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INSTITUTE OF AEROSPACE ENGINEERING

LETECKÝ ÚSTAV

**DESIGN PROPOSAL AND MODAL ANALYSIS OF
FIXTURE FOR CUBESAT VIBRATION TESTS**

NÁVRH A MODÁLNÍ ANALÝZA PŘÍPRAVKU PRO VIBRAČNÍ ZKOUŠKY CUBESATU

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Desing proposal and modal analysis of fixture for CubeSat vibration tests

Brief Description:

Fulfilment of the vibration tests is one of the mandatory requirements for the satellite's integration within the launch vehicle. During the launch, CubeSats are placed inside of the standardized launch box – so called dispenser. Vibration test evaluates the modal characteristic of the CubeSat located inside of the dispenser. In case no dispenser is available (for example in current BUTCube project), it is necessary to design a suitable dispenser model. Preparation of the vibration tests than includes both test requirements compilation, but also test–dispenser design proposal and manufacture.

Master's Thesis goals:

- review of the mechanical testing of the satellites, vibration test requirements for CubeSats;
- design proposal of the support structure for the vibration test;
- FEM modal analysis of the proposed support structure;
- design and manufacture requirements verification.

Recommended bibliography:

PUIG-SUARI, J. a B. TWIGGS. CubeSat Design Specification. Rev. 13. USA: California Polytechnic State University, 2014.

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Abstrakt

Hnutí CubeSatů se v současné době těší vzrůstající oblibě, především díky možnosti zapojení širšího okruhu institucí do vesmírného výzkumu. Tento zájem zároveň vyvolává nutnost provádět mechanické zkoušky CubeSatů dříve, než je bude možné vypustit do vesmíru.

Tato závěrečná práce zpracovává problematiku mechanických zkoušek u CubeSatů a provádění jejich vibračních zkoušek. Na základě této rešerše je proveden návrh přípravku o velikosti 6U včetně modální analýzy a ověření vyrobiteľnosti.

Klíčová slova

CubeSat, Deployer, modální analýza, MKP, vibrace, mechanické zkoušky

Abstract

The CubeSat movement is currently growing in popularity, mainly due to the possibility of involving a wider range of institutions in space research. This interest is also driven by the need to conduct mechanical tests of CubeSats before they can be launched into space.

This master's thesis deals with the issue of mechanical testing of CubeSats and the performance of their vibration tests. Based on this research, the design of a 6U size fixture is performed including modal analysis and manufacturability verification.

Keywords

CubeSat, Deployer, modal analysis, FME, vibration, mechanical testing

Rozšířený abstrakt

Vesmírný průmysl prochází vlnou inovací, ke které dochází za pomoci nových raket, nových technologií a mezinárodních partnerů. Nové poznatky ve vědě, které vedly ke zmenšení výzkumných zařízení, vytvořily prostor pro novou kategorii malých satelitů nazvaných SmallSat. Tyto satelity představují unikátní možnost pro vlády, univerzity a soukromé společnosti vypouštět vlastní zařízení za zlomek ceny a mnohem kratší vývojový čas oproti standartním satelitům.

Zmenšení satelitů však nevedlo ke snížení nároků na ověření správné funkčnosti satelitů. Schopnost prokázat, že satelit přežije start rakety a vibrace přitom vznikající, stejně tak jako nehostinné prostředí volného vesmíru, zůstává stěžejní součástí jakéhokoliv vesmírného projektu a tato diplomová práce se zabývá právě touto problematikou.

První kapitola pojednává o požadavcích na mechanické zkoušky CubeSatů. Postupně jsou rozebrány jednotlivé druhy těchto testů. Důraz je kladen na vibrační zkoušky, které představují klíčovou oblast testování. V kapitole jsou popsána i některá vypouštěcí zařízení, protože pro každou raketu platí jiné požadavky na environmentální testy.

V další kapitole jsou popsána vypouštěcí zařízení, ve kterých je CubeSat uložen během startu. Zároveň je provedena rešerše komerčně dostupných zařízení. Pochopení požadavků a konstrukce těchto vypouštěcích zařízení je stěžejní pro úspěšný návrh vlastního přípravku.

Po provedení rešeršní části práce následovala kapitola o stanovení základních požadavků na vyvíjený přípravek nazvaný BUTPOD. Bylo rozhodnuto o velikosti přípravku, maximální velikosti testovatelného CubeSatu, materiálu na přípravek a případné povrchové úpravě.

Po stanovení požadavků došlo k vlastnímu koncepčnímu návrhu 3 verzí přípravku. Jednotlivé varianty představují unikátní přístup k řešení. Před porovnáním, která verze je nejlepší pro detailní návrh, byla provedena modální analýza, za účelem nalezení vlastní frekvence a tuhosti konstrukcí. Poté následovalo porovnání jednotlivých verzí.

Z porovnání jako nejlepší verze vyplynula druhá varianta. V další kapitole tedy došlo k detailnímu návrhu této verze BUTPODU. Především došlo k návrhu systému uchycení panelů, vnitřního systému kolejí a výtlačné desky. Po provedení detailního návrhu došlo k optimalizaci některých dílů.

Po provedení návrhu došlo k ověření vyrobiteľnosti a volbě výrobní metody jednotlivých dílů. Součástí kapitoly je i ověření technických požadavků, které jsou stanoveny pro vypouštěcí zařízení, ale musí je splňovat i BUTPOD.

V předposlední kapitole došlo k porovnání navrženého přípravku s komerčně dostupnými alternativami. Z porovnání vyplývá, že BUTPOD vyniká především ve velikosti testovatelného CubeSatu a modulárnosti.

Na závěr byla provedena diskuse nad možnostmi dalšího vývoje a představena doporučení pro tento vývoj.

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POSPÍŠIL, Jakub. *Design proposal and modal analysis of fixture for CubeSat vibration tests* [online]. Brno, 2023 [cit. 2023-05-25]. Available at: <https://www.vut.cz/studenti/zav-prace/detail/149204>. Master's thesis. Brno University of Technology, Faculty of Mechanical Engineering, Institute of Aerospace Engineering. Supervisor Václav Lazar.

Declaration of authenticity

I declare that I have written my master's degree thesis on the topic of "*Design proposal and modal analysis of fixture for CubeSat vibration tests*" independently, with usage of information provided by literature, and other sources, which are all quoted at the end of the thesis, at section list of bibliography.

In Brno on May 26, 2023

.....

Jakub Pospíšil

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Introduction

The space industry is undergoing a new wave of innovation with the help of new launch service providers, new launch vehicles, new space systems technologies, and international partnerships. New advances in science, which have led to the downsizing of research instruments, have created space for a new category of small satellites called SmallSats. These satellites represent a unique opportunity for governments, universities, and private companies to launch their own equipment at a fraction of the cost and much shorter development time than standard satellites.

The downsizing of the satellites has not led to a reduction in the requirements for verifying the correct functionality of the satellites. The ability to demonstrate that a satellite can survive a rocket launch and the vibrations generated by that launch as well as the hostile environment of outer space remains a crucial part of any aerospace project, and this thesis addresses this very issue.

One of the main objectives of this thesis is to determine what mechanical tests need to be performed to qualify the CubeSat. As well as the specific parameters of each test so that individual tests can be performed based on this thesis.

Testing the CubeSat itself is not possible because the satellite is placed in the deployer during the launch. Therefore, these devices need to be tested as a package. However, this deployer is not always available during the CubeSat test phase. This problem has given rise to fixtures that simulate the Deployer environment and allow for satellite testing. Which leads to the next main goal of this thesis. To create a custom BUTPOD fixture that will be used for testing CubeSats designed at Brno University of Technologies.

After the conceptual and then detailed design of the BUTPOD, the properties of the product need to be verified by modal analysis. Once the overall design is complete, the manufacturability of the individual parts will be analysed, and the fixture will be compared to commercially available solutions. Based on this comparison, possible recommendations for further development of this project will be discussed.

1. CubeSat testing requirements

Environmental tests are necessary to ensure the safety of CubeSat, deployer and primary mission. During launch and deployment, the assembly is exposed to a dynamic launch environment characterized by random vibrations and shocks [1]. Based on the knowledge from previous missions, standards have been developed to verify the correct operation of CubeSat and deployer. These standards formulate basic tests, but they serve only as a reference. For a specific mission, environmental tests need to be performed according to the requirements of the Launch provider [2].

1.1 Vibration testing

The first group of tests are vibration tests. The CubeSat and deployer are subjected to mechanical loads in the form of vibrations from the engines and aerodynamic forces acting on the rocket during launch and flight. The objective is to find the natural frequencies and ensure that there is no resonance between the CubeSat and the deployer. As well as verifying that no malfunction occurred during launch, such as loose screws, disconnected cables, integrity of PCB connections and boards.

In-flight vibration data is usually not available. For this reason, tests have been developed to simulate these conditions. The basic tests are the random vibration and the sine sweep test. In practice, these tests are used individually or as a group of tests [3]. The flow of such a test is shown in Figure 1.

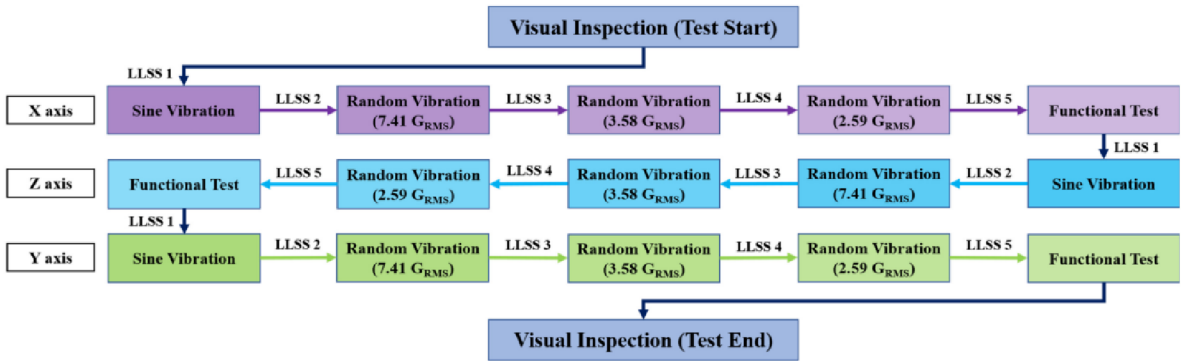


Figure 1 Vibration testing flow diagram [3]

1.1.1 Random Vibration test

For random vibration (CubeSat and Deployer), NASA specifies requirements [4] in the form of Maximum Predicted Environment (MPE) according to MIL-STD-1540C [5]. Dynamic Environments random MPE envelopes and P95/50. This means that during 95% of flights with 50% confidence, the loads will not exceed the MPE. These NASA requirements [4] are shown in Table 1.

Table 1 Environment test - random vibration [4]

Test	Qualification by Test	Protoflight Test	Acceptance Test
Random vibration	MPE + 6 dB for (3) minutes, each of (3) axes	MPE+3 dB for (2) minutes, each of (3) axes	MPE for (1) minute, each of (3) axes

The vibration environment is described as acceleration spectral density (ASD) or power spectral density (PSD) in g^2/Hz for a frequency interval of at least 20 to 2000 Hz [5].

Each launch vehicle (LV, [6] [7]) has its own random vibration test levels for each stage of the LV. For a specific mission, the Launch provider's requirements must be followed. The General Environmental Verification Standard (GEVS, [8]) represents the "worst case" PSD that can occur during LV flight. GEVS envelopes the most used LVs (Table 2), so if successfully passed, there should be no problem passing the test levels for a specific LV. Random vibration levels for GEVS, Soyuz and Falcon 9 are plotted in Figure 2.

Table 2 Generalized random vibration test levels (GEVS) [8]

Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 Db/oct	-6 Db/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

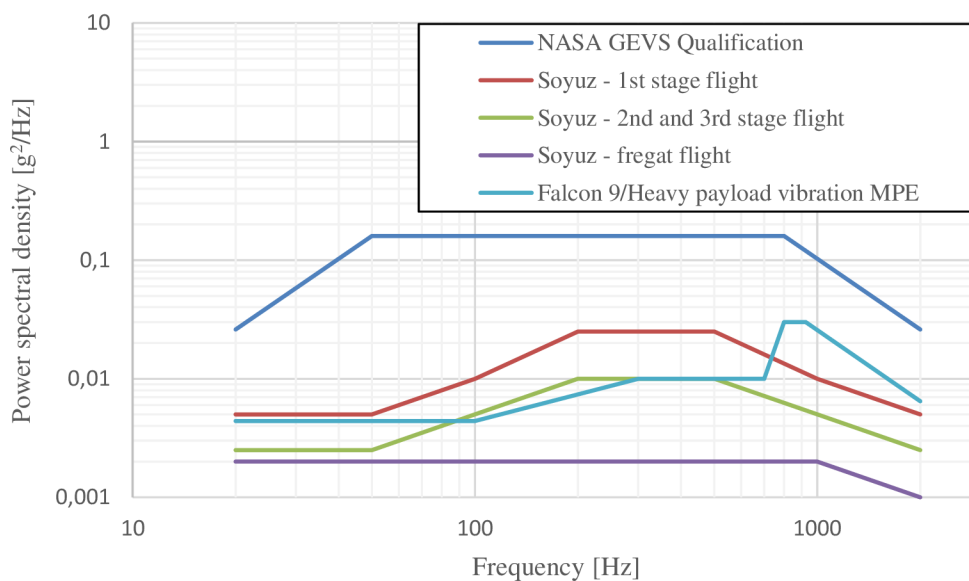


Figure 2 Limit flight levels of random vibrations [8] [6] [7]

1.1.2 Sinusoidal vibration test

Sinusoidal vibration can be induced by rotational movement of components, flutter, or combustion. The amplitude of the vibration load is typically specified as acceleration g [9]. Acceleration amplitudes that exceed 0.016 times the frequency in Hz are tested.

