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CubeSat System Structural Design

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Abstract

This work presents a cubeSat metallic structure design, which considered vitroceramics coatings. Nowadays, existing commercial options of cubeSat are availables, nevertheless they do not solve all the requirements for a specific mission. Therefore, it is proposed to follow a design protocol to satisfy the structural requirements. This protocol has four stages: 1) planning and clarification, 2) conceptual design, 3) preliminary design and 4) detail design. Thereby, it is described the structural dynamics as a consequence of the induced loads by the launch vehicle. Also, it includes a verification process that assess numerical simulations performed using ANSYS, such as convergence analysis. The results are presented in two parts: 1) the metallic structure geometry and 2) behavior evaluation on special-mechanics loads conditions, which must to bear. This evaluation is supported by statics, modal & harmonic response, random vibration and response spectra analysis. Finally, according the proposed protocol, a metallic structure was obtained, which complies with the requirements and specifications defined by the first stage of the design protocol allowing the integration with other CubeSat subsystems.

Keywords: cubesat, structural requirements, static and dynamic loads.

1. Introduction

Some universities have pioneered the development of small satellites, satellites that are simpler but use the same technologies as the big satellites. Small satellites are classified into four categories: Microsatellite mass ranging from 10 kg to 100 kg, the nanosatellite from 1 kg to 10 kg, Picosatellites from 0.1 kg to 1 kg and finally femtosatellites with mass of 10 g to 100 g. The cubeSat is a miniaturized standardization of a satellite in the nano category whose measuring length, width and length are 10 cm x 10 cm x 10 cm and no more than 1.33 kg total weight. The general concept emerged in 1998 as a result of work done by students of the Laboratory for Space Systems Development Stanford University (SSDL, Space Systems Development Laboratory) project in the Annex microsatellite project Launcher Automated Orbital picosatellites (OPAL, Orbiting Picosatellite Automated Launcher). Notably, the CubeSat project was proposed by professors Jordi Puig-Suari Polytechnic State University California (CalPoly, California Polytechnic State University) and Professor Robert Bob Twiggs of Stanford University whose goal was to design, build, test and operate a spacecraft with similar capabilities to Sputnik I. The CubeSat philosophy differs from the large satellite projects, its low cost in its development, and that, for assembly and unskilled construction and high-tech equipment needed spaces.

The satellite structure plays an important role in the segment of launching a spacecraft, because it supports static, sinusoidal loads (due to engines), as well as the noise generated during flight shock and vibration generated by the separation of rocket parts in the different stages of launch (ignition and the expulsion of the fairing). Once in orbit, the payload structure protects the spacecraft components environment. It is for this reason that the structure should faithfully fulfill the structural requirements in order to ensure its mechanical properties, and the requirements of mass, volume and shape. Consequently the study of structural dynamics addresses to static random vibration and modal analysis, structural design applied to the CubeSat (CIIIAsaT) showed in this work.

2. Methodology

Planning and clarification (Phase I) is obtained together with the information about the requirements and restrictions that must be satisfied. Its importance, involves the establishment of conditions that need to be resolved. Identifying the objectives to be achieved. Conceptual Design (Phase II) is the development of concepts and diagrams representing the design specifications thus generating alternative solutions, evaluating the requirements and restrictions. Thus obtaining the geometry that best suits the spatial criteria. Preliminary Design (Phase III) with geometry and design specifications established seeks to model and analyze spatial mechanical conditions for structural dynamic response corresponding to the conceptual model. Detail design (Phase IV) is devoted to refine and define in detail the final design of the structure in the CubeSat standard, outlining the geometry, dimensions

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and properties of all elements. Verification: error and uncertainty in the computer simulation results against the mathematical models is evaluated. Verification is the process of determining whether a computer simulation accurately represents the conceptual model, but there is no evidence of the relationship of the simulation with the reality.

