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Quasi-Static and Dynamic Response of a 1U Nano-Satellite during Launching

Ali Alhammadi, Muneera Al-Shaibah**, Abdulla Almesmari, Thu Vu, Alexandros Tsoupos, Firas Jarrar and Prashanth Marpu,*

Khalifa University of Science and Technology, Abu Dhabi, UAE

PO Box 127788, Abu Dhabi, UAE

ali.nalhammadi@ku.ac.ae, muneera.alshaibah@ku.ac.ae, abdulla.almesmari@ku.ac.ae, firas.jarrar@ku.ac.ae prashanth.marpu@ku.ac.ae , vu.thu@ku.ac.ae *and* aletsoup@gmail.com

Abstract

During launching a CubeSat, it will be subjected to accelerations many times larger than the gravitational acceleration. Most of the failures occur due to the resultant dynamic loads, therefore; this paper estimates and analyzes the structural responses of MYSAT-1 due to the launch vehicle. Finite Element Analysis (FEA) software ABAQUS™ was utilized to perform the structural analysis (Quasi-static and modal analyses). Hence, the vibration experimental results validated the numerical analysis, it is found that the static loading resulted in maximum stresses and deflections that are not harmful to the structure.

1.Introduction

Over the past couple of decades, miniaturized satellites known as CubeSats became widely popular across the Globe. They pose as an attractive technology in the industry due to their much lower cost, power and size compared to the bulkier traditional satellites. Moreover, they have a fast development timeline that could span between 1 to 2 years, whereas, the traditional ones would take approximately 5 years. The concept of a CubeSat was first introduced in early 2000s [1]. CubeSat projects serve as a great platform for space development projects for universities and students, enabling them to educate, familiarize themselves and test their ideas in space. CubeSats fall under nanosatellite category that ranges between 1 – 10 kg in mass, which are classified based on the number of units. Each unit (1U) is 10 cm x 10 cm x 10 cm in dimensions and does not exceed 1.33 kg. Similar to regular satellites, CubeSats contain several subsystems that each are responsible for certain tasks.

The framing structure that envelopes and support other components of the satellite is typically made of space-grade Aluminum due to its strength and low density. During its lifetime, a CubeSat is subjected to several mechanical and thermal loads. Thermal loads are in the form of thermal cycles between hot and cold while it's in orbit. On the other hand, mechanical loads result from the high accelerations and vibrations mainly during the launch and in case of direct collision, which is highly unlikely. These loads compromise the success of any space mission. In this paper, the mechanical loads during rocket's launching and their effect on a 1U CubeSat are simulated, tested and discussed.

During a rocket launch, a satellite undergoes several dynamic and static mechanical loads and vibrations (Figure 1); quasi-static, sinusoidal, acoustic and pyrotechnic. A quasi-static load is an external time independent or slowly varying loading that is due to inertia of the components and structure from gravity or steady acceleration [4]. Low frequency vibrations (sine waves) are critical since they excite the structural skeleton of the satellite and stimulate the natural frequencies, continuously at low energies. Acoustic fluctuations occur due to the different engine operations [4,5]. These fluctuations become external random and shock vibrations. Lastly, separation operations such as in fairing, satellite and solar panel deployment cause a shock on the CubeSat known as pyrotechnic shock [4]. This occurs at high frequencies due to the explosive nature of the operation. It is not necessarily critical to the mechanical structure; however, small brittle components will face high risk or failure [6].