GEVS [8] suggests low level sine (LLS) as a generally appropriate method for determining the fundamental frequency. NASA's requirements for sinusoidal vibration are in Table 3. Maximum limit-level equivalent sine environment for Falcon 9, Heavy and Soyuz are plotted in Figure 3.

Table 3 Environment test - Sinusoidal vibration [4]

Test	Qualification by Test	Protoflight Test	Acceptance Test
Sinusoidal vibration	MPE + 6 dB ¹	1,25 × MPE ¹	MPE ¹

(1) Testing shall be performed for content that is not covered by random vibration testing

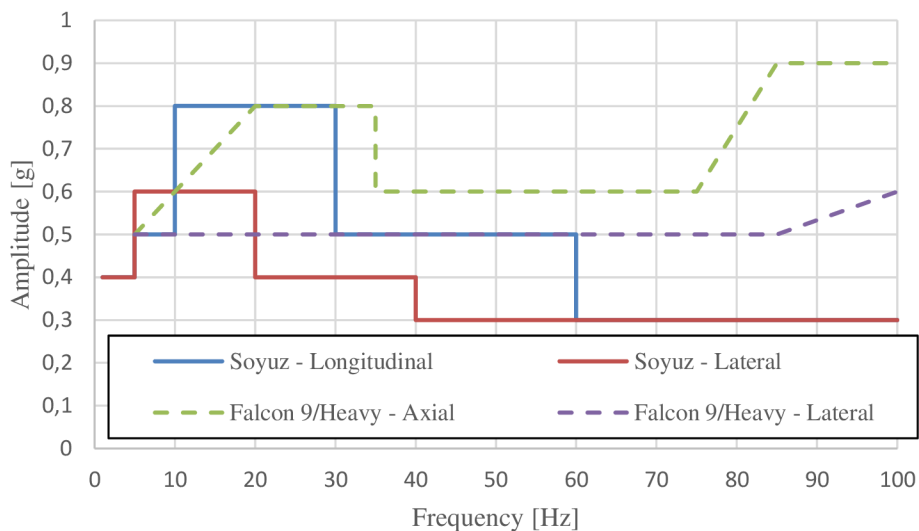


Figure 3 Limit level equivalent sine environment [6] [7]

1.2 Shock testing

Another test characterized by dynamic loading is shock. During flight, a number of load-inducing events occur that can be characterised as shock.

- Release of the launch vehicle hold-down at lift-off [7]
- Booster separation [7]
- Stage separation [7] [6]
- Fairing deployment [7] [6]

- Spacecraft separation [7] [6]

This type of mechanical loading is characterized by high acceleration (up to $100\,000\text{ m/s}^2$ [9]) and very short duration ($10\text{-}20\text{ ms}$ [9]). The corresponding acceleration time history or shock response spectrum (SRS) in the frequency domain is used to describe shock loads. NASA's [4] requirements for Shock testing are in Table 4. This standard also specifies when the shock test does not need to be performed. These requirements are:

1. The qualification random vibration test spectrum when converted to an equivalent shock response spectrum (3-sigma response for $Q = 10$) exceeds the qualification shock spectrum requirement at all frequencies below 2000 Hz [4].
2. The maximum expected shock spectrum above 2000 Hz does not exceed (g) values equal to 0.8 times the frequency in Hz at all frequencies above 2000 Hz, corresponding to the velocity of (50 in/s) [4].

Table 4 Environment test - Shock

Test	Qualification by Test	Protoflight Test	Acceptance Test
Shock	MPE + 6 dB, 3 times in both directions of 3 axes 1	MPE + 3 dB, 1 time in both directions of 3 axes 1	N/A

(1) Shock MPE envelops P95/50 for at least (3) samples, with 4.5 dB uncertainty factor applied where less than (3) samples are used.

1.3 Thermal and vacuum testing

Thermal and vacuum testing is used to verify functionality in a space environment. The basic types of thermal tests are thermal balance, bakeout, vacuum and cycling test. Unlike mechanical tests, which focused mainly on loads during launch, thermal testing also helps to verify functionality during the space mission.

Thermal balance (TB) test is used to determine the thermal load. From this data, the numerical thermal model is optimized. Thermal bakeout is very important, during this test the sample is forced to outgas most of the volatile components that are coming from the production process. During thermal vacuum cycling (TV or TVC), components are exposed to vacuum and several temperature cycles. The profile of the cycle depends on the mission parameters [9].

1.4 Strength Qualification Requirements

Strength requirements and safety factors must be considered in the design. The safety factor takes into account different material properties, manufacturing and design procedures [5]. To qualify the equipment, analyses and tests are needed to verify the ability to function under the given load. NASA's requirements [4] for CubeSat and Deployer specify the size of the safety

qualification factor (Table 5) depending on the limit load. The limit load occurs during flight under the worst flight and environmental loads [4].

Table 5 Strength Qualification Requirements [4]

Qualification Method	Qualification Factors of Safety	
	Yield strength	Ultimate strength
Strength Analysis Only	$1.6 \times \text{limit load}$	$2.0 \times \text{limit load}$
Structural Test ¹	$1.1 \times \text{limit load}$ ²	$1.25 \times \text{limit load}$ ³

(1) A combination of structural test and analysis maybe used for qualification.

(2) With no detrimental yielding of test article

(3) with no structural failure of test article

1.5 Qualification / Acceptance test flow

Based on the mission requirements and standards, a CubeSat design is made. The CubeSat should then undergo qualification or protoflight testing. Literature Space Engineering: verification guidance [10] from ESA describes the various models that can be used as verification requirements. The most important models are described in the following subsection. The design of such a test procedure according to [1] is shown in Figure 4.

1.5.1 Qualification

Qualification testing is designed to demonstrate that the equipment will function properly during launch and on-orbit operations. The equipment is subjected to conditions worse than those encountered during the mission. The main objective is to detect defects that could lead to mission compromise [1] [8]. The parameters of these tests are specified by the Launch Provider. The advantage is the possibility to perform many tests and the possibility to use simplified equipment [1] [8]. This observation is crucial for this thesis because it allows to replace the Deployer with a simplified device (TestPod) for testing, whose design is the main focus of this thesis.

1.5.2 Protoflight

Protoflight testing is performed on the flight model CubeSat. The parameters of the tests are again set by the Launch provider. These tests are not as demanding as the qualification testing. CubeSat shall not be disassembled or modified after protoflight testing. Additional testing will be required in that case [1].

1.5.3 Acceptance

The last test is acceptance. After delivery and integration of CubeSat into Deployer, additional testing can be performed. Testing is performed by the Launch provider, which specifies the test

parameters. After successful integration and testing, Cubesat shall no longer be removed from the Deployer [1].

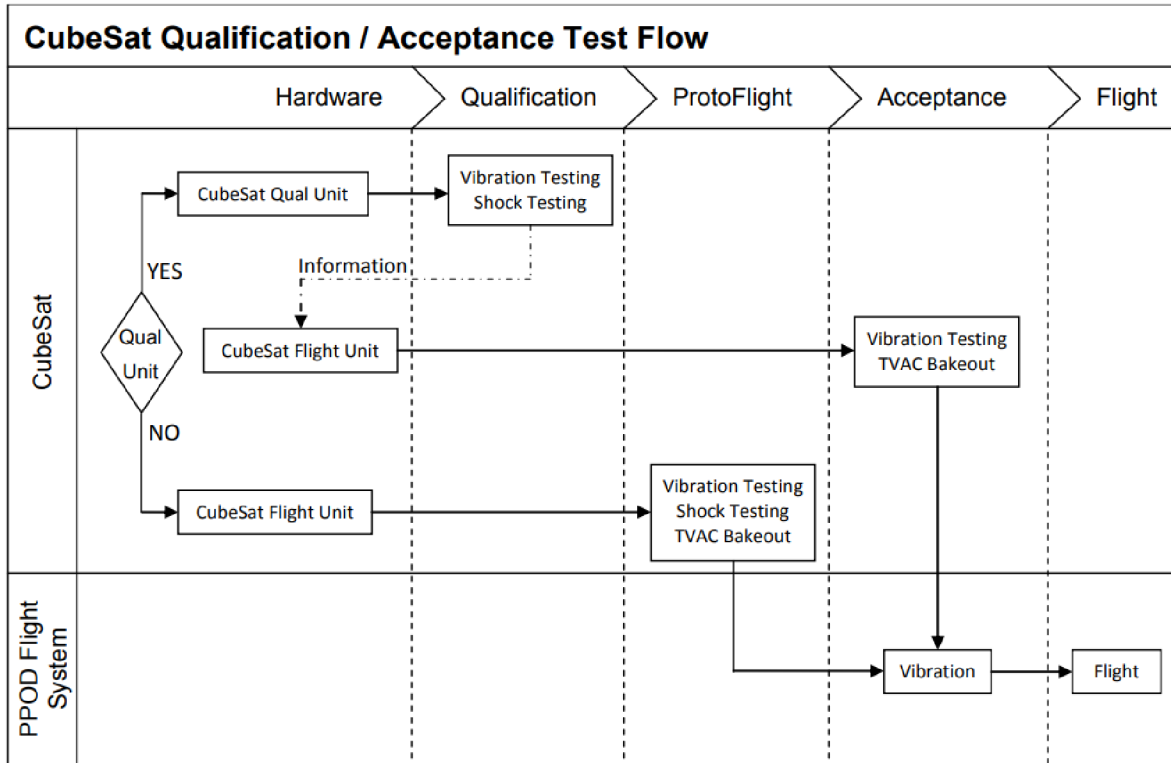


Figure 4 CubeSat General Testing Flow Diagram [1]

1.6 Launch system

An important aspect of TesPod design is the analysis of commercially available LVs. The payload is subjected to load through the Payload Adapter (Figure 5). Individual Launch Providers have their own requirements regarding environmental testing the requirement for the minimum resonant frequency of the payload.

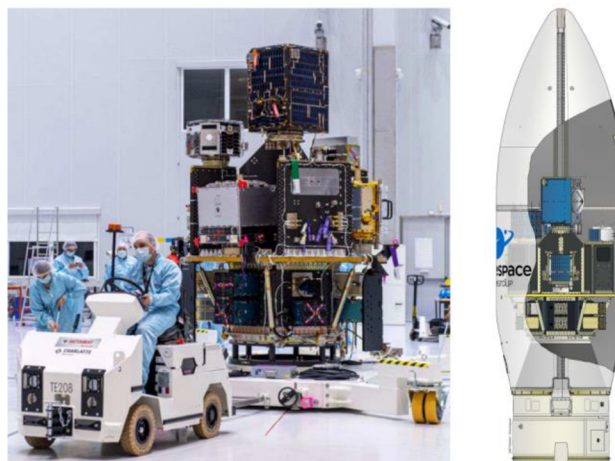


Figure 5 Vega's payload adapter [11]

1.6.1 Falcon 9

Falcon 9 (Figure 6) is a two-stage rocket designed and manufactured by SpaceX. The rocket is designed to carry payload and passengers into Earth orbit. It is the first reusable rocket capable of traveling into orbit. The main advantage is in the reusability of the rocket's first stage. SpaceX uses its own Merlin rocket engines on the Falcon 9 [12] [7].

The requirements for the environmental tests according to the manual [7] are shown in Figure 2 and Figure 3. The rocket parameters are shown in Table 6.

