14

Experimental and numerical modal test results comparison

<table>
<tr><th rowspan="2">Axis</th><th rowspan="2">1st mode test freq., Hz</th><th colspan="2">1st mode simulation freq., Hz</th><th rowspan="2">Results sensitivity, %</th></tr>
<tr><th>TestPod</th><th>Microsatelite</th></tr>
<tr><td>X</td><td>295</td><td rowspan="2">328</td><td rowspan="3">359</td><td rowspan="3">0.9 – 9.5</td></tr>
<tr><td>Y</td><td>325</td></tr>
<tr><td>Z</td><td>255</td><td>246</td></tr>
</table>

The maximum difference in the results is less than 10%. For the comparison, the difference in frequency of simulation and test results presented in the paper [15] is less than 5%. Another research [16] demonstrates the first six natural frequencies of the test pod were generated with an average 7% error and an average 4% error for the first eight modes of the test pod with mass model assembly.

The main source of errors can be attributed to the geometrical complexity of the microsatellite assembly whose geometry was simplified in the numerical model in order to save time and computing resources. On the other hand, strict requirements on the accuracy of the simulations were not imposed. In further research we propose to develop a computational model, simulation and testing of a 2U CubeSat prototype.

5. Conclusions

The TUMnanoSAT design meets the structural requirements for space purposes. The static and dynamic analyzes show that the assembly is robust and will withstand high static and dynamic loads during the launch. The value of minimum margin of safety obtained for yield strength is 1.48 and for ultimate strength is 1.09 satisfying the condition (1). Another resistance condition (2) calculated with the ratio of maximum applied stress and ultimate strength of the material <30% is also satisfies (the maximum value obtained ≈24%).

Vibration tests also validate the computational model and simulations of the dynamic stresses of the microsatellite within acceptable limits. The maximum difference in frequency of simulation and test results is less than 10%.

The computational model is experimentally validated with good accuracy and can be applied for the analysis of microsatellites with different configuration.

Conflicts of interest: The authors declare no conflict of interest.

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