Static and Random Vibration Analyses of a University CubeSat Project

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Abstract. This work presents hands on experience of the configuration process and strength analyses of a student’s CubeSat project at the German University in Cairo. The static and dynamic performance of the primary structure, during launching phase, are investigated and checked against the strength requirements in addition to making sure that stiffness constraints imposed by the P-POD and the candidate launchers are met. The static response of the primary structure is performed using ANSYS Finite Element Software by exposing the structure to the maximum quasi static launch load in each of three flight directions separately. Modal analysis results are presented in order to check the compliance of the longitudinal and lateral natural frequencies, of the proposed model, with the launchers requirements. In addition, random vibration response is performed using frequency domain analysis, assuming that the structure will be subjected to launch random vibration loads in all directions. Finally, fatigue life analysis is presented in order to ensure that primary structure will safely survive the launching mechanical environments.

1. Introduction

The CubeSat is a pico-class satellite, originally developed and standardized at Stanford University’s Space Systems Development Laboratory, which has been gaining more interest of the space industry in general and of the academic community in particular. The basic standardized approach is the 1-Unit CubeSat, which is a cube-shaped satellite with dimensions 100x100x100 mm and mass up to 1.33 kg. This category of satellites is launched as a secondary payload while being encapsulated in an Orbital Deployer (P-POD), developed by California Polytechnic State University. CubeSat missions become one of the most appealing and evolving categories among the space industry since a cluster of such pico-satellites can efficiently substitute an expensive large one. CubeSat missions have proved useful in testing new components and software to be space-qualified for future use. Alongside with that, these standardized pico-satellites made the space technology readily accessible to university as a learning topic in undergraduate and postgraduate programs where they originally started. The current CubeSat project is intended to provide the students, of the German university in Cairo, the capacity and expertise to join the quest for space technology. Such satellite project will engage engineering students in a multi-disciplinary design process that will leverage their academic expertise across all backgrounds.
Swartwout [1] presented a comprehensive review on the first one hundred CubeSat missions, along with an on-orbit performance evaluation while classifying the missions according to size, origin, and mission life. It was found that several design and implementation errors, though correctable, still plague the university CubeSat missions. In addition, the P-POD launch container, not the CubeSat specification, proved to be the true supporting technology for this category of missions. Long et al. [2] presented an overview of an extremely low frequency magnetic signatures detection CubeSat mission, to study earthquake precursor phenomena, developed by Space Systems Development Laboratory (SSDL) at Stanford University. Alminde et al. [3] addressed the educational value of university CubeSat projects by describing the overall architecture of Aalborg university AAU-CubeSat project, which was launched into space on the 30th of June 2003. Results from the operation phase were presented, providing recommendations for further work on pico-satellite designs. Noca et al. [4] presented the project organization, mission, and satellite description of their first pico-satellite project, SwissCube, developed at Space Center of Lausanne Federal Institute of Technology. Technical and programmatic lessons were addressed, as the main objective of this project was to provide hands-on experience of the whole satellite-development cycle. Cote et al. [5] outlined the efforts the power, propulsion, and structure subsystems of Worcester Polytechnic Institute’s initial endeavor to experiment a CubeSat. Each of the three subsystems teams managed to design and specify a baseline set of components for their subsystem and to perform rudimentary testing. Castello [6] created a MATLAB toolbox to assist the CubeSat developers with understanding the CubeSat restrictions, optimizing their systems, and decreasing the design development time while conforming to the initial requirements.

High requirements have been set for the integrity of their structures in order to survive high static and dynamic loads without jeopardizing neighboring satellites during launching. Moreover, the stiffness of primary and secondary structures should be designed to ensure that their fundamental longitudinal and lateral frequencies are satisfying the minimum prescribed values set by the candidate launcher. Cghan [7] introduced the design and analyses of the structure and mechanism subsystem of second CubeSat project at Istanbul Technical University. Two different designs were proposed for such mission and the final selection was based on certain target performance parameters. Eiswy et al. [8] presented the overall design process of the structures subsystem of certain CubeSat mission, in the frame work of a university project, along with the static and modal analyses using finite element method. Bürger et al. [9] presented static and modal analyses of the structure subsystem of a CubeSat project developed at the Brazilian Technological Institute of Aeronautics. Oh et al. [10] introduced the structure design of a CubeSat mission, based on the 1U Standard, developed by the Space Technology Synthesis Laboratory of Chosun University. In addition, the validity of their proposed design has been investigated by performing quasi-static and modal analyses. Raviprasad et al. [11] performed modal, harmonic, and random vibration analysis of nano-satellite mission and their results were compared to the CubeSat and launch-vehicle provider standard mechanical requirements. Arroyave et al. [12] proposed a design protocol that help in satisfying all of the specific structural requirement of a given CubeSat mission. In addition, they did evaluate the static and dynamic behavior, subject to special mechanical loads conditions, of certain case study by performing static, modal, harmonic, and random vibration analyses.