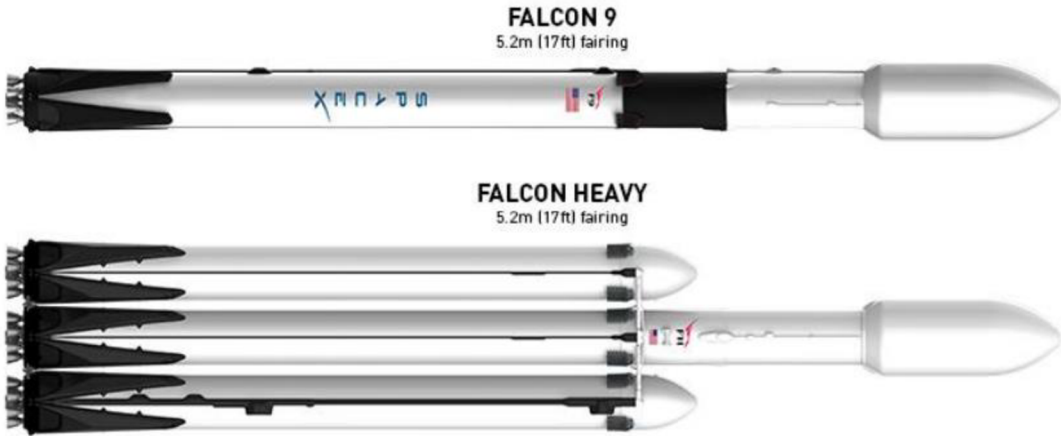


Figure 6 Falcon 9 and Falcon Heavy [7]

Table 6 Falcon 9 overview [12] [7]

Height	Diameter	Mass	Payload		Payload minimum resonant frequency		
			LEO ¹	GTO ²	Lateral	Axial	Secondary structure
m	m	kg	kg	kg	Hz	Hz	Hz
70	3.7	549 054	22 800	8 300	10	25	35

(1) Low Earth orbit
 (2) Geostationary transfer orbit

1.6.2 Vega

The Vega [13] rocket is a product of the European Space Agency (ESA). Vega rockets (Figure 7) are operated by Arianespace. It is a four-stage rocket designed for small and medium payloads. Arianespace offers a shared launch capability for small satellites under the Small Spacecraft Mission Service (SSMS) programme. The Vega rocket is therefore an ideal launch vehicle for CubeSats. The rocket parameters are shown in Table 7.



Figure 7 Vega rocket [14]

The Vega-C manual [11] specifies frequency requirements (Table 7) specifically for CubeSat and Deployer.

Table 7 Vega overview [14] [13]

Height	Diameter	Mass	Payload	CubeSat minimum resonant frequency	
			Polar Orbit	Lateral	Longitudinal
m	m	kg	kg	Hz	Hz
30	3	137 000	1 500	115	115

1.6.3 Soyuz

One of the most successful rockets in history is undoubtedly the Soyuz [6]. Since the launch of the first satellite into space, Soyuz has regularly launched payloads into orbit, including astronauts, to the International Space Station (ISS) in upgraded versions of the rocket. The Soyuz rocket can launch payloads to a wide range of orbits (LEO, GTO, SSO, etc.). The latest version is the Soyuz-2 (Figure 8). The rocket parameters are shown in Table 8.



Figure 8 Soyuz-2 [6]

Table 8 Soyuz overview [6]

Height	Diameter	Mass	Payload	Payload minimum resonant frequency	
			LEO	Lateral	Longitudinal
m	m	kg	kg	Hz	Hz
46	2.95	312 000	4 850	15	35

2. Deployers and TestPods

Deployer serves as an interface between CubeSat and LV. One of its main functions is to launch a satellite into orbit. Currently, there are several Deployers that can launch CubeSats up to a size of 24U. The Deployer guarantees a smooth deployment with a small spin rate [4].

For many environmental tests (Chapter 1) where Deployer cannot be used (e.g. deployer is not available), a simplified Deployer in the form of TestPod can be used. TestPod is used for CubeSat vibration tests. Its main function is to simulate the environment inside the Deployer.

2.1 Deployer Technical Requirements

When designing a TestPod, it is necessary to consider the requirements that are placed on the Deployer, both general requirements and requirements from the Launch provider.

In its Launch Services Program (LSP [4]) document, NASA describes essential requirements for Deployer. These requirements are:

- Deployer has to be designed and tested according to the environment requirements in [4]
- Deployer shall be structurally qualified in accordance with Strength Qualification Requirements (Table 5)
- Deployer will be fully filled with CubeSat, which has limiting dimensions according to [4].
- Static and dynamic envelopes of the primary mission shall not be breached by the Deployer.
- LV avionics qualification status or architecture should not be affected by Deployer.
- Deployer should have a built-in sensor that will check whether the door is open or closed.
- When launching, the deployer should give the CubeSat enough of a boost to avoid colliding with the Primary Mission hardware.
- Deployer should not be used to launch CubeSat mass simulator(s).
- Deployer shall utilize industry standards for locking methodologies on all fasteners consistent with NASA-STD-6016.
- Materials used on the Deployer should be in accordance with NASA-STD-6016.
- Deployer shall conduct vehicle specific CubeSat separation analyses.
- Deployer should have a natural base frequency higher than 120 Hz.

2.2 Deployer design

After the Launch vehicle sends the signal to launch the CubeSat, the actuation mechanism releases the Deployer door and allows the initiators (spring, gas, or shape memory material) to move the pusher plate towards the open door, pushing the payload outwards in the direction of

the rails or tabs [15]. A visualisation of the Deployer with a description of each part is shown in Figure 9.



Figure 9 EXOpod 12U CubeSat Deployer [16]

Deployer chassis

The chassis consists of five side panels and a door. The chassis is the main isolation mechanism between the CubeSat and the rest of the LV. It serves as the main interface for load transfer between the LV and the Deployer. The side panels (-X and +X) have access ports (visible in the Figure 9) that are used for diagnostics and possible work on the integrated CubeSat [15] [17].

Deployer door

The door is usually located on the front side (+Z) of the deployer. The door acts as a barrier against premature launch of the CubeSat into space. When a signal is sent from the LV to the Deployer, a spring-loaded door will open and allow the CubeSat to be launched using the main deployment spring. For most deployers the closed-door touches right at the end of the rails or tabs [15] [17].

Deployer pusher plate

The CubeSat is secured against movement (-Z) by a pusher plate. The pusher plate pushes the CubeSat out when the door is opened. The movement occurs along the rails/tabs and the impulse is provided by the deployer initiators [15]. The pusher plate can be fitted with a large hole in the centre. The use of this is that the CubeSat can be fitted with a so-called Tuna Can, the cylindrical extension on the back (-Z) of the CubeSat [1].

Deployment mechanism

CubeSat launch is initiated by an electrical signal from the LV to the deployer door release mechanism. Proper operation of this mechanism is critical for successful mission execution. To minimize shock to the CubeSat, pyrotechnics are not used for the door release. Deployers use actuators to open the door and release the payload [15] [17]. There are currently several commercially available mechanisms for use in space. However, for the purposes of this thesis, it is not necessary to discuss these solutions further.

Deployment initiators

To launch a CubeSat from a Deployer, spring (spring plunger), compressed gas or shape memory material are used as initiators. The advantages and disadvantages of each method according to [18] are described in Table 9. All methods work on the same principle, when the door is opened, energy is transferred through the pusher plate to the CubeSat, causing it to be ejected [15]. The simplest mechanism is a spring (Figure 10), which does not need its own trigger.

Table 9 Comparison of the most used deployment initiators [18]

Method	Advantages	Disadvantages
Compressive Spring	+ Efficiency	- Additional spring space
	+ Simplicity	
	+ Instant reaction to door release	
Compressed Gas	+ Higher energy release	- The interior must be airtight
	+ Compact	- Requires separate trigger
Shape Memory Material	+ Higher amount of energy	- Heat or chemical trigger release
	+ Small size requirements	

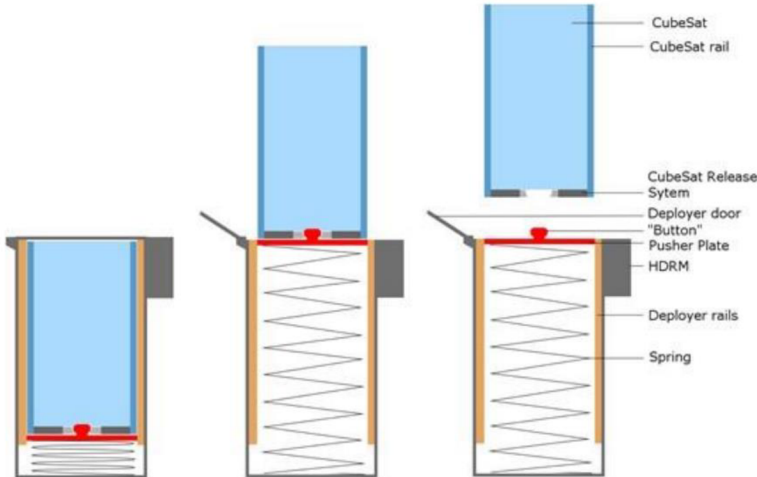


Figure 10 Mechanism of CubeSat Ejection [19]

Rails and tabs

Rails/Tabs are used to launch CubeSats along a straight linear path. These elements also prevent the CubeSat from moving in the XY axis, and some in the Z axis. Rails work on the principle of constraining the CubeSat in four corners. Tabs allow attachment via two flanges on the bottom of the Deployer (Figure 11) [15]. Constraint by Tabs creates a stiff invariant load path. A CubeSat constrained with Rails can vibrate due to manufacturing tolerances (0.5 mm), causing problems in dynamic response modelling [20].

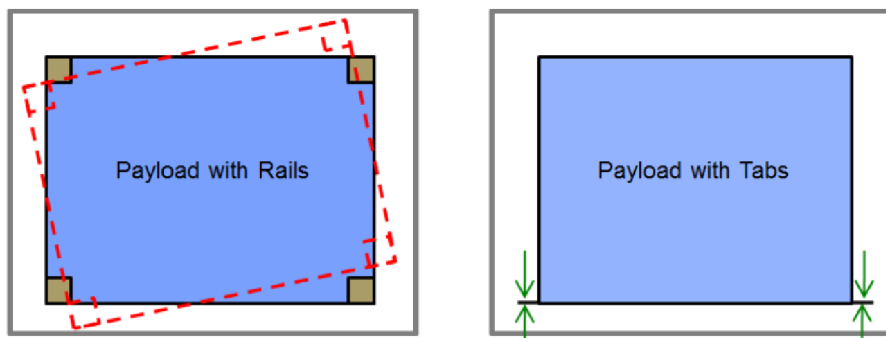


Figure 11 Comparison of interface with rails and tabs [20]

2.3 P-POD

To design the optimal TestPod, it is necessary to research commercially available Deployers and analyse their design. The first such deployer, which was created at the beginning of the entire CubeSat movement at California Polytechnic State University (Cal Poly), is the Poly Picosatellite Orbital Deployer (P-POD) [17]. P-POD is a standard launch system that allows CubeSat manufacturers to proof common physical requirements. It also serves as an interface between the LV and the CubeSat.



Figure 12 P-POD Mk. III [17]

P-POD [17] has a long flight heritage. Over time, upgrades and improvements have been made, and the Mk. III (Figure 12) currently represents the latest variant in development. However, the

basic dimensions have remained the same. The deployer can hold deployable hardware of 340,5×100×100 mm (standard 3U CubeSat). The P-POD design is represented by 6 panels, with a total of 6 access ports on the sides (+/-X). A combination of springs and rails is used as the ejection mechanism of the CubeSat. The whole P-POD is made from aluminium 7075-T73. The basic parameters are summarized in the Table 10.

Table 10 P-POD Basic parameters [17]

Size	Mass	Deployment velocity	Inner volume
	kg	m/s	mm
3U	3	2	340.5×100×100

2.4 ISIPOD

Another popular deployer is the ISIS Payload Orbital Dispenser (ISIPOD) from Innovative Solutions In Space (ISISPACE). ISIPOD (Figure 13) provides a simple interface for CubeSat integration and Deployer attachment to LV. ISIS has created a range of ISIPOD sizes up to 16U with customization options.



Figure 13 ISIPOD 3U CubeSat Deployer [21]

Unlike the P-POD, which has dedicated access ports, the ISIPOD uses a system where the entire side can be removed, allowing full-length access to the CubeSat. For the needs of CubeSat development, ISIPOD is designed with additional space to create a larger CubeSat (rail spacing remains the same). The launch mechanism is the same as for the P-POD, consisting of a spring, a pusher plate, and rails [21] [22]. The basic parameters of the ISIPOD are summarized in the Table 11.

Table 11 ISIPOD Basic parameters [21] [23] [24] [25]

Size	Mass	Deployment velocity	Inner volume
	kg	m/s	mm
1U	1.5	1 - 2	113.5×100×100
2U	1.75		227×100×100
3U	2		340.5×100×100

2.5 CSD

The last Deployer to be mentioned is the Canisterized Satellite Dispenser (CSD) [26] from Planetary Systems Corporation (PSC). The CSD (Figure 14 [27]) design allows for mounting on any side, which allows the Deployers to be placed more densely on the LV. The difference to, for example, P-POD is the use of tabs that allows preloading and creates a stiff and modellable load path for the CubeSat satellites.