3. Results and discussion

3.1. Phase 1: Planning and Clarification

Requirements and restrictions in the design solution were studied as well as the addition of the launch vehicle conditions LV (LaunchVehicle) and the interface between the satellite (S/C, Spacecraft) and LV. Some general requirements for the design of satellite structure in the cubeSat standard are the structural requirements. Since the structure must protect subsystem components during launch and space environment. Easy integration with other subsystems and the P-POD interface (Poly Pico-Satellite Orbital Deployer) between the satellite and the LV. Mass requirements for 1U-CubeSat unit, should not exceed 1.33 kg. The center of gravity should be located within 2 cm measured from the XY plane of the geometric center in the Z direction. The design requirements, dictates to have an access area on a side face to manipulate the inner parts of the satellite. External components other than the rails should not touch the inside of the P-POD. The components of the side and top surfaces must not exceed 6.5 mm normal face. The rails should have a minimum width of 8.5 mm. The rails must have a surface roughness of less than 1.6 microns. The edges of the rails will be rounded with a radius of at least 1 mm. The ends of the rails on the sides ± Z have a minimum contact area of 6.5 mm x 6.5 mm for neighboring rails. At least 75% of the rail contact surface should be in contact with the rail P-POD. For the structure and rails should be used aluminum alloys 7075, 6061, 5005 or 5052. The sides of the rails, which are in contact with the rails of the P-POD, aluminum contact rails should avoid cold welding with an anodizing process. The CubeSat elastic separators should be used to ensure adequate separation. Separators springs must be compressed below the level of face confrontation. Elastic spacers will be focused on the contact faces of the tip ends -Z side. The structure must comply with the coordinate system defined by the standard. The release requirements should withstand the static acceleration of LV. The operational requirements indicate that all parties must stay together during launch and operation expulsion. The -Z face will be the first face that must be inserted into the P-POD [1, 2, 3, 4, 5, 6].

3.2. Phase II: Conceptual Design

The bodies are assumed to be homogeneous and isotropic, obey Hooke's law and its vibration is within the elastic limit. Mathematically, functions of position and time are needed to describe the vibration of a continuous system, resulting in partial differential equations [7]. Each piece of a CubeSat is subjected to various mechanical stresses, especially at the beginning of the launch phase [8, 9]. Spatial mechanical conditions applied to the structure is divided into four types of loads. Static acceleration: they are generated by the propulsion systems, aerodynamic loads and inertia loads. They change slowly in terms of time and result in relatively low structural responses. It also involves static loads applied to the P-POD CubeSat expulsion due to spring [9, 10]. For Ariane 5, the maximum longitudinal acceleration occurs in the final stage of the rocket and the momentum does not exceed 4.55 g (gravity g = 9.81 m / s). The higher static lateral acceleration is up to 0.25 g [11]. Sinusoidal vibrations: this phenomenon occurs as a result of the interaction between modes of natural frequency of the launch vehicle and loads due to rapid growth in the breakaway pulse and combustion engines, whose loads are transmitted to the satellite through adapters and separation systems [12]. Sinusoidal vibration levels at the base of the spacecraft does not exceed the average value of 1 g in a bandwidth of 2 Hz to 100 Hz for both lateral and longitudinal directions for LV Ariane 5 [13]. Random vibrations (Random): themost acoustic noise excitation occurs during takeoff from the launch vehicle, this event is governed by the noise reflected by the launch pad and the air pressure [12, 13]. The structural response to acoustic noise is predicted and measured in terms of random vibration, its magnitude through the frequency domain is expressed in terms of acceleration spectral density (ASD Acceleration Spectral Density) also known in the literature (PSD, Power Spectral Density). Figure 1 shows spectral acceleration profiles for different launch vehicles. Usually the typical bandwidth of operation for this type of vibration is 20 Hz to 2000 Hz [13].

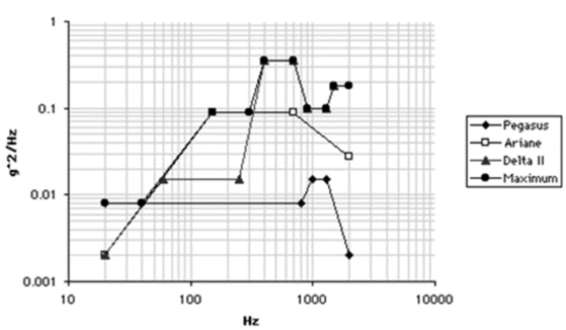

Figure 1: Spectrum PSD acceleration for some launchers [11].

Vibration shock: they are forces that occur in the short term, especially transient mechanical loads. Shock loads generated during starting pitcher for the ignition of the propellant systems and especially for the pyrotechnic activation of release mechanisms (e.g. phase separation, fairing separation and release of the satellite). This type of mechanical load is characterized by high accelerations (up to 100,000 m / s) and it is very short (10 ms - 20 ms). Shock loads are specified by the shock response spectrum (SRS Shock Response Spectrum) in the frequency domain [8, 9, 13]. The table 1 shows the spectral envelope of shock for the Ariane 5 launch vehicle.