This paper presents hands on experience of the configuration process and strength analyses of a student’s CubeSat project at the German University in Cairo. The static and dynamic performance of the primary structure, during launching phase, are investigated and compared with the strength requirements in addition to making sure that stiffness constraints imposed by the P-POD and the candidate launchers are met. The static response of the primary structure is performed using ANSYS Finite Element Software by exposing the structure to the maximum quasi static launch load in each of three flight directions separately. Modal analysis results are presented in order to verify the compliance of the longitudinal and lateral natural frequencies, of the proposed model, with the launchers requirements. In addition, random vibration response is performed using frequency domain analysis, assuming that the structure will be subjected to launching random vibration loads in all directions. Finally, fatigue life analysis is presented in order to ensure that primary structure will safely survive the launching mechanical environments.
2. Project Overview

The current pico-satellite project is a 1-U CubeSat for earth observation purposes and is based on commercial off-the-shelf (COTS) components. The primary structure developed and analyzed, in the current work, aims toward acquiring a CubeSat platform having the strength and flexibility to be utilized for the planned CubeSat mission at the German University in Cairo. The proposed primary structure matches the P-POD specifications developed by California Polytechnic State University [13]. The structure of printed circuit boards (PCBs) are made of an isotropic material with mass and stiffness properties tailored to approximately simulate those of the different subsystems. The components of the CubeSat are packaged, while trying to compromise between the following multiple, yet conflicting, design requirements set by the different satellite subsystems [14]: the center of mass must be within 2 cm from the CubeSat geometric center as per the CubeSat standards; the mass distribution need to be as symmetric as possible in order to minimize the products of inertia; it is better to keep massive components, like the power subsystem, near the launch vehicle interface; electrically linked components should be located near each other to reduce cabling; Equipment, which require accurate orientation, need to be located in a way that facilitates optical inspection for mounting accuracy; electromagnetic interference should be considered; and the required thermal conditions of the different subsystems need to be considered as well. All of these design considerations have been taken into account during the configuration process of the proposed CubeSat shown in Fig.1. As mentioned before, it is planned to use COTS components which include camera module, power subsystem, communication subsystem, onboard computer board including an attitude determination subsystem along with the structure subsystem presented in this paper. Aluminum 6061-T6 is chosen for the primary and secondary structures because it provides excellent joining characteristics, good acceptance of applied coatings and combines relatively high strength, good workability, and high resistance to corrosion.

Figure 1. Layout of the proposed primary structure with and without side panels
3. Results and Discussion

Static Analysis

All the analyses presented, hereinafter, are intended to check the static and dynamic behavior, of the current proposed CubeSat primary structure, in response to the mechanical environment of Soyuz and Ariane 5 as two candidate launchers. The static response of the satellite structures is simulated while being exposed to a quasi-static acceleration of 10g in the x-, y- and z- directions simultaneously. The structure was assumed clamped at the bottom surfaces of the corner rails. The present scenario simulates the satellite inside the P-Pod with the load of two other CubeSats acting on the structure in the z-direction. This case must be examined if the satellite would be placed 1st in the deployer while being aligned in z-direction during launching. The present analyses did not consider the stiffening effect of being encapsulated in the P-Pod. Figures 2 and 3 show the distributions of the equivalent stress and total deformations, respectively, of the primary and secondary structures. It is seen that the satellite structure experiences a maximum stress of 16.576 MPa which is fairly safe, in terms of yielding, compared to the 275 MPa which is the yield value of the aluminum 6061-T6. It is seen in Fig. 3 that the structure responds with a maximum value of total deflection equals 0.021 mm which is found very acceptable in terms of the static deflection interference of the different components of the satellite.

Figure 2. Equivalent (von-Mises) stress distribution subject to static loads of 10g in all directions

Figure 3. Total Deformation subject to static loads of 10g in all directions
Modal Analysis

The stiffness of the primary and secondary structures are designed to ensure that their fundamental longitudinal and lateral frequencies are satisfying the minimum prescribed values set by the candidate launchers. According to the specifications of Ariane-5, the proposed CubeSat Structure is required to have its fundamental lateral frequency to be a minimum of 50 Hz and a fundamental longitudinal frequency to be a minimum of 100 Hz [15]. Figure 4 depicts the natural frequency and mode shape of the fundamental frequency of the proposed structure, including the effect of the different subsystems, and it shows a value of 487 Hz which is found in line with both launchers requirements. In addition, Table 1 presents the natural frequencies of the first ten modes.