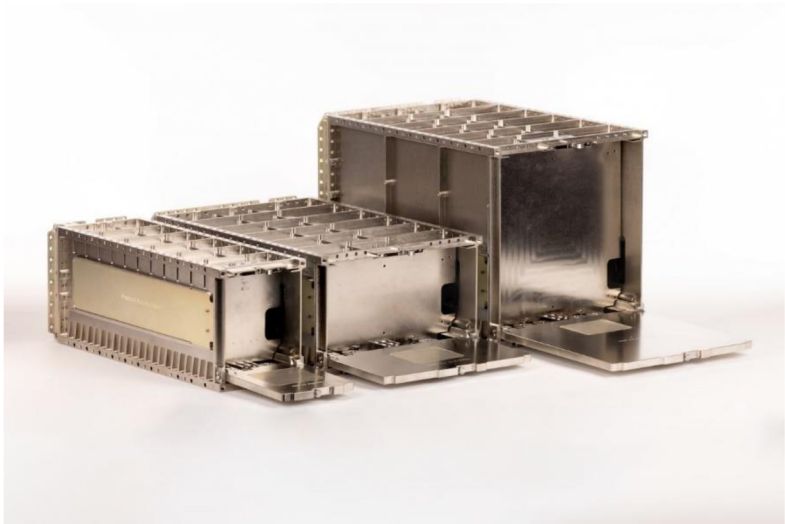


Figure 14 Canisterized Satellite Dispenser 3U, 6U and 12U

The tabs design leads to the possibility of launching a CubeSat with up to 15% more volume than a standard CubeSat. But it has its disadvantages, the tabs are placed only on the sides, which means that it is not possible to launch for example two 3U CubeSats from a 6U Deployer. CSD is made of 6061-T6 or 7075-T7 aluminium alloy. The CSD parameters collected from [20] [26] are in the Table 12.

Table 12 CSD Basic parameters [20] [26]

Size	Mass kg	Deployment velocity m/s	Inner volume mm
3U	3.32	0.6 - 3 ⁽¹⁾	113×116×366
6U	4.5		239×116×366
12U	5.65		239×229×366

(1) Depends on the number of springs and the weight of the payload

2.6 Exolaunch TestPod

Some companies also offer the option to purchase specialized TestPods along with their Deployers. One such company is Exolaunch, which offers a TestPod [28] (Figure 15) developed for mechanical testing of CubeSats. The advantage of such a commercial solution lies mainly

in the possibility of a complete mechanical qualification of the CubeSat. Which serves as a safe verification of compatibility with a real Deployer (ExoPod).



Figure 15 Exolaunch 3U TestPod with adapters [28]

In terms of design, Exolaunch provides TestPods in 3U, 8U and 16U sizes. It also allows the option of using an adapter that makes it possible to test CubeSats smaller than 3U. The TestPod uses a combination of a clamping mechanism and set screws to eliminate potential tolerance gaps between the TestPod and the CubeSat. A distinguishing feature is the solid flange on the bottom which allows for easy mounting on the shaker.

2.7 Summary

The information from [17], [20], [21], [22], [23], [24], [25], [26], [27] and [28] were used to create a Table 13, in which the basic parameters of Deployers and TestPods are mentioned. This information is used to design the TestPod and determine the basic geometric and design requirements.

The first important factor coming out of the research is the requirement for the value of the first natural frequency, given by LV. The Vega rocket presents the most critical requirements (>120 Hz), these requirements are met by the P-POD and the Exolaunch TestPod. While the TestPod appears to be the stiffest, this is due, among other things, to its more robust design, which has to withstand a number of repeated tests, unlike the Deployer, which only undergoes one launch.

As for the materials used to make the Deployer, all producers follow the requirements according to [1], including the anodizing of the rails. When it comes to the size of a usable CubeSat, all Deployers are the same, except CSD, which uses tabs that make the size of the CubeSat partially different. An important factor is the ability to install extra payload on the sides and end of the CubeSat (tuna can). This solution uses ISIPOD and Exolaunch TestPod. A very interesting addition is the use of adapters for the Exolaunch TestPod. Their use allows to test even smaller CubeSats than the size of the TestPod. P-POD is a solution that has been proven over the years but lags behind in the possibility of using accessories unlike ISIPOD.

Table 13 Comparison of Deployer and TestPod parameters

	P-POD	ISIPOD			CSD			Exolaunch TestPod		
Sizes	3U	1U	2U	3U	3U	6U	12U	3U	8U	16U
Length (Z)⁽¹⁾ [mm]	340.5	113.5	227	340,5	366	366	366	340.5	454	454
Length (X)⁽¹⁾ [mm]	100	100	100	100	113	239	239	100	226.3	226.3
Length (Y)⁽¹⁾ [mm]	100	100	100	100	116	116	229	100	100	226.3
Deployment initiators	Spring/Spring plunger	Spring/Spring plunger			Spring/Spring plunger			-		
Take-off mechanism	Deployment rails	Deployment rails			Payload tabs			Deployment rails		
Mass [kg]	3.00	1.50	1.75	2.00	3.32	4.50	5.65	-		
Structural material	Aluminium Alloy 7075-T73	Aluminium Alloy 7075-T73 and 6061-T6			Aluminium Alloy 7075-T7 and 6061-T6			Aluminium Alloy		
Anodized Take-off mechanism	YES	YES			YES			YES		
Access ports/panels	YES	YES			YES			YES		
Additional mass (Z)	NO	YES			NO			YES		
Additional mass (at CubeSat's sides)	NO	YES			NO			YES		
Natural frequency [Hz]	>120	>90			>90			>400	>350	>200

(1) Dimensions of the CubeSat compartment

3. Design assumptions

After conducting research of commercially available Deployers, it is necessary to define the design assumptions that are needed when designing a BUTPOD. The maximum allowable dimensions of the CubeSat need to be defined. It is also necessary to decide what material, including surface treatment, is best to use for the BUTPOD. In this chapter, the aim is to decide on the following points:

- BUTPOD size
- Maximum dimensions of the tested CubeSat
- Structural material
- Surface treatment

3.1 Primary requirements

The primary requirement for BUTPOD is to faithfully simulate the Deployer environment. At the same time, however, it is necessary to consider the fact that BUTPOD should be a simple device capable of performing a longer series of tests. Hence the requirement for a more robust and rigid design that will be able to meet these parameters. All this while meeting several requirements that are placed on Deployers [4] and cannot be omitted from the BUTPOD.

Currently, to test different sizes of CubeSat, you need a TestPod of the appropriate size. Some companies are attempting to overcome this shortcoming by using various adapters (e.g. Exolaunch [28]) to "fill in" the empty space and test the CubeSat in a fixture designed for larger CubeSats.

The solution using adapters is not optimal. Therefore, the question arises whether it would not be possible to create a BUTPOD that is modular to some extent and allows changing the size by replacing a certain number of parts. For this idea, a combination of CubeSat size 6U and 3U is ideal. In TestPods of size 6U it is possible to test one CubeSat of size 6U or two satellites of size 3U. Testing only one CubeSat in one half would lead to imbalance. However, with appropriate modification and swapping of parts, it would be possible to create a BUTPOD of size 3U. Therefore, further design assumptions will be directed in this modular direction.

3.2 Dimension requirements

The internal usable volume of the BUTPOD is a basic requirement that needs to be established at the very beginning to be able to develop the design further. Due to the unique situation of CubeSats, which have fixed basic dimensions and the standard for a given size precisely specifies the so-called rail to rail distance, this requirement is greatly simplified.

The general dimensional requirements according to the CubeSat Design Specification [1] are given in Table 14 and the respective dimensions are shown in Figure 16. The dimensions are specified for 3U and 6U CubeSats. The values show that the only difference is the width of the

CubeSat in the x-axis (Dimension B) and the resulting protrusion width. The protrusion is the only dimension not specified by the standard and its size is an optional addition by the CubeSat and Deployer manufacturers. The size of the protrusion may vary for different CubeSat sizes. However, in this thesis the same size is considered, which the author finds sufficient for both sizes.

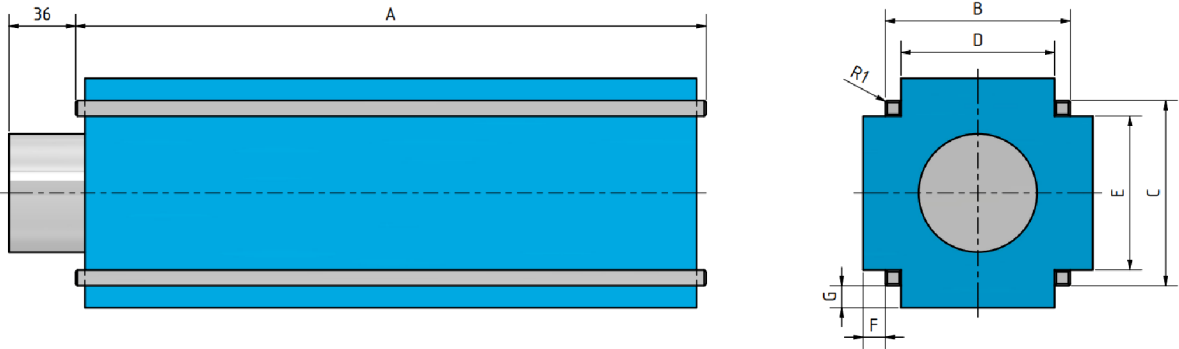


Figure 16 Maximum allowable dimensions for CubeSat

Table 14 Maximum CubeSat dimensions

Description	Units		3U	6U	Tolerance
CubeSat Rail Length (Z)		A	340.5 / 366		± 0.5 mm
CubeSat Rail Width (X)		B	100	226.3	± 0.1 mm
CubeSat Rail Height (Y)		C		100	± 0.1 mm
Max Space Between Rails (X)	mm	D	85	211.3	-
Max Space Between Rails (Y)		E		85	-
Max Protrusion from Rail (X)		F	12		-
Max Protrusion from Rail (Y)		G			-
Number of Tuna Cans	-	-	1	2	-

In addition to the protrusions on the sides of the CubeSat, the satellite can be equipped with a cylindrical "tuna can" extension on the back of the CubeSat in the z-axis (Figure 17). The position and size are again defined by [1].

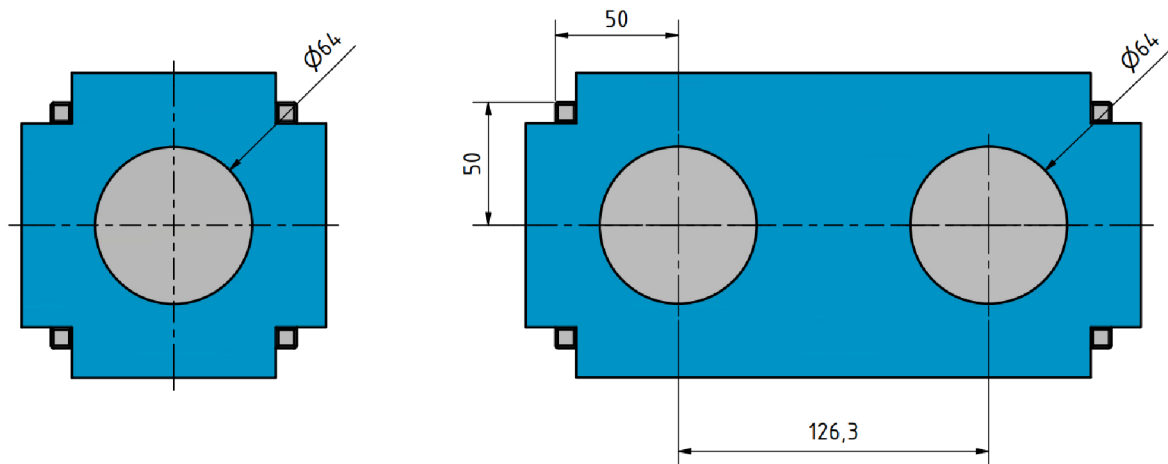


Figure 17 Maximum tuna can dimension for 3U and 6U CubeSat

3.3 Structural material

An important factor in the design is the appropriate choice of structural material. The choice of material determines many of the resulting properties of the designed device. To achieve optimal mechanical and thermal properties of the spacecraft, it is necessary to use materials with the lowest resulting weight but the best possible properties. For CubeSats, the situation is somewhat simpler because the CubeSat Design Specifications (CDS) [1] specify the use of 6061, 7075, 5052, or 5005 aluminium alloys for the CubeSat main structure and rails [15]. If materials other than aluminium alloys are used, it is recommended to contact the Launch provider or Deployer manufacturer to verify compatibility.

One of the most widely used aluminium alloys in the Aerospace industry is 7075 (composed of 90.0 % Al, 5.6 % Zn, 2.5 % Mg, 0.23 % Cr, and 1.6% Cu). This alloy uses Zinc as the main alloying element. 7075 aluminium alloy is one of the strongest aluminium alloys available, making it valuable in high-stress situations. To further improve the properties of 7075 aluminium alloy, a heat treatment process called tempering is used. There are several tempering methods that give the alloy distinct values and characteristics. [29] [30]

Another widely used aluminium alloy is 6061 (composed of 97.9 % Al, 0.6 % Si, 1.0 % Mg, 0.2 % Cr, and 0.28 % Cu). The main alloy elements are magnesium and silicon. The alloy has good formability, weldability, and corrosion resistance. 6061 is a good all-purpose alloy used for a wide range of applications where, as with 7075, the tempering process is used to improve its characteristics. [30] [31]

The last of the aluminium alloys considered is 5052 (composed of 97.25 % Al, 2.5 % Mg, and 0.25 % Cr). The absence of copper as an alloy element in 5052 results in better corrosion resistance compared to alloys containing copper. Unlike 7075 and 6061 alloys, 5052 cannot be

strengthened by heat treatment processes and other processes are used to improve the characteristics. [30] [32]

The material properties of the respective aluminium alloys are shown in Table 15. The values from the ASM Handbook [33] were used to create this table.