Table 1. Ariane 5 shock spectrum

Frequency (Hz)	Acceleration (g)
100	20
400	650
665	880
1000	2000
10000	2000

The primary structure has seven main parts, firstly, three of which form the outer body shaping the bucket, and on the other, has four integrators axes that allow the entire assembly of the structural assembly. It should also be mentioned that the connections and settings (design tolerance ± 0.1 mm) of the mechanical parts are carried by sliding and locking rings Seeger type. Eliminating threaded connections, these missions have led some to failure by the phenomenon of rotation of screws and nuts, to be subjected to vibrational loads. The volume and mass of the primary structure is: 9.4175 x 10-5 m³ and 0.25474 kg respectively.

Different components and subsystems nanosatéllite CIIIAsaT are showed in figure 2. It should be noted also that the side faces of the cube has a coating like Thermal Barrier Coating (TBC), equivalent to passive thermal control of the satellite. A ceramic matrix material like amorphous silica (SiO_2) reinforced with nanoparticles of titanium oxide (TiO_2), alumina (Al_2O_3) and Zirconia (ZrO_2). With a thickness of 10 µm and a peel strength of 40 GPa; mechanical properties it emerges as an isotropic material with an elastic modulus ranging between 20 GPa to 100 GPa, Poisson modulus of 0.3 and a density of 2300 kg / m³.

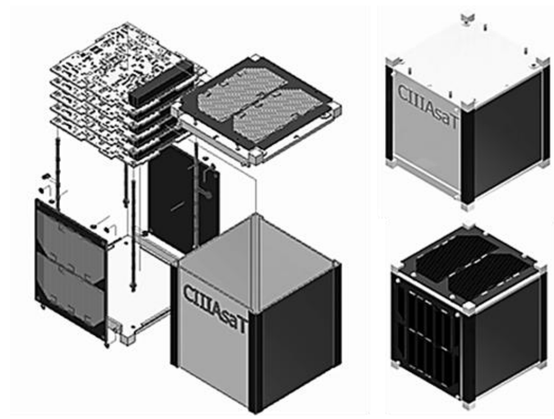

Figure 2: CIIIAsaT CubeSat structure

3.3. Phase III: Preliminary Design

Finite element analysis (FEA, Finite elemental analysis) is a powerful mathematical tool for the study of structural dynamics. This method simplifies the real problem in order to obtain structural design features. [14]. The results are also obtained deformations, efforts and energy they are also modal frequencies, vibration modes, response to harmonic vibrations and frequency response. The different analyzes are presented. Static analysis: initially for this study must consider two general requirements, first is the positioning of the satellite launch vehicle and the second is load applied by the spring to the structure plus the mass of the two nano- P-POD container. For the results upright + Z considered ground and aligned with the longitudinal axis of the LV. The total longitudinal load applied is 300 N, from static acceleration of the two CubeSat (2.66 kg) and the P-POD load, evaluated with a safety factor of 1.8. Load must be distributed symmetrically to the four corners of the face + Z. In figure 3 the results obtained for structural studies because static load acceleration.

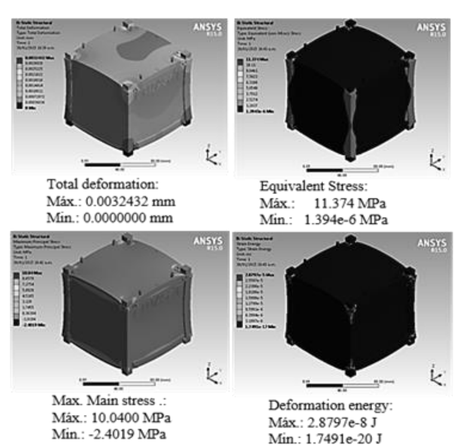

Figure 3: CIIIAsaT Static Analysis

Modal analysis: the most important requirement to be met by this analysis is to study that no modal frequency below the frequency range of random vibration spectrum that is below 100 Hz is found. Table 2 shows, the first 6 modal frequencies found in a range of vibration between 0 Hz - 2000 Hz, for structural assembly CIIIAsaT.