![Figure 4. First mode shape of the satellite](image)

Table 1. Natural frequencies of the first ten modes

| Mode | Frequency (Hz) |
|------|----------------|
| 1    | 487.39         |
| 2    | 489.14         |
| 3    | 507.63         |
| 4    | 567.71         |
| 5    | 581.41         |
| 6    | 596.69         |
| 7    | 618.58         |
| 8    | 636.18         |
| 9    | 730.45         |
| 10   | 740.03         |

Random Vibration

This section presents the random vibration response, performed using frequency domain analysis, assuming that the structure will be subjected to launching random vibration loads of the two candidate launchers. The main purpose of performing this analysis is to identify the stress peaks, of each loading phase, corresponding to the resonance frequencies to be used later in the cumulative fatigue assessment. Table 2 shows the PSD random vibration loading of Soyuz specifying the expected duration of each launching stage that will be used in estimating the number of load cycles for each stress peak of the random vibration response depicted hereinafter.
However, as per Ariane 5 user manual, the random vibration excitations below 100 Hz are considered the same as of the sinusoidal excitation depicted in Table 3. As for its random excitations of the frequencies higher than 100 Hz, it is advised to use the acoustic excitations provided in Table 4 [15].

Table 2. The limit flight levels of random vibrations of Soyus launcher

| Event          | Frequency Band (Hz) | Time (s) |
|----------------|---------------------|----------|
|                | 20-50               | 100-200  |
|                | 50-100              | 200-500  |
|                | 200-1000            | 1000-2000|
| PSD, Power Spectral Density $10^{-3}$ g/Hz |
| 1st stage      | 5.0                 | 10.0     |
|                | 5.0                 | 25.0     |
|                | 10.0                | 25.0     |
|                | 10.0                | 10.0     |
|                | 10.0                | 5.0      |
|                | 10.0                | 2.5      |
| 2nd stage      | 2.5                 | 5.0      |
|                | 5.0                 | 10.0     |
|                | 10.0                | 5.0      |
|                | 5.0                 | 2.5      |
| 3rd stage      | 2.0                 | 2.0      |
|                | 2.0                 | 2.0      |
|                | 2.0                 | 1.0      |
| Fregat Flight  | 2.0                 | 1100     |

Table 3. Ariane 5 Sine Vibrations Levels

| Direction       | Frequency Band (Hz) | Sine amplitude (g) |
|-----------------|---------------------|--------------------|
| Longitudinal    | 2-50                | 1.0                |
|                 | 50-100              | 0.8                |
| Lateral         | 2-25                | 0.8                |
|                 | 25-100              | 0.6                |

Table 4. Ariane 5 Acoustic Vibration Levels

| Octave center frequency (Hz) | Flight limit level (dB) (reference: 0 dB = 2 x 10^5 Pa) |
|------------------------------|--------------------------------------------------------|
| 31.5                         | 1128                                                   |
| 63                           | 131                                                    |
| 125                          | 136                                                    |
| 250                          | 133                                                    |
| 500                          | 129                                                    |
| 1000                         | 123                                                    |
| 2000                         | 116                                                    |

Figures 5 – 8 show the random vibration response, of primary and secondary structures, subject to random excitations of Soyuz and Ariane -5 random excitations in all directions in order to simulate the different expected orientations of the CubeSat during launching. It is noticed in all figures that the stress PSD response considerably peak at two main influential frequencies which represent the fundamental longitudinal and lateral frequencies of the structure subsystem. Therefore, it would be fairly conservative to calculate the number of stress cycles at each frequency, assuming that the total duration of the given launching stage is split equally between these two frequencies.
Figure 5. Random vibration response subject to 1st Stage of Soyuz (Hz – Stress PSD (Pa^2/Hz))
Figure 6. Random vibration response subject to 2nd & 3rd Stages of Soyuz (Hz – Stress PSD (Pa²/Hz))
Figure 7. Random vibration response subject to fregat flight Stage of Soyuz (Hz – Stress PSD (Pa²/Hz))
This section presents an analysis of the cumulative fatigue behavior of the structure subsystem subjected to the random vibration response, of the two candidate launchers, which was presented in the previous section. As mentioned before, the number of stress cycles $n_i$, at the two frequencies found to be most influential, will be calculated while assuming that each of those two frequencies will happen to last for the total duration of the given launching stage. Therefore, the frequency peak found to have the highest $(n_i/N_i)$ value, for the given launching stage, will be considered in calculating the total cumulative effect of all stages, as depicted in tables 4 and 5. Referring to the S-N curve of the selected aluminum alloy, it was found that all of the stress levels reported in the previous section fall in the category of high cycle fatigue. Therefore, it would be conservative to use $5 \times 10^8$ as the number of cycles to fail for all the simulated values of the stress.