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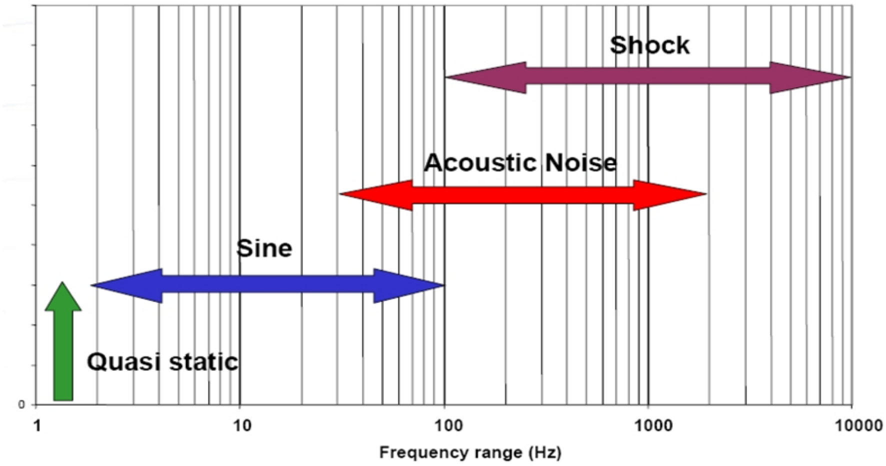

Figure 1: Static and dynamic environment specification according to [3]

Testing and simulations are important. Based on their results, the success of the mission can be predicted and affect the level of confidence. To confirm the survival confidence of the CubeSat and mission, launchers require the CubeSat to pass through a number of qualification and acceptance tests that follow their own standards and requirements. During launching, the accompanying loads impose great amount of force, vibrations and shock. Therefore, it is considered the most crucial stage for the CubeSat's structure. A shaker or rate table is used to conduct the dynamic tests; whereas FEA tools such as ABAQUS^{TM} are used for simulation on the different axes of the CubeSat.

1.1 MYSAT-1

MYSAT-1 is a 1U CubeSat that consists of an on-board computer (OBC), electrical power system (EPS), attitude determination and control system (ADCS), antennas, transceiver, solar panels, a camera and an experimental battery payload as a payload. Both a flight model (FM) and an engineering model (EM) of MYSAT-1, which is an exact replica of the FM, were used for testing (Figure 2).
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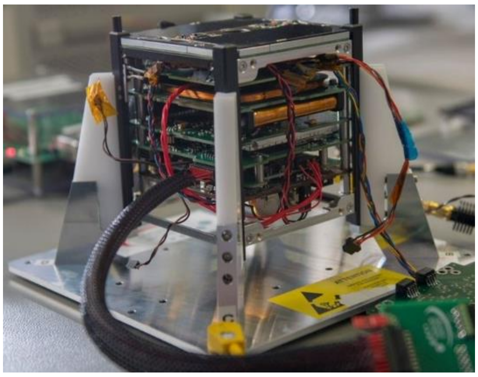

Figure 2: MYSAT-1 engineering model

This paper is organized as follows. Section II presents the methodology and the parameters used for the FEA simulations and testing. The following section demonstrates the results of the analyses and testing. These results are discussed in Section IV. The paper is concluded is Section V.

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2. Methodology

This section addresses the parameters and setup used for the simulations and tests.

2.1 Finite Element Analysis (FEA)

In this study, Abaqus/CAE 6.14 was used to conduct quasi-static and modal analyses. There are often geometrical features in the products design that are unimportant with regards to stress or modal analysis that lead to increase in mesh complexity, element's number and analysis run time. Therefore, a simplified 3D model that neglects such features and fine details of the CubeSat components was created and simulated in the FEA. All components of the subsystems retained their main features, utilizing simple geometrical shapes such as cylinders and cubes, and unwanted fillets and chamfers were removed. However, the mechanical structure maintained all of its features as it is the crucial part in these analyses. For maximum accuracy, 3D elements were used throughout the entire analysis. The final model shown in Figure 3 ensures the simplicity of the meshing process, while maintaining the precise representation of the full problem domain.