Table 2. CIIIAsaT Modal Frequency

Mode	**Modal Frequency (Hz)**
1	962.5
2	995.1
3	1022.0
4	1079.7
5	1155.8
6	1244.9

Harmonic Analysis: This analysis is performed according to the load amplitude sinusoidal 9.81 m / s2. For a sweep frequency of 2 Hz -100 Hz, in direction Z. Since there is no modal frequency within this range the analysis extends to 2000 Hz. Likewise the largest dynamic deformations in the longitudinal axis of the system are presented in the upper face. It should be note that the maximum equivalent stress occurs in one of the upper joints with a value of 42040 Pa. Figure 4 shows the dynamic behavior of the upper body with a directional deformation of 0.0127 mm at a natural frequency of 1160 Hz. Analysis random vibration: after considering a load profile as shown in figure 4, the structural dynamics is determined.

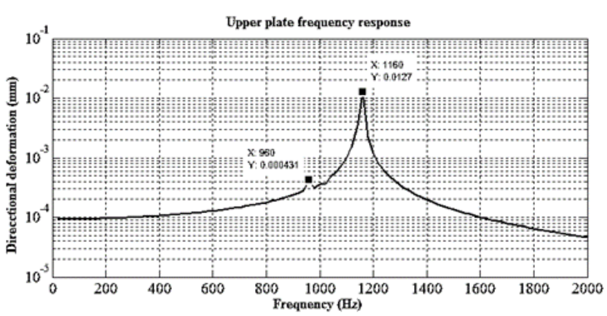

Figure 4: Face + Z frequency response

Figure 5a, illustrates the distribution of von-Mises equivalent stress to the upper face of the structure. Getting a maximum of 3.6 MPa stress in one of the upper joints with probability scale 1σ (68,269%). Also a maximum shear stress of 1368 MPa. At the junction of the same axle but this time in the -Z face. Impact vibration analysis: these loads are between 100 Hz to 10000 Hz (for Ariane 5), with a maximum density of 2000 G acceleration. They are therefore deterministic loads are treated with ANSYS modules spectral response analysis. In the figure 5b shows the distribution of shear stresses in the XY plane of the -Z face with a maximum value of 64,085 MPa and 153.76 MPa maximum equivalent stress, affecting both efforts at the joint between the bottom plate and the axis.

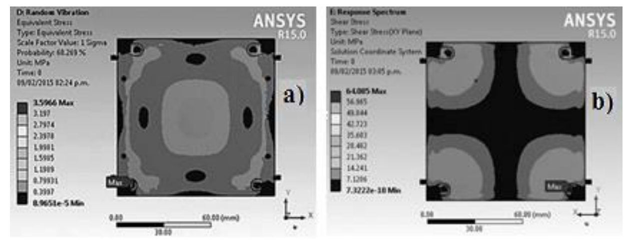

Figure 5: a) + Z face von-Mises equivalent stress b)-Z face shear stress

At this point all documents and drawings for manufacturing and assembly were developed. The relevant information in the project design, is the preparation of the planes with the final dimensioning of all parties that make up the satellite structure, assembly, specifying surface finish, tolerances, scale, dimensions and processes.

Phase IV: Validation

In the verification activities, the accuracy is generally measured relative to reference solutions of problems with simplified models. By reference solutions is well understood analytical solutions or highly accurate numerical solutions [15, 16, 17].

Is complex to perform theoretical an analysis of structural dynamics by size differential matrices describing the mechanical behavior of the parts of the satellite and even more for a 3-diminssional, therefore it is proposed for a process verification performed case studies of basic parts (such as a beam or plate), performed theoretical studies and compare computational studies (ANSYS) establishing a statistical analysis with the results of both methods, to have a parameter uncertainty , by indicating that the results converge computationally according to mathematical models. Another step in the verification strategy is to show that the data do not depend on the mesh (FEM), ie if we change the size of the mesh the computational results do not change (Figure 6).

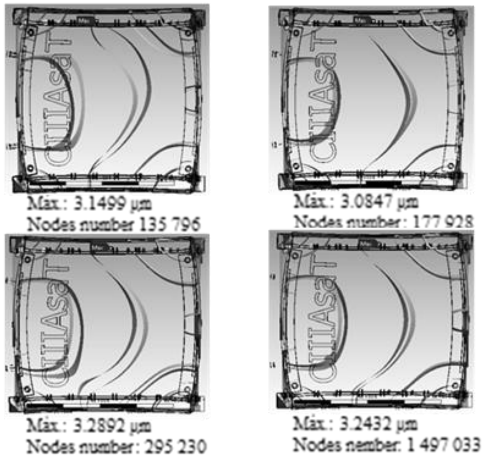

Figure 6: Contours created with different mesh types in the static analysis

4. Discussion

The CubeSat satellite structural design meets the minimum geometric characteristics, weight and size for release purposes. In addition to whole staying into its component, tolerances and deformation caused by internal and external loads. Therefore, the structural dynamics of satellite resists vibration and random frequencies induced by selected launch vehicle.