Figure 8. Random vibration response subject to Ariane 5 random excitations (Hz – Stress PSD (Pa^2/Hz))
Miner’s law for cumulative fatigue has been implemented for both launchers cases, as shown tables 5 and 6, and the structure is found safe with large margin of safety, which calls for more optimization to reduce the weight of the structure which is currently around 270 grams.

### Table 5. Cumulative fatigue damage analysis subject to Soyuz random loads

| Loading phase | No. of cycles at 1st stress peak $n_1$ | No. of cycles to fail at 1st stress peak $N_1$ | No. of cycles at 2nd stress peak $n_2$ | No. of cycles to fail at 2nd stress peak $N_2$ | $\left(\frac{n_i}{N_i}\right)_{\text{max}}$ |
|---------------|---------------------------------|-----------------------------------------------|---------------------------------|-----------------------------------------------|------------------|
| 1st stage     |                                |                                               |                                |                                               |                  |
| x             | 58471                           | $5 \times 10^8$                              | 68136                          | $5 \times 10^8$                              | $1.35 \times 10^4$ |
| y             | 58712                           | $5 \times 10^8$                              | 68143                          | $5 \times 10^8$                              | $1.36 \times 10^4$ |
| z             | 58680                           | $5 \times 10^8$                              | 68143                          | $5 \times 10^8$                              | $1.36 \times 10^4$ |
| 2nd & 3rd Stages |                                |                                               |                                |                                               |                  |
| x             | 136996                          | $5 \times 10^8$                              | 159001                         | $5 \times 10^8$                              | $3.18 \times 10^4$ |
| y             | 136433                          | $5 \times 10^8$                              | 158973                         | $5 \times 10^8$                              | $3.17 \times 10^4$ |
| z             | 136923                          | $5 \times 10^8$                              | 159001                         | $5 \times 10^8$                              | $3.18 \times 10^4$ |
| Fregat Flight |                                |                                               |                                |                                               |                  |
| x             | 535986                          | $5 \times 10^8$                              | 624536                         | $5 \times 10^8$                              | $12.48 \times 10^4$ |
| y             | 838197                          | $5 \times 10^8$                              | 624646                         | $5 \times 10^8$                              | $12.49 \times 10^4$ |
| z             | 538109                          | $5 \times 10^8$                              | 624646                         | $5 \times 10^8$                              | $12.49 \times 10^4$ |
| Total cumulative effect of all stages | | | | | $0.0052$ |

### Table 6. Cumulative fatigue damage analysis subject to Ariane-5 random loads

| Loading phase | No. of cycles at 1st stress peak $n_1$ | No. of cycles to fail at 1st stress peak $N_1$ | No. of cycles at 2nd stress peak $n_2$ | No. of cycles to fail at 2nd stress peak $N_2$ | $\left(\frac{n_i}{N_i}\right)_{\text{max}}$ |
|---------------|---------------------------------|-----------------------------------------------|---------------------------------|-----------------------------------------------|------------------|
| All stages    |                                |                                               |                                |                                               |                  |
| x             | 733905                          | $5 \times 10^8$                              | 851790                          | $5 \times 10^8$                              | $17.04 \times 10^4$ |
| y             | 730890                          | $5 \times 10^8$                              | 851640                          | $5 \times 10^8$                              | $17.03 \times 10^4$ |
| z             | 733515                          | $5 \times 10^8$                              | 851820                          | $5 \times 10^8$                              | $17.04 \times 10^4$ |
| Total cumulative effect of all stages | | | | | $0.0051$ |

### 4. Conclusion

The static and dynamic performance of the primary structure, during launching phase, were investigated and compared with the strength requirements in addition to making sure that stiffness constraints imposed by the P-POD and the candidate launchers are met. The evaluation of the static response of the primary structure is performed using ANSYS Finite Element Software by exposing the structure to the maximum quasi static launch load in each of three flight directions separately. It was found that the satellite structure experiences a maximum stress of 16.576 MPa which is fairly safe, in terms of yielding, compared to the 275 MPa which is the yield value of the aluminum 6061-T6. The maximum total deflection was found to be 0.021 mm which is acceptable in terms of the static deflection envelopes of the different components of the satellite. Modal analysis results were presented and the fundamental frequencies, lateral and longitudinal, were found in compliance with both candidate launchers requirements. In addition, random vibration response was performed using frequency domain analysis, assuming that the structure will be subjected to launching random vibration loads in all directions. Finally, cumulative fatigue damage analysis was performed, using Miner’s simple law, and the structure is found safe with large margin of safety, which clearly indicates that there is a possibility for further weight reduction.
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