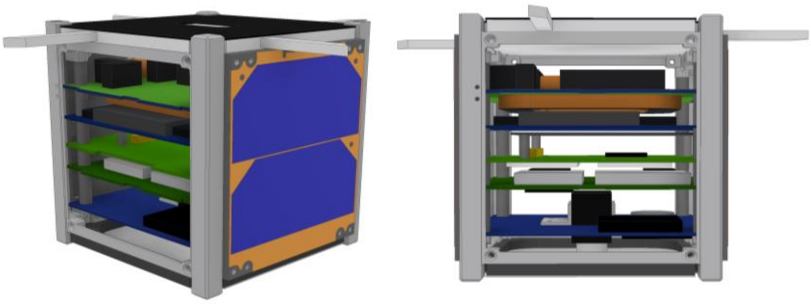

Figure 3: Simplified 3D model of MYSAT-1 used for FEA simulations

The structure is made of Aluminum-6061, whereas, connectors such as screws, rods and spacers are made of Stainless Steel-304. Hence, these the well-known properties of these two materials were assigned to their corresponding components in the structural model. In regards with the other subsystem's components, since they consist of a combination of materials, their average densities were defined by dividing their mass over volume. Each component volume was obtained through ABAQUS™ and its mass was found from the datasheets. This approach for determining the components' densities is key for obtaining accurate results, since the applied load considered in the analysis is an inertia load. Any other approximate values of the densities would result in incorrect masses and thus incorrect loads. Other mechanical properties such as Young's Modulus and Poisson's ratio were based on the FR4's properties, since it has lower Elasticity Modulus, simulating the worst-case loading scenario. Table 1 contains the material properties of MYSAT-1's components.

Table 1: Material properties of the CubeSat's components

Component	Density (tonne/mm^3)	Young's Modulus (MPa)	Poisson's Ratio
Ribs	2.7×10^{-9}	68900	0.33
Frames	2.7×10^{-9}	68900	0.33
Side Plates	2.7×10^{-9}	68900	0.33
Flanges	2.7×10^{-9}	68900	0.33
Connectors	8×10^{-9}	193000	0.30
Antennas	2.265×10^{-9}	24000	0.136
Camera Board	3.510×10^{-9}	24000	0.136
Camera	5.041×10^{-9}	24000	0.136
EPS	2.101×10^{-9}	24000	0.136
OBC	3.951×10^{-9}	24000	0.136
Magnetorquer	3.873×10^{-9}	24000	0.136
TRXVU	2.614×10^{-9}	24000	0.136

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There are two main types of solid elements in ABAQUS^{TM}; tetrahedral and hexahedral meshes. The FEA model was meshed into a total of 378,733 elements; 44,681 linear hexahedral elements of type C3D8R were used for the rods and spacers (no prior partitioning was needed), and 334,052 quadratic tetrahedral elements of type C3D10 for the rest of the CubeSat. Mesh size as small as 1 mm was used due to the detailed surfaces (Figure 4). Based on QB50 standard [6], a 13G acceleration was applied along each axis, creating the three loading scenarios. On the other hand, the modal analysis results contained the natural frequencies of the structure, along with their mode shapes.

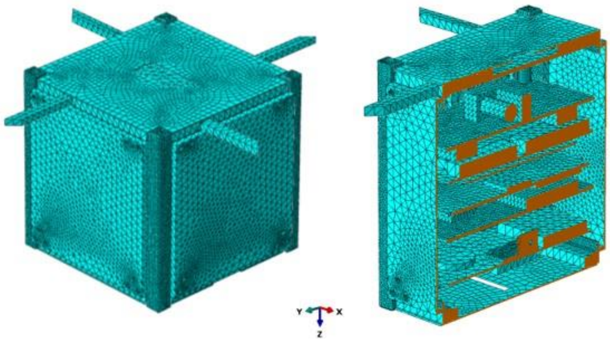

Figure 4: Meshed model

2.2 Experiment

MYSAT-1 was tested for qualification and acceptance levels. All of the subsystems were functionally tested at a unit level test prior to integration. As the vibration testing requirements were identical for the EM and FM modals, only the FM modal results will be illustrated and discussed.