Table 15 Material properties of selected aluminium alloys

Material Properties	Units	Aluminium Alloy 7075-T6	Aluminium Alloy 6061-T6	Aluminium Alloy 5052 - H32
Composition	[%]	Al: 87.1 – 91.4	Al: 95.8 – 98.6	Al: 95.7 – 97.7
		Zn: 5.1 – 6.1	Mg: 0.8 – 1.2	Mg: 2.2 – 2.8
		Mg: 2.1 – 2.9	Si: 0.4 – 0.8	Cr: 0.15 – 0.35
		Cu: 1.2 - 2	Cu: 0.15 – 0.4	Fe: max 0.4
		Cr: 0.18 – 0.28	Cr: 0.04 -0.35	Si: max 0.25
Density	[g/cm ³]	2.81	2.70	2.68
Melting Point	[°C]	475- 635	580- 650	607- 650
Poisson's Ratio	[-]	0.33	0.33	0.33
Hardness (Brinell)	[-]	150	95	60
Ultimate Tensile Strength	[MPa]	570	310	230
Tensile Yield Strength	[MPa]	505	275	195
Modulus of Elasticity	[GPa]	72	69	70
Fatigue Strength	[MPa]	160	95	115
Shear Modulus	[GPa]	26.9	26	25.9
Shear Strength	[MPa]	330	205	140
Elongation at Break	[%]	11	12	12

3.4 Surface treatment

Only the tempering heat treatment process is not sufficient for the parts of the Deployer where contact with the CubeSat occurs. These parts (rails) need to be treated with a surface treatment. The CDS requirements [1] prescribe the use of hard anodizing as a surface treatment method. The main reason for this has historically been to prevent cold welding between the Deployer and the CubeSat. The anodizing also acts as electrical isolation and protects the CubeSat [15].

Anodizing [34] is an electrochemical process by which a protective oxide layer is formed on the surface of a treated metal component. The treated component is immersed in an electrolyte where it acts as an anode, then an electric current is applied to the electrolytic cell. The result is a hard, compact aluminium oxide layer with excellent properties such as corrosion resistance, wear resistance, dielectric insulation, etc. Specifically, CubeSats use Type III: Hard Anodic Coating, which creates a thicker layer than other types of anodizing.

Type III hard anodizing creates a thick layer of oxide coating, which impacts the final dimensions of the product. This must be considered when specifying the design dimensions. NASA specifies a default layer thickness in its process specifications [35] if no other thickness is specified on the engineering drawing. In that case, the thickness of the anodized layer shall be 0.051 mm with a tolerance of 0.013 mm . If a different thickness is required, the recommended values according to [35] including the recommended radiuses are in Table 16.

Table 16 Recommended coating values

Coating Thickness	Recommended Radius
mm	mm
0,025	0,762
0,051	1,524
0,076	2,286

The design must also take into consideration the fact that the new anodised layer will penetrate the original surface and only half of the anodised layer will extend above the surface of the original material (Figure 18) [35].

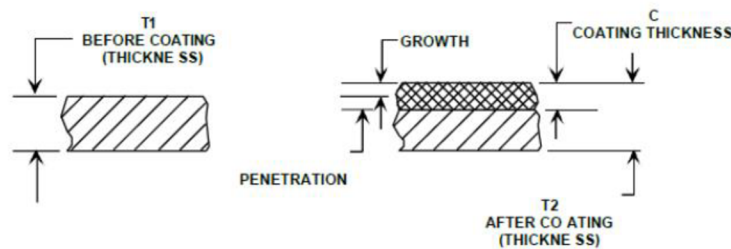


Figure 18 Coating thickness

3.5 Solution approach

After considering the CubeSat's dimensional, material and coating requirements, the design assumption chapter is complete. Based on these assumptions and the goals outlined at the beginning of this chapter, the following decisions were made:

- BUTPOD will be in 3U and 6U sizes
- Maximum dimensions of the testable CubeSat according to Table 14.
- The entire BUTPOD will be made of 6061-T6 aluminium alloy
- The rails will be finished with TYPE III hard anodizing

It is now possible to determine the next procedure for the conceptual design and the other chapters of this thesis. The diagram in Figure 19 represents the next workflow. The goal is to create 3 BUTPOD designs, for which the possibility of creating a modular version for testing CubeSats of 6U but also 3U size will be evaluated. The comparison of the different versions will be supported by a modal analysis to verify the minimum natural frequency requirement. In

the following chapters, the detailed design will be discussed and evaluated in terms of manufacturability and comparison with commercially available TestPods. This will also fulfil all the main objectives that have been set for this thesis.

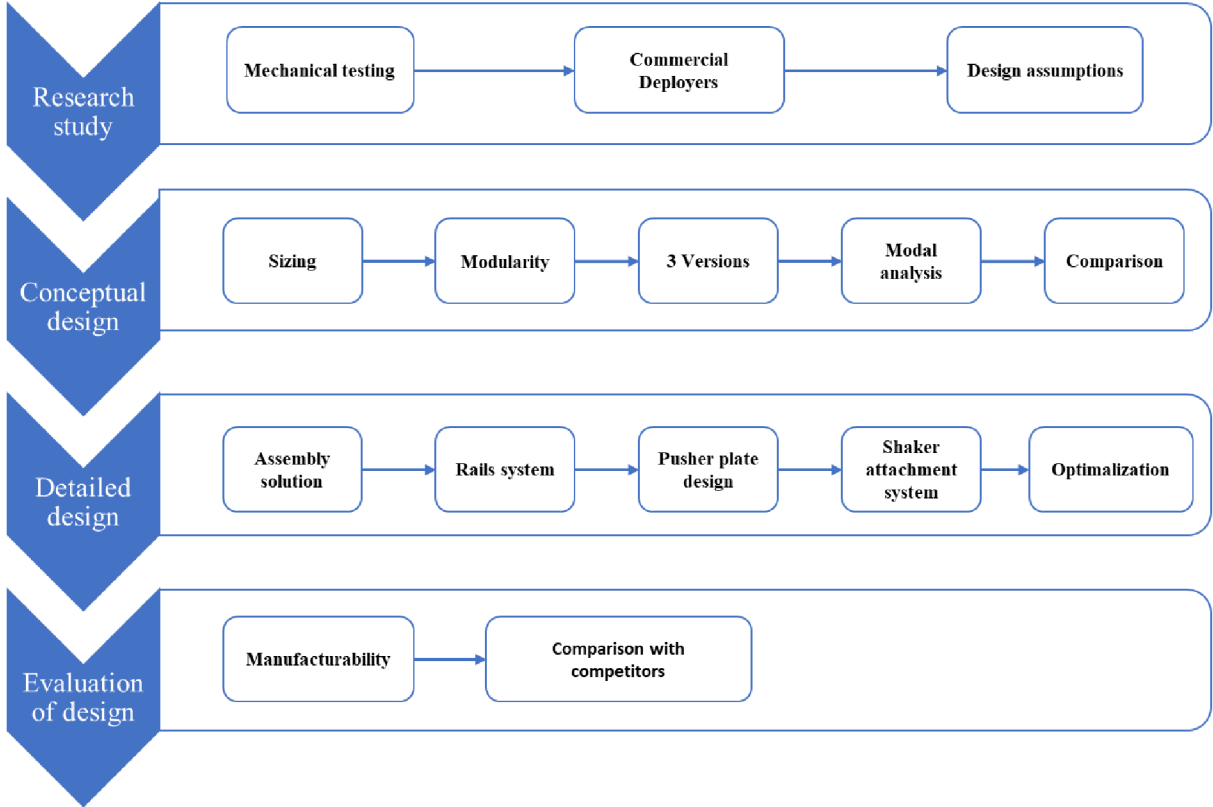


Figure 19 Solution approach

4. Conceptual design of the BUTPOD

After evaluating all the requirements for Deployers and design assumptions, we can proceed to the actual conceptual design. As is evident from the chapter on Deployers there are a variety of design approaches, each of which presents unique challenges. The following concepts were developed from the data collected in the previous chapters.

4.1 Version 1

The first solution (Figure 20) represents the conventional design method and serves for comparison with other solutions. The design is created mainly with regard to ease of manufacture and simplicity of assembly. While maintaining the basic philosophy of Deployer design.

The design consists of simple panels on the bottom and top, with a noticeable lightweighting on the top plate. The side panels are designed with access ports. Compared to the Deployer, there is a noticeable difference in the doors, which are panel only. This panel does not use any opening mechanism and there are no brackets or hinges on the structure to do so.

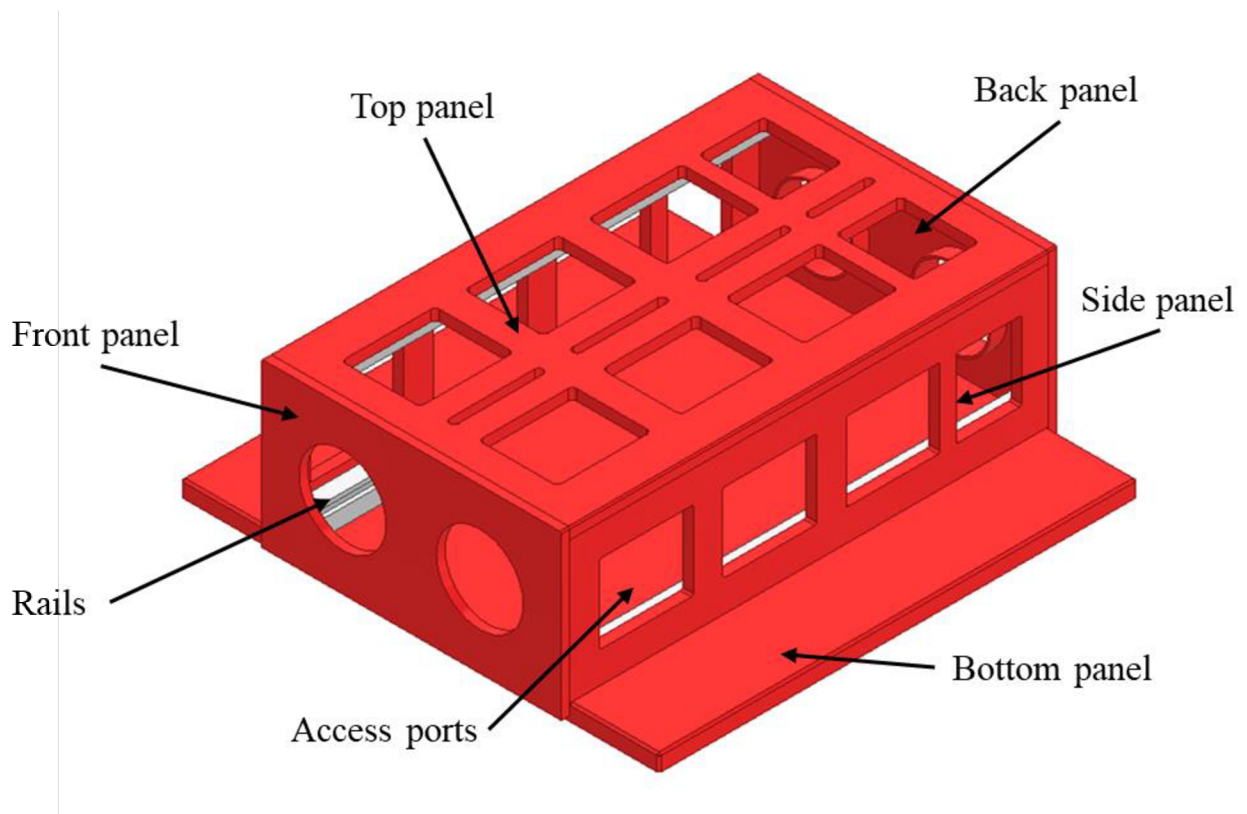


Figure 20 First version of the proposed structure (6U variant)

A distinctive feature is the large panel on the underside. Its function consists in the possibility to create any set of holes for anchoring on the Shaker. This method ensures the certainty of a

simple installation, and at the same time it can be made to suit the specific machine (the interested party), without having to interfere with the rest of the structure.

The rails for guiding and aligning the CubeSat also act as an auxiliary connection between the side panels and the panels on the top and bottom. This connection can be seen in Figure 21. The front and rear panels also contribute to increased rigidity.