5. Conclusion

The CIIIAsaT is a design that meets the structural requirements with space purposes. In turn, both static and dynamic analyzes show that is able to withstand the mechanical conditions of the launch pad for Ariane 5. This being one of the platforms that produce vibrational values and higher loads with respect to the families of launchers, CIIIAsaT therefore is not only suitable for space programs tied to Ariane 5, but also for families pitching different space agencies. Notably, a distinctive structural design of this satellite is not possess threaded joints, leading to eliminate property mismatches or loosening of joints by vibrations.

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References

[1] Deparment-Of-Defense-MIL-STD-1540D, Product Verification Requirements for Launch, Upper Stage, and Space Vehicle, in MIL-STD-1540D. Deparment of Defense - United States Of America. p. 28, 1999

[2] NASA-STD-6016, Standard Materials and Processes Requirements for Spacecraft, in NASA Technical Standard. National Aeronautics and Space Administration: Washington, DC. p. 67, 2008.

[3] CalPoly-CDS-Rev.13, CubeSat Design Specification. California Polytechnic State University: California, San Luis Obispo. p. 42, 2014.

[4] CalPoly-P-POD-Rev.E, Poly Picosatellite Orbital Deployed User Guide. California Polytechnic State University: San Luis Obispo, CA 93407. p. 21, 2014.

[5] NASA-LSP-REQ-317.01-Rev-B, Program Level Dispenser and CubeSat, in Launch Service Program NASA: Florida - USA. p. 14, 2014.

[6] NASA-GSFC-STD-7000A, General Environmental Verification Standard (GEVS). NASA: Greenbelt, Maryland. p. 203, 2013.

[7] Kelly, S.G., Mechanical vibrations: theory and applications, SI. United States of America: Cengage Learning, 2012.

[8] Brieß, K., Spacecraft Design Process, in Handbook of Space Technology, W. Ley, K. Wittmann, and W. Hallmann, Editors. John Wiley & Sons, Ltd: Singapore. p. 906, 2009.

[9] Garrett, H.B., Space Environments and Survivability, in the International Handbook of Space Technology, M. Macdonald and V. Badescu, Editors. Springer association with Praxis: Chichester, UK, 2014.

[10] Miglioreno, G. Henriksen, T.K., Structure, Mechanisms and Deployables, in the International Handbook of Space Technology, M. Macdonald and V. Badescu, Editors. Springer association with Praxis: Chichester, UK, 2014

[11]Ariane-5-Users-Manual-Issue-5, Ariane 5 User's Manual Ariane Space. p. 271, 2011.

[12] Navarrete, M.A.S., Análisis mecánico de la estructura conceptual de un sistema de separación para microsatélites, in Facultad de Ingenieria. Universidad Nacional Autónoma de México: México D.F., 2013.

[14] Houghton, J.M., Spacecraft Structures, in Spacecraft System Engineering, P. Fortescue, J. Stark, and G. Swinerd, Editors. John Wiley & Sons. Ltd. p. 352, 2004.

[14]Pierlot, G. Oufti-1: Flight System Configuration and Structural Analysis. Aerospace and Mechanical Engineering Department. University of Liège. p. 139, 2009.

[15] AIAA_G-077, Guide for the verification and validation of computational fluid dynamics simulations. Reston, VA: American Institute of Aeronautics and Astronautics. viii, 19 p., 1998.

[16] Oberkampf, W.L., Trucano, T.G. Hirsch, C. Verification and Validation for Modeling and Simulation in Computational Science and Engineering Applications. in Foundations for Verification and Validation in the 21st Century Workshop of Conference. Laurel, Maryland: Johns Hopkins University/Applied Physics Laboratory. 2002.

[17] El-Hebeary, M.M.R., Arafa, M.H. Megahed, S.M., Modeling and experimental verification of multi-modal vibration energy harvesting from plate structures. Sensors and Actuators A: Physical, 193: p. 35-47. 2013.