The vibration testing was performed using a low force electrodynamic shaker (VDS-780). A CCLD accelerometer (BKSV 4534-B) served as the control input for the closed-loop control system. The response of the test article was measured using one more BKSV 4534-B. An additional external accelerometer ADXL1002 was used for a backup response measurement. Due to the absence of a slip table, two distinct adaptors were manufactured to test MYSAT-1 along the orthogonal X, Y and Z axes. Figure 5 shows the test setup for X and Y directions. In regards to the Z axis, and L-flange adaptor was used. Nano-racks ICD specifications [7] were used for the random vibration profile. To ensure that no damages to the CubeSat's structure or any modal frequencies shifting occurred, low level sine sweep was performed at before and after the random vibration test. Table 2 shows the designated testing profile for all tests.

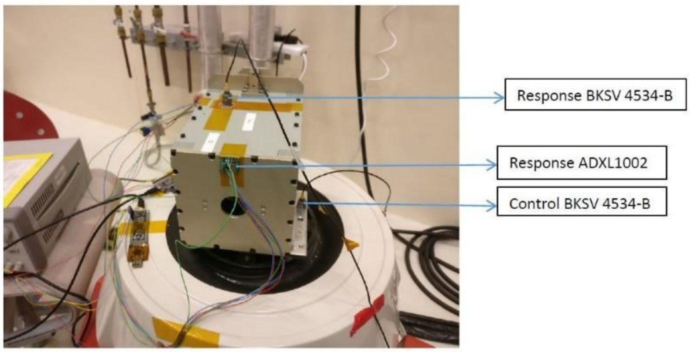

Figure 5: MYSAT-1 test set-up (X and Y directions)

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Table 2: MYSAT-1 testing profiles

	Frequency (Hz)	Amplitude (g)	Rate (oct/min)
Low Level Sine-Sweep	10 - 2000	0.2	2
	Frequency (Hz)	**Maximum Flight Envelope (g^2/Hz)**	
Random Vibration	20	0.057 (g^2/Hz)	GRMS ~ 9.47 g Duration = 60 s/axis
	20-153	0 (dB/oct)	
	153	0.057 (g^2/Hz)	
	153-190	+7.67 (dB/oct)	
	190	0.099 (g^2/Hz)	
	190-250	0 (dB/oct)	
	250	0.099 (g^2/Hz)	
	250-750	-1.61 (dB/oct)	
	750	0.055(g^2/Hz)	
	750-2000	-3.43 (dB/oct)	
	2000	0.018 (g^2/Hz)	

3. Results

This section presents the results of the FEA simulations and testing.

3.1 Quasi-Static – FEA

As shown in Table 3, the Z-axis loading scenario has the highest stress response and deflection, with values of 29 MPa and 0.1 mm, respectively (Figure 6. The location of the maximum stresses and deflections are indicated in the Table 3 and also pointed at in the (Figures 6-8).

Table 3: Quasi-static analysis results from maximum stress and deflection

Loading Axis	Maximum Mises Stress (MPa)	Maximum Stress Location	Maximum Deflection (mm)	Deflection Location
X	24.05	Skeleton-Rod	0.008	OBC
Y	11.29	Skeleton-Rod	0.007	OBC
Z	29.01	Flange-Camera Board	0.1	Camera Board

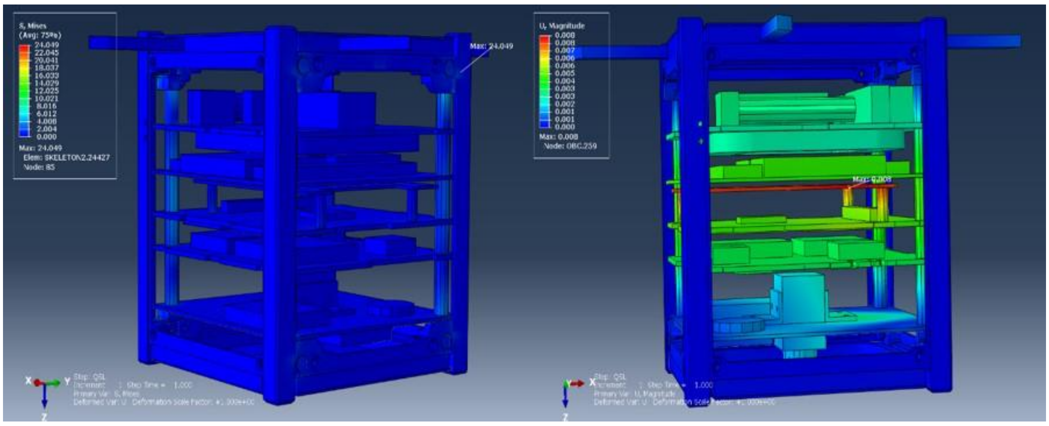

Figure 6: The stress and deflection in the X-axis

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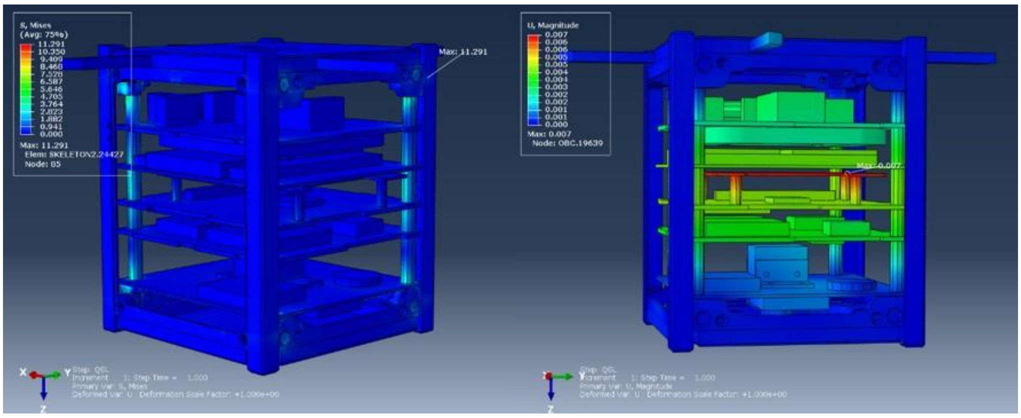

Figure 7: The stress and deflection in the Y-axis

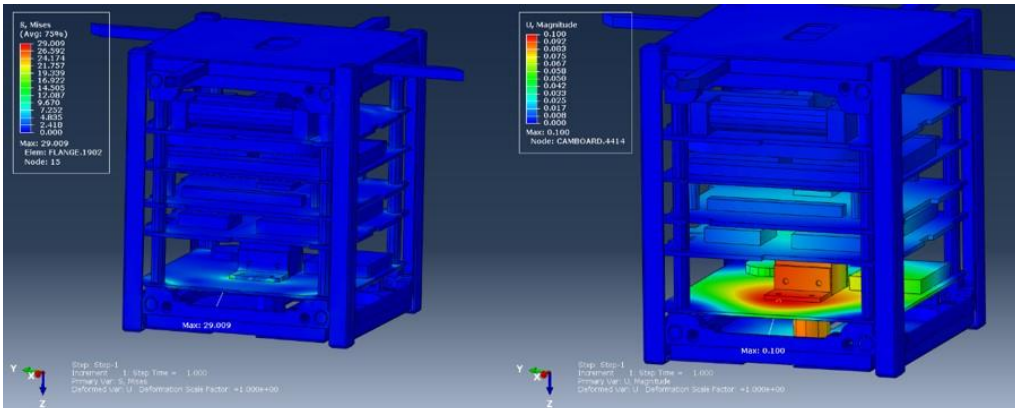

Figure 8: The stress and deflection in the Z-axis

3.2 Modal Analysis – FEA

Table 4 below exhibits the first 11 modes and their frequencies, which range between 0-750 Hz. Additionally, it includes the participation factors, along with the most affected direction of each mode. The modal participation factor is a measure of how strongly a mode contributes to the response of the structure to a force or a displacement in a specific direction.

Table 4: Modal analysis result

Mode Number	Frequency (Hz)	Participation factor (X-direction)	Participation factor (Y-direction)	Participation factor (Z-direction)	Most affected direction
1	204.063	0.0246	0.0051	1.4527	Z-axis
2	348.012	-0.11866	0.0399	1.9895	Z-axis
3	399.688	-0.0539	0.0818	1.6666	Z-axis
4	441.893	-0.0145	0.0063	1.7427	Z-axis
5	490.057	-0.3476	0.0142	1.2819	Z-axis
6	570.728	-0.1197	0.3413	0.4031	Z-axis
7	574.458	0.2627	0.3294	0.0829	Y-axis
8	640.930	1.0537	1.7393	-0.1182	Y-axis
9	676.462	-0.9763	1.2976	-0.8971	Y-axis
10	709.605	0.4648	0.0225	1.5569	Z-axis
11	740.065	2.2314	-1.5245	-0.2876	X-axis

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3.3 Testing

Figure 9 illustrates the low-level sine sweep response for X, Y and Z axes. The Reference blue line represents the launchers profile (Table 2), the control lines (orange and violet) represent the control accelerometers (on the base structure of the flanges as shown in figure 5), the response lines (yellow and green) represent the response accelerometers (attached at the top of the test pod), and before and after basically refer to overall test results before and after the vibration tests. whereas, Figures 10-12 demonstrate the random vibrations response. In these plots, the profile green line represents the launchers standards, the input green line shows the response accelerometer readings and the white line represents the control accelerometer readings.

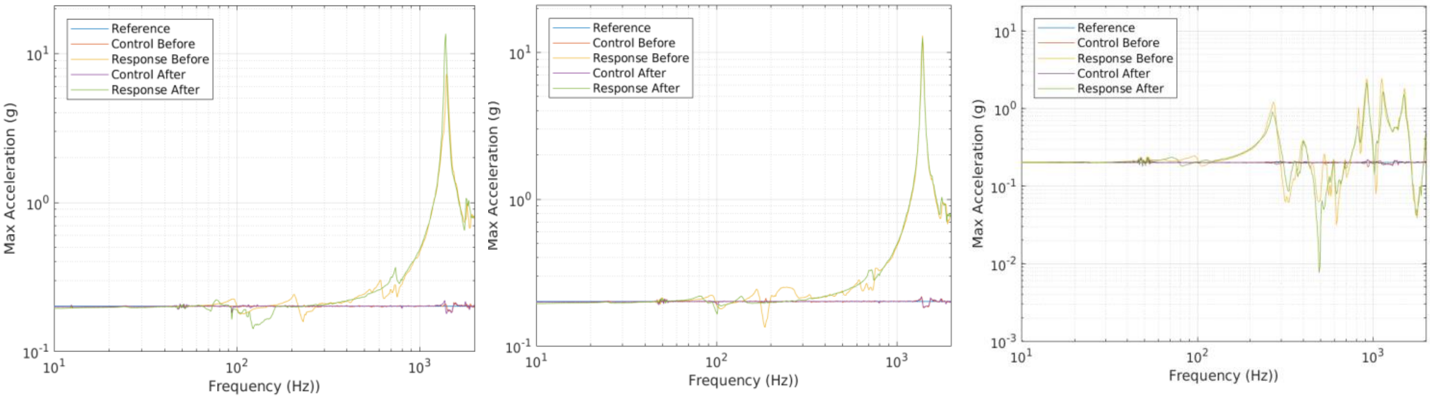

Figure 9: Low-level sine sweep response for X, Y and Z axes (left to right)

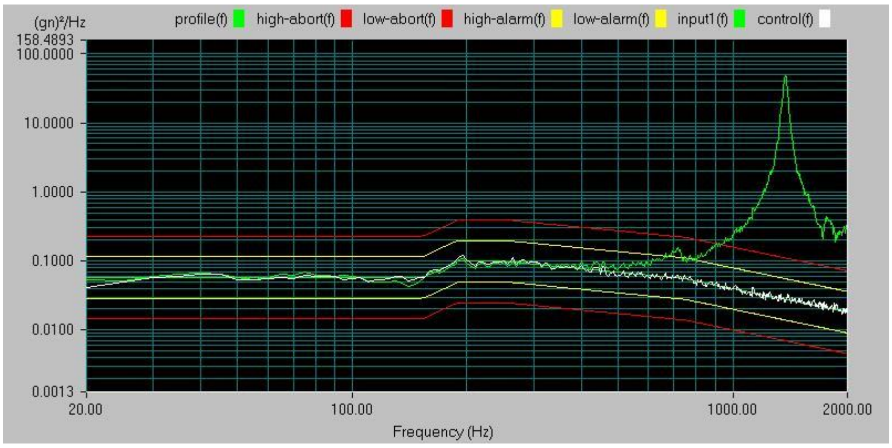

Figure 10: Random vibrations response for X axis

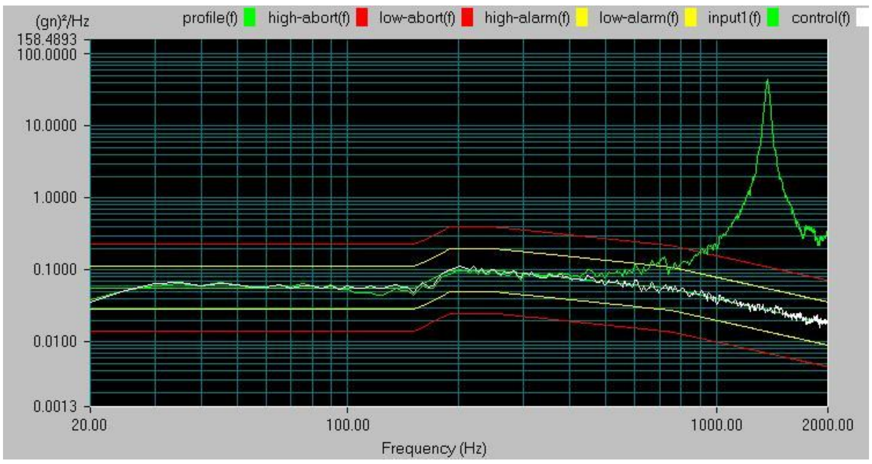

Figure 11: Random vibrations response for X axis

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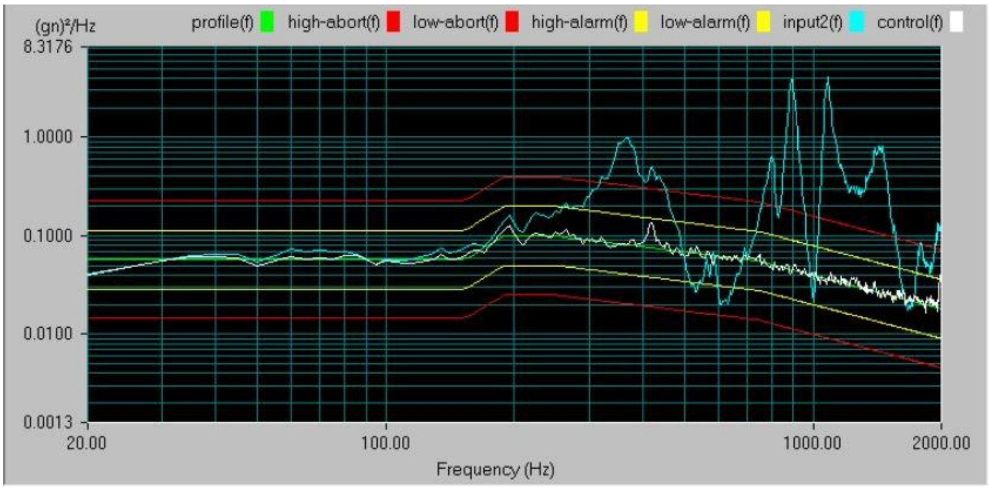

Figure 12: Random vibrations response for X axis

3.4 Discussion

Based on the simulation results, the maximum stresses for all cases occurred on the rods at their point of contact either with the boards or the structure. Such result is to be expected as the rods support and carry most of the loads in the CubeSat. However, the maximum deflections were detected in two locations; OBC and camera boards. In all of the loading cases, the maximum deflections were perpendicular to the affected surfaces, and in the same direction as the maximum stresses, which is expected as well. Moreover, in the Z axis loading case, the maximum deflection occurred at the maximum stress locations. All of the stresses were almost less than the Yield strength for all of the assumed materials. Hence, it is safe to conclude that no plastic deformations would take place.

The modal analysis showed that the first mode for the model is at approximately 204 Hz. The CubeSat should have no modes within the launching rocket's frequency range, which typically is around 100 Hz. Therefore, the simulation results of MYSAT-1 meet such conditions. Moreover, up to 720 Hz, 7 out of 11 potential modes were correlated with the simulation. Hence, it is safe to conclude that the prediction is quite accurate until 700 Hz (Table 5).

Table 5: Possible correlated modes between testing and modal analysis results

Test (Hz)	FEA (Hz)	Prominent Direction
200	204.063	Z-axis
320	348.012	Z-axis
400	441.893	Z-axis
490	490.057	Z-axis
600	640.930	Y-axis
620	709.605	Z-axis
720	740.065	X-axis

Based on the participating factors, the prominent direction of the mode in most of the modes, being the Z direction, is within expectation; since the CubeSat geometry is asymmetric (due to the components) in the Z direction. The first six modes are found to be more effective on the Z-axis. Furthermore, testing demonstrate similar results, where the peaks' amplitude for the them is higher in the Z-axis. Another observation that can be made is that the Z-axis modes are more common. All of these findings could be traced back to the CubeSat's design; stacking along the Z-axis.

Test results demonstrated the natural frequency of the MYSAT-1's flight model. High amplitude peaks, which represent the structure's resonance frequencies are prominent after 100 Hz meeting the launcher's requirements. The small noise peaks at the beginning of the plots represent the resonance frequencies of the small components in the CubeSat, not the structure's; hence negligible. From the results of these analyses and tests, the confidence in MYSAT-1's survival after launching is high.

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4.Conclusion

Launching is a critical stage of a CubeSat's life. It contains the high number of survival risks and failure possibilities. Therefore, it is essential to simulate for such conditions. MYSAT-1 is a 1U CubeSat developed in Khalifa University in the UAE. A simplified 3D model was created and simulated for quasi-static loads and modal analysis. Furthermore, a flight model was constructed and tested for low level sine sweep and random vibrations per the launcher's requirements. The results of the simulation and testing increased the level of confidence in the success and survival of the MYSAT-1 and led to its qualification and acceptance by the launcher.

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References

[1] Herrera-Arroyave, J. E., Ferrer-Pérez, J. A., Colín, A. and Bermúdez-Reyes, B. (2016). CubeSat System Structural Design. 67th International Astronautical Congress (IAC).
[2] Abdelal, G., Abuelfoutouh, N. and Gad, A. (2013). Finite Element Analysis for Satellite Structures.
[3] A. Bahaddin, "Effect of Acoustic Vibration on the Satellite Structure at Launch Stage," in International Conference on Modeling and Simulation, India, 2009.
[4] A. Calvi, "Spacecraft Structural Dynamics & Loads -A. Calvi Spacecraft Structural Dynamics & Loads An Overview," European Space Agency, The Netherlands, 2010.
[5] R. J. Ott, "Understanding Pyrotechnic Shock Dynamics and Response Attenuation Over Distance," Utah State University, Utah, 2016.
[6] System Requirements and Recommendations, 7th ed. Qb50, 2018.
[7] NanoRacks CubeSat Deployer (NRCSD) Interface Definition Document (IDD), NanoRacks LLC, 2018.