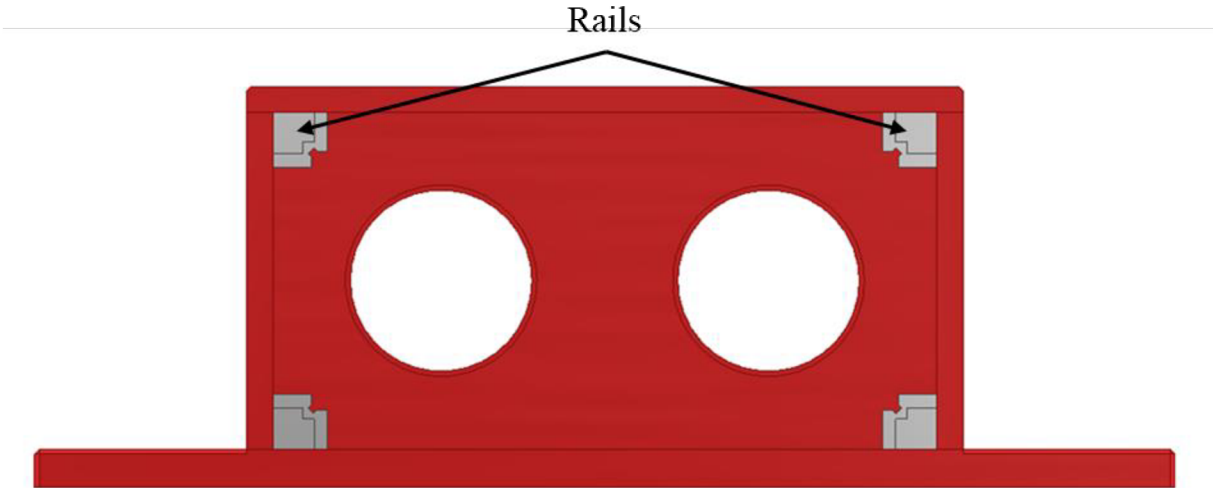


Figure 21 Front view of the panel layout in version 1

The BUTPOD can accommodate a 6U CubeSat or two 3U CubeSats. An illustration of such a placement is shown in Figure 22. When placing two CubeSats, you need to install a middle rail on the bottom and top and a panel dividing the space between the CubeSats. This solution allows two CubeSats to be tested, but it also does not allow access from one side to the CubeSat, which can be a problem during testing.

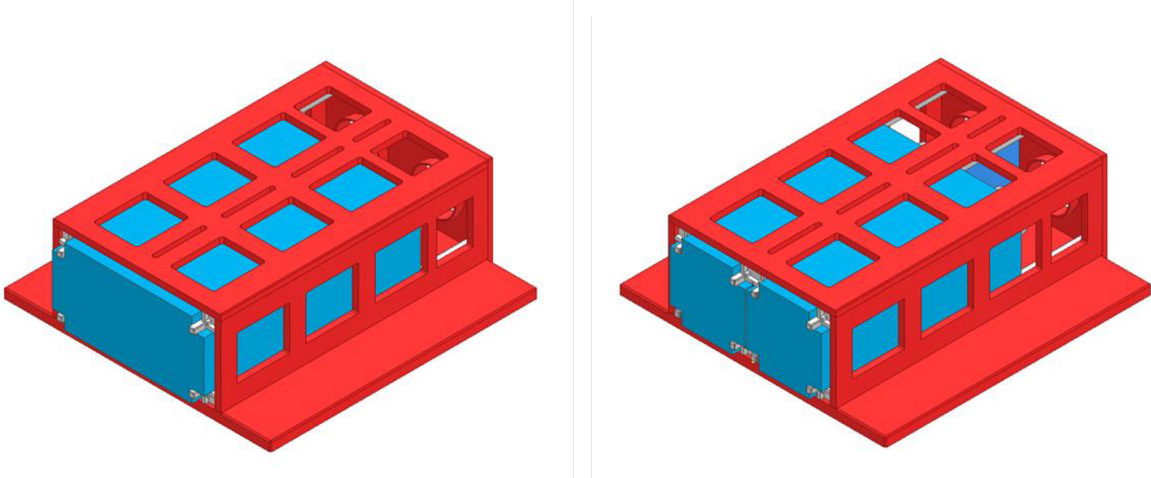


Figure 22 Placement of tested CubeSats in BUTPOD version 1

After the creation of the 6U variant, a 3U variant was also created using the same side panels and rails. It also uses the bottom panel as a flange to attach to the Shaker. At the same time, for greater lightness, the top panel has a large opening along its entire length, this lightness allows to control the tested CubeSat along its entire length. This configuration is shown in Figure 23.

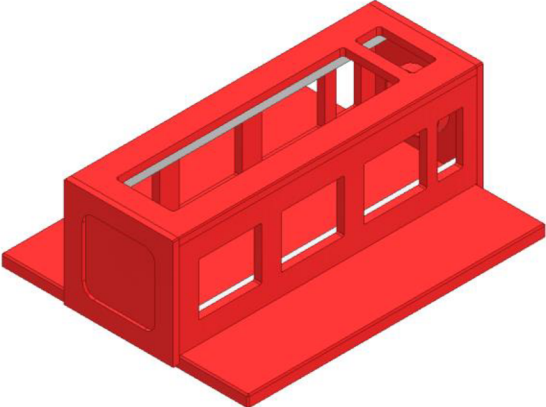


Figure 23 First version of the proposed structure (3U variant)

4.2 Version 2

The second solution (Figure 24) shares basic features with the first solution. In this case, the design is more optimised for modularity. The ability to easily manufacture and assemble is still maintained. Using the same panel on the top and bottom leads to simplified manufacturing and weight reduction.

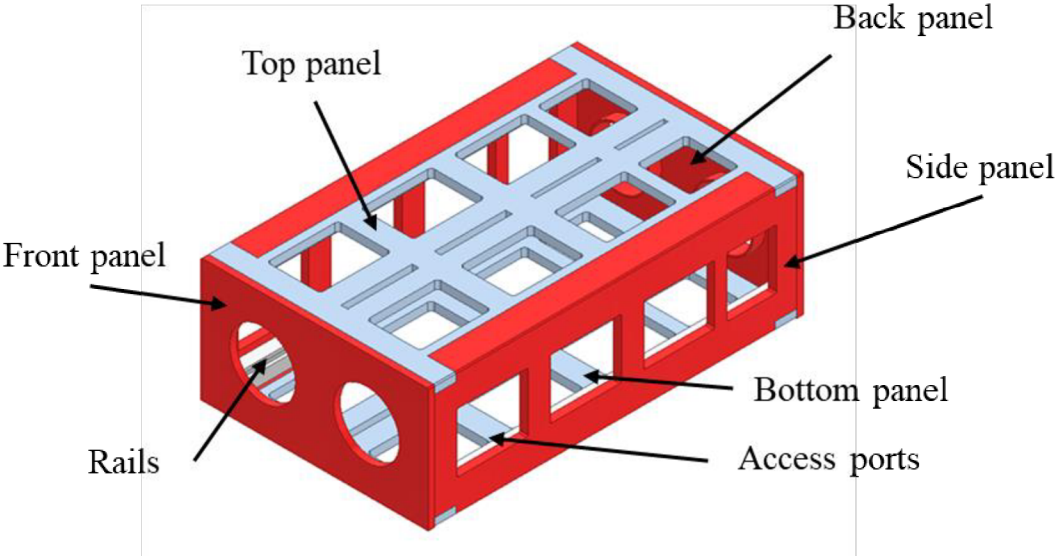


Figure 24 Second version of the proposed structure (6U variant)

The first big change from the first version is in the design of the side panels (Figure 25). In this case, the panels are added with a protrusion and form part of the top and bottom of the BUTPOD. This solution reduces the number of screws used to connect the panels and creates an alignment into which the top and bottom panels can be accurately positioned. This design also allows the rail to fit precisely on the panels, as the entire rail is attached to one panel instead of two. This leads to a reduction in the number of tolerances prescribed for a good connection of the side panels to the top and bottom panels.

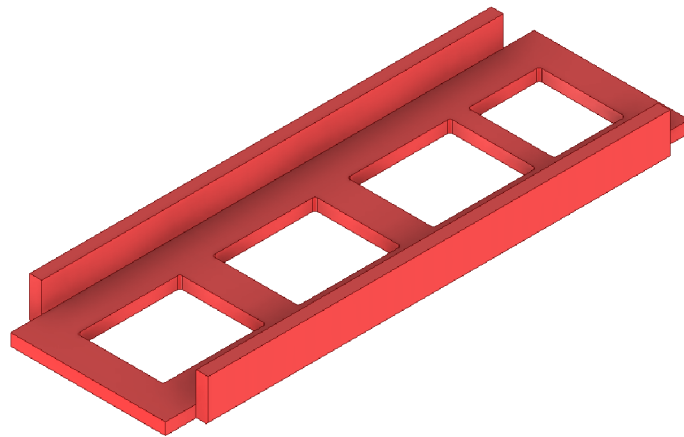


Figure 25 Side panel design for version 2 structure

In terms of modularity, the main feature is the replacement of the top and bottom panels. The side panels, along with the rails, remain the same for both the 6U and 3U BUTPOD. The top and bottom panels are designed to allow for a rail to be installed in the middle section in the larger version to create space for testing two CubeSats. The smaller variant is primarily used to connect the side panels and is significantly lightweight to reduce weight. A visualisation of these panels is shown in Figure 26. Both variants also require unique front and rear panels.

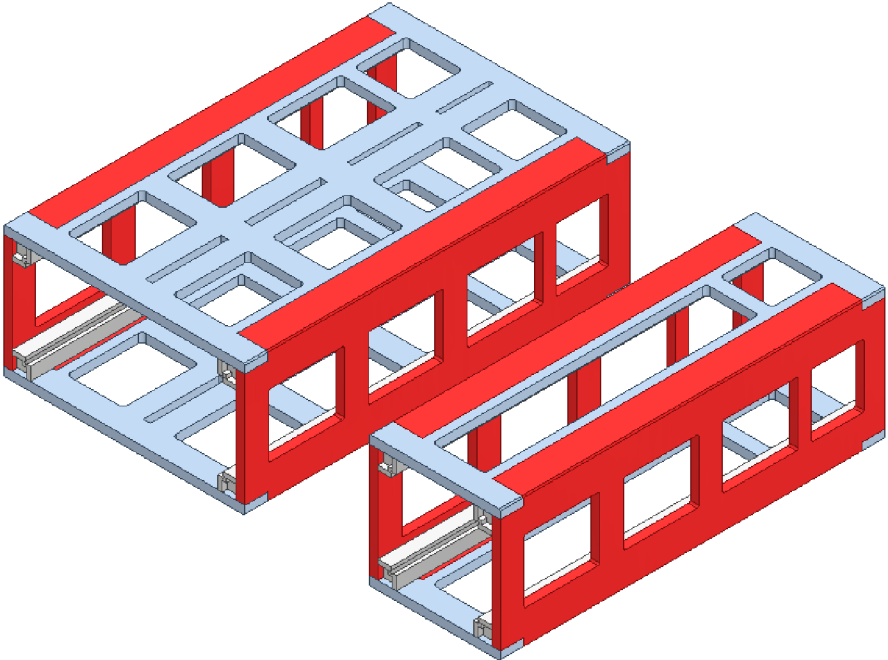


Figure 26 Top and bottom panel design for version 2 structure

After replacing some of the panels, it is possible to create a 3U BUTPOD (Figure 27) from a 6U BUTPOD in which it is possible to test 3U size CubeSats that have a protrusion on the sides and at the end. Theoretically it would be possible to test smaller CubeSats using an adapter to fill the empty space, but that is not the scope of this thesis.

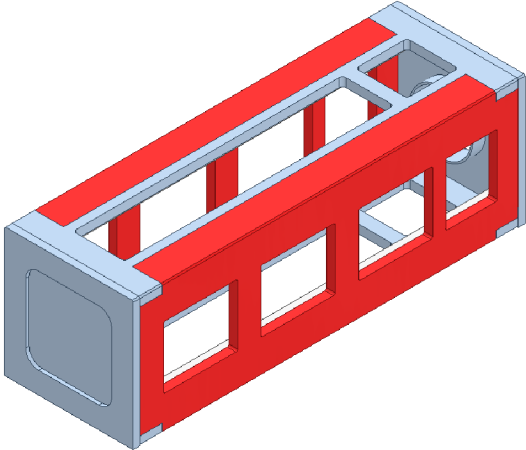


Figure 27 Second version of the proposed structure (3U variant)

4.3 Version 3

The third solution (Figure 28) represents a different design philosophy from the previous two versions. It takes inspiration mainly from ISIPOD's Deployer (2.4 ISIPOD). The change consists in the possibility to detach entire side panels, this method allows to access the CubeSat in a larger area from all sides. However, this change leads to a significant change in the design compared to previous designs.

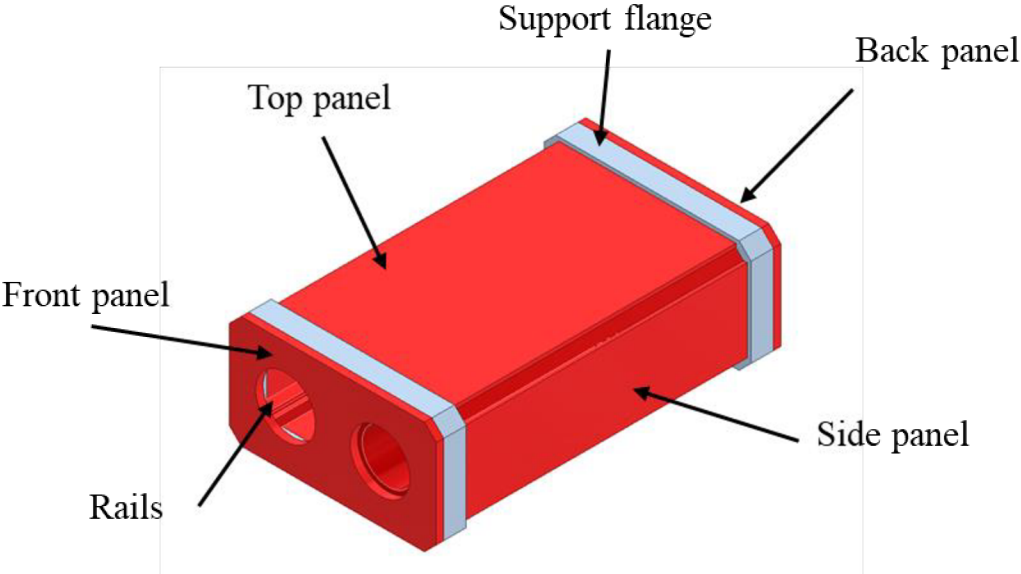


Figure 28 Third version of the proposed structure (6U structure)

In this design, the supporting structure (Figure 29) and the rails form a single unit. This reduces the need to install the rails on the panels and the need to accurately machine the surfaces for fitting. The longitudinal bars with rails are attached to the support flange at each end. These flanges also serve to attach the front and rear panels. If required, a middle rail can be installed on the 6U variant to test multiple CubeSats. This solution leads to a reduction in weight, but this is compensated for by the use of panels in sheet form, which are not lightened in any way. So, the resulting weight is like the previous version.

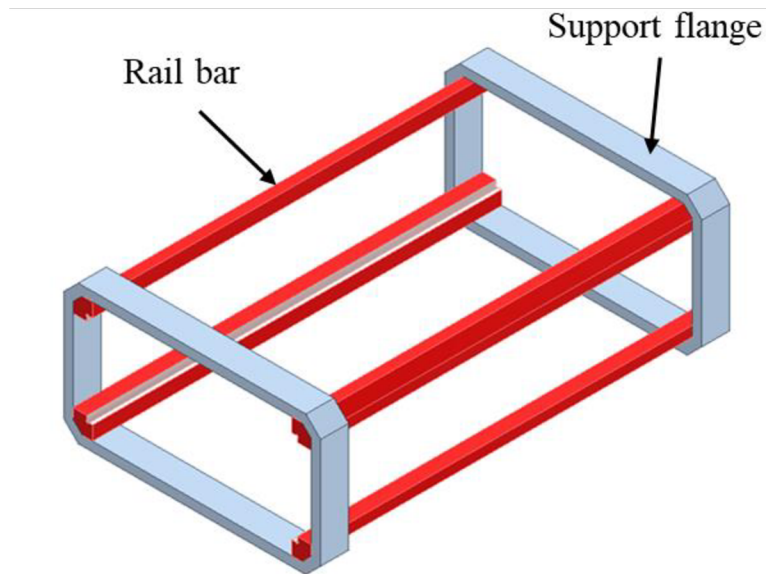


Figure 29 Support structure for design version 3

To be able to convert the BUTPOD from 6U to 3U (Figure 30), the support flanges need to be replaced. The longitudinal bars are the same for both variants. As with the previous variant, the front and rear panel sizes also need to be different. The top and bottom panels are also unique for each BUTPOD size.

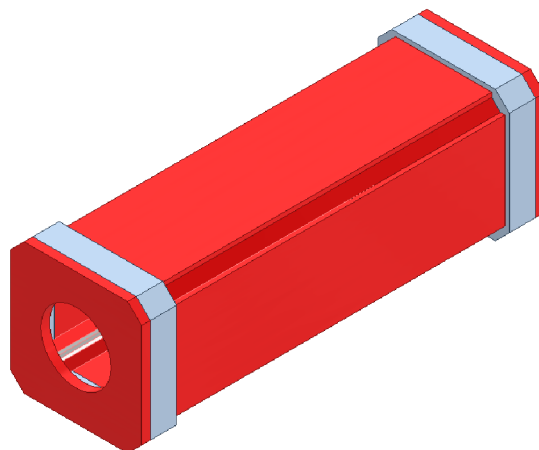


Figure 30 Third version of the proposed structure (3U variant)

4.4 Modal analysis

Before deciding which version is best for developing a detailed design, a modal analysis is performed. The objective is to obtain the normal modes of the system, which represent the motion patterns of the system at their natural frequencies. The natural frequencies represent one of the parameters to be considered in the evaluation of each version, since it is according to the requirements of LV providers to prove that the first natural frequency is higher than the

specified minimum. It also gives important information about the stiffness of the whole structure. Ansys was chosen as the software of choice for the analysis because of its simple tools for materials, meshing and defining boundary conditions.

4.4.1 Geometry

Before the actual modal analysis, it is necessary to create models that can be analysed. All three versions of BUTPOD were modelled in Inventor and then imported into Ansys.

The chosen geometry does not include complex shapes that would need to be simplified for analysis, yet modifications were made to the individual models. Compared to the final version, the individual versions tested do not have screw holes (Figure 31). Since the models were created in Inventor, the individual parts on all versions of the BUTPOD are separated and different mechanical properties and mesh size can be assigned to each plate if necessary.

Although the absence of screw holes may represent a considerable simplification, other studies [36] have already shown that this simplification scheme is possible, and the results obtained correlate well with data obtained from a real test fixture.

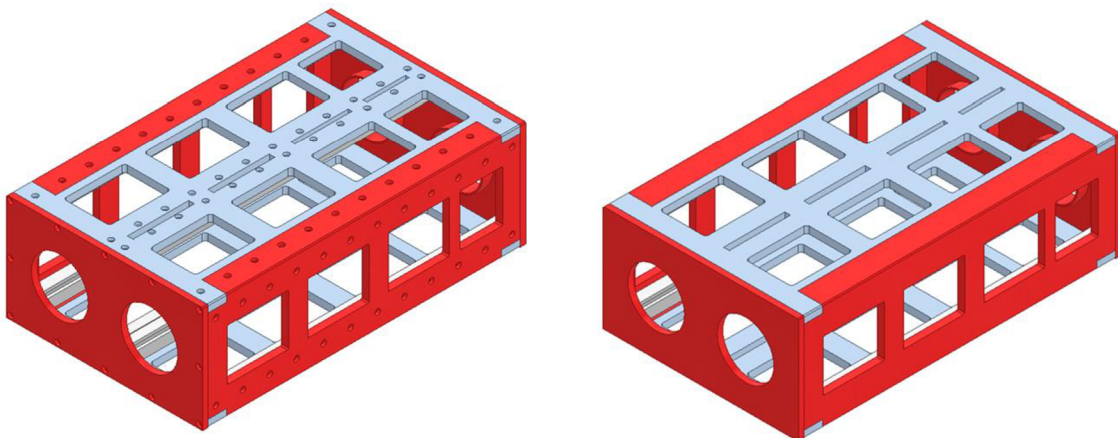


Figure 31 BUTPOD simplification without holes

4.4.2 Meshing

For Finite Element Analysis (FEA), it is necessary to divide the model to be analysed into a set of small fragments called elements. These grouped elements form a mesh. There are a variety of shapes of these elements (Figure 32) that are suitable for different loading and model geometries [37]. Since the models of the respective versions of BUTPOD are made up of solid bodies, 3D elements were used to create the mesh. More precisely, these are Quadratic (10-noded) tetrahedral, which are suitable for their versatility.

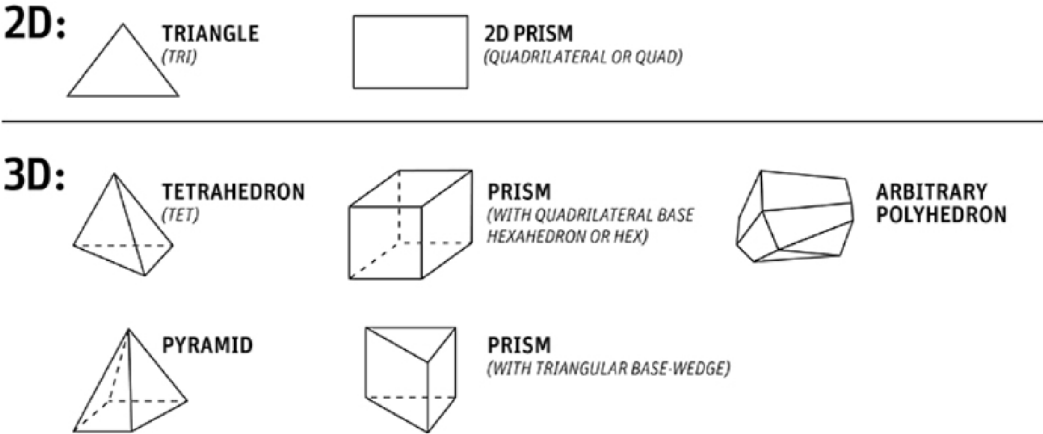


Figure 32 Common types of Mesh element [37]

An important element in the creation of the mesh is the correct choice of the size of the elements. In general, a finer mesh with smaller elements produces more accurate results, but at the same time, a larger element count leads to more computation required and therefore more computation time. For the analysis, it was determined that the maximum size of the elements must be equal to or less than the smallest width of any part of the BUTPOD. This solution will ensure that all parts are included in the analysis and the results will converge. The mesh on the BUTPOD using different element size is shown in Figure 33.

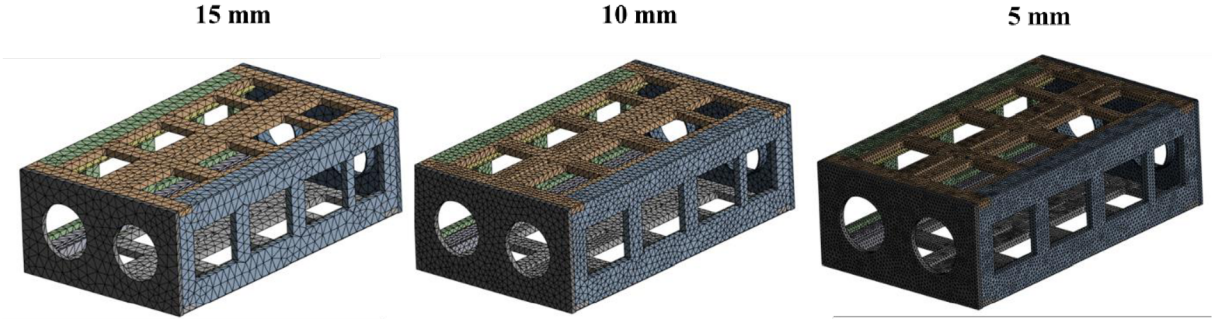


Figure 33 Different size of mesh elements

4.4.3 Boundary conditions

The last thing that needs to be set are the boundary conditions. For the purpose of analysis and simulation of the real connection, the bottom panel of the BUTPOD (all versions) is fixed against translational and rotational motions in three axes (Figure 34). The bottom panel has holes for attachment to the Shaker using a screw connection, this effectively locks the BUTPOD to the Shaker.

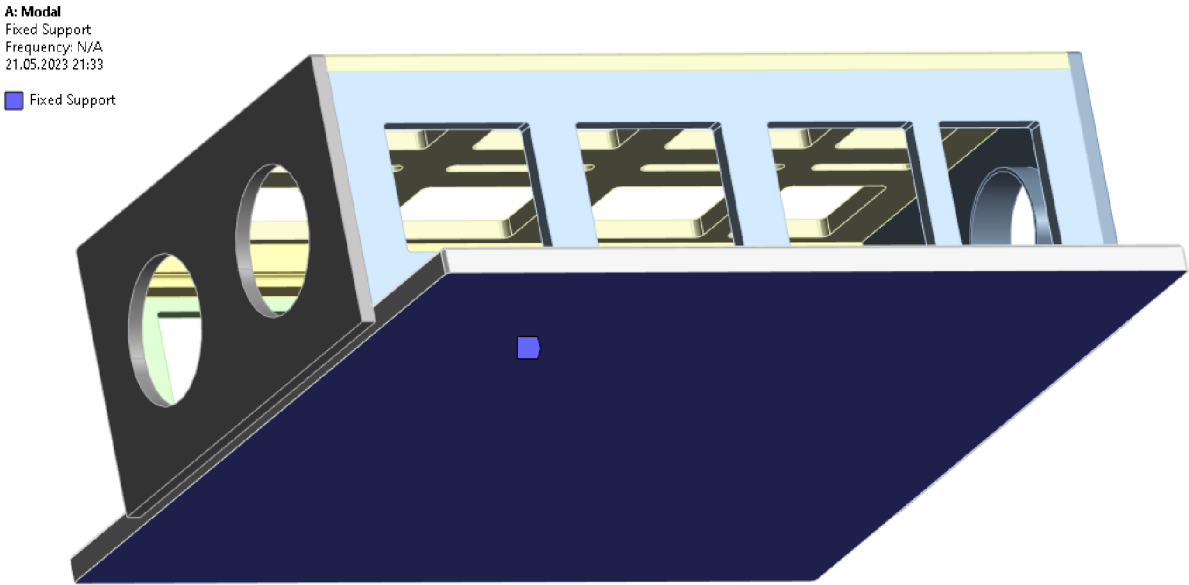


Figure 34 Boundary condition applied to the base of the BUTPOD

4.4.4 Results

After setting all necessary parameters and constraints, modal analysis was performed for all three versions of BUTPOD. The mod frequency limit was set around 2000 Hz, which is the limit set for testing according to NASA GEVS [8]. From the results, the first 10 eigenmodes and natural frequencies were determined. The results from the modal analysis are shown in Table 17, Table 18 and Table 19. At the same time, the first eigenmodes of each BUTPOD variant were plotted, these are shown in Figure 35, Figure 36 and Figure 37.

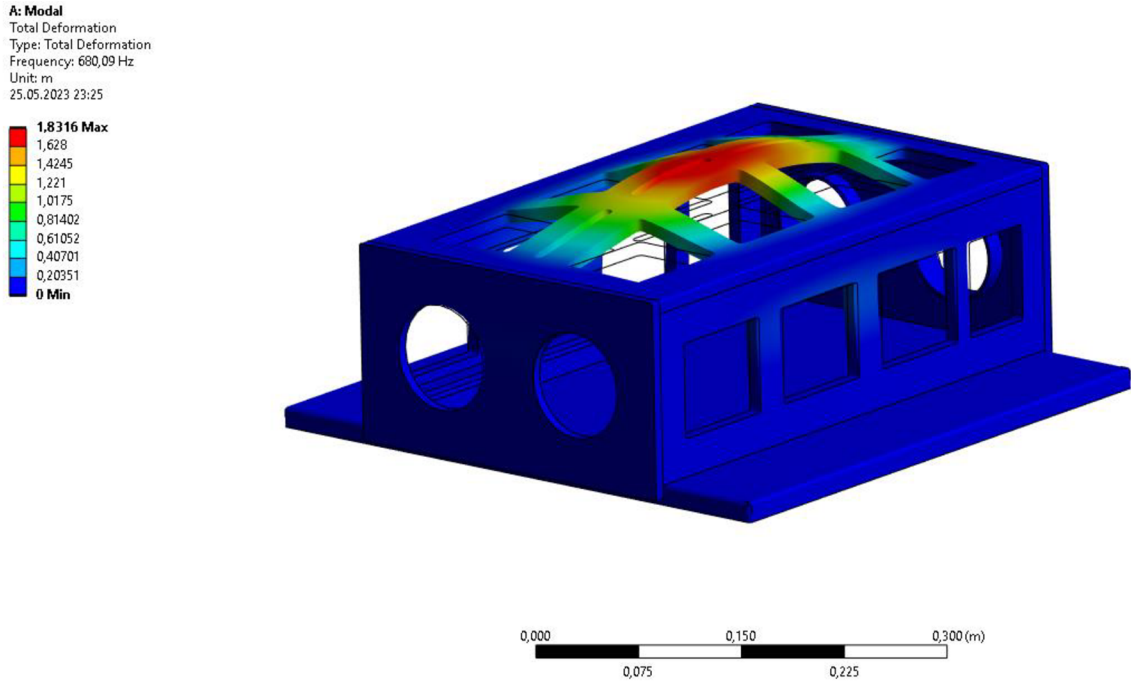


Figure 35 First eigenmode of 6U BUTPOD Version 1

Table 17 Natural frequencies of 6U BUTPOD Version 1

Version 1	
Mode	Frequency Hz
1	680
2	913
3	975
4	1014
5	1517
6	1544
7	1828
8	1842
9	2162
10	2270

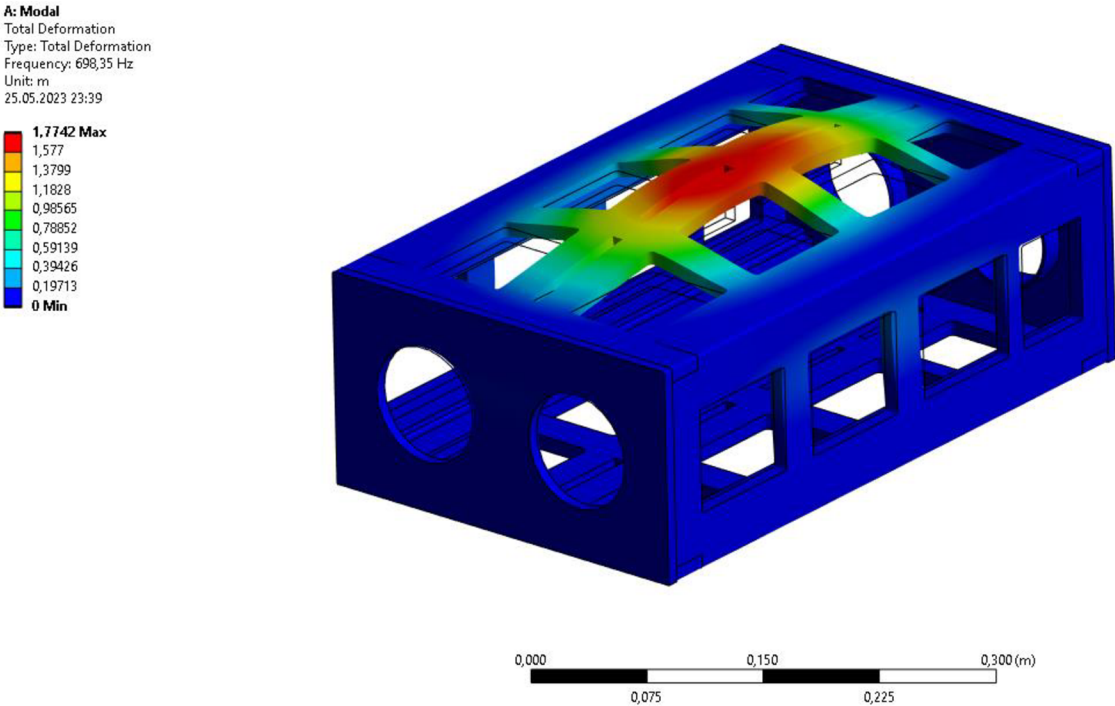


Figure 36 First eigenmode of 6U BUTPOD Version 2

Table 18 Natural frequencies of 6U BUTPOD Version 2

Version 2	
Mode	Frequency Hz
1	698
2	948
3	975
4	1038
5	1552
6	1609
7	1774
8	1867
9	2204
10	2234

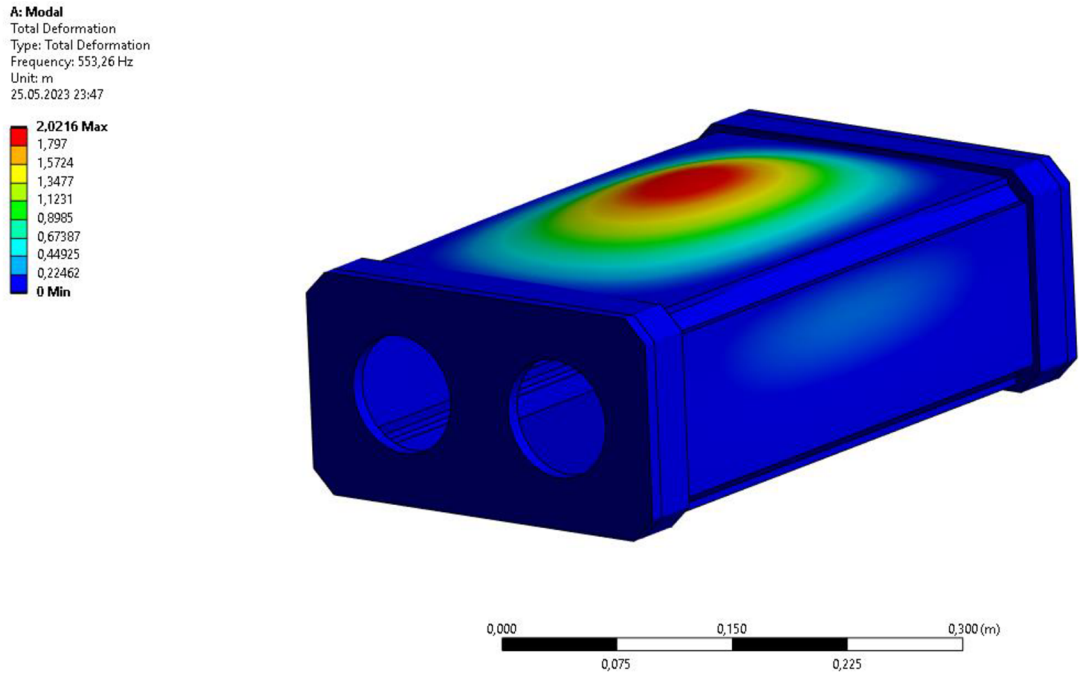


Figure 37 First eigenmode of 6U BUTPOD Version 3

Table 19 Natural frequencies of 6U BUTPOD Version 3

Version 3	
Mode	Frequency Hz
1	553,05
2	846
3	1189
4	1253
5	1405
6	1681
7	1755
8	1761
9	2222
10	2285

The results show that the first and second versions of BUTPOD have very similar eigenmodes, this is mainly due to the very similar design. The third design shows a slightly lower first natural frequency. This is mainly due to the nature of the structure, which consists of a "skeleton" and a plate, which are used only for covering. However, this design also safely meets the minimum natural frequency requirements. From the first eigenmodes, movement in a perpendicular direction relative to the Shaker is evident in all versions. This is primarily due to the nature of the design, with the top plate representing the largest free area. Hence the need to ensure that

no contact with the CubeSat occurs at maximum deformation. This can be ensured by selecting the maximum thickness of the protrusion on the CubeSat under test to guarantee sufficient deflection space.

4.5 Comparison

After the conceptual design and modal analysis of the three versions of BUTPOD, their parameters and other metrics can be compared. The comparison yields the most suitable variant for detailed design. The compared parameters are shown in Table 20.

Table 20 Comparison of proposed structures

Configuration	Version 1		Version 2		Version 3	
	6U / 2×3U	3U	6U / 2×3U	3U	6U / 2×3U	3U
Length (Z) [mm]	456	456	456	456	460	460
Length (X) [mm]	440	340	276,3	150	276,3	150
Length (Y) [mm]	155	155	150	150	150	150
Mass [kg]	16.2	10.5	10.3	6.2	10.1	5.9
Number of parts	18 / 25	16	18 / 25	16	20 / 27	18
Number of shared parts	10		10		11	
Natural frequency ⁽¹⁾ [Hz]	> 680	-	> 698	-	> 550	-
Additional mass (Z)	Yes	Yes	Yes	Yes	Yes	Yes
Additional mass (X and Y)	Yes	Yes	Yes	Yes	Yes	Yes
Structural material	Aluminium 6061-T6		Aluminium 6061-T6		Aluminium 6061-T6	
Spring initiators ⁽²⁾	Yes	Optional	Yes	Optional	Yes	Optional
Assembling simplicity ⁽³⁾	★★★	★★★	★★★	★★★	★★	★★
Modularity ⁽³⁾	★★		★★		★★	
Accessibility ⁽³⁾	★	★	★★	★★	★★★	★★★
Manufacturing simplicity ⁽³⁾	★★★	★★★	★★	★★	★	★

(1) First eigenmode

(2) 3U Deployers do not need to use a spring, a spring plunger is sufficient

(3) Rating: three stars = High, one star = Low

All three versions are usable for testing a 6U CubeSat or two 3U CubeSats. At the same time, each variant can be converted to a smaller 3U BUTPOD for testing smaller CubeSats. There are no differences between the versions in this respect. The first difference is in size, especially between the first version and the other two. This is mainly due to the large flange that forms the underside of the first version, which significantly increases the area of the BUTPOD.

In terms of weight, it comes out as the heaviest first version, which is again due to the "massive" bottom plate, which increases the weight considerably, but at the same time allows for a simple interface for attachment to the Shaker. The second and third versions have a very similar weight. The second version, for example, has a symmetrical weight distribution compared to the first

version, as the top and bottom plates are identical. In the third version, the skeleton of the structure together with the front and back plates make up most of the weight.

The number of parts is the same for the first and second version, as well as the number of parts that can be used for both the 6U and 3U versions. These are mainly side panels, tracks and part of the CubeSat fixing system inside the BUTPOD. The third version, by nature of the design, uses a larger number of parts, but these cannot be shared between the two configurations.

All versions can accommodate the same size CubeSat. The same aluminium alloy is used as well. As for the system of securing the CubeSat inside the BUTPOD, a spring is required for the 6U version, for smaller configurations only a spring plunger can be used. However, an analysis of commercial solutions shows that it is also possible to use fixed locking with screws that do not allow any movement in the Z-axis.

Other comparisons use a star system for rating. The first aspect considered is simplicity of assembly. This is very high in the case of the first and second version and the assembly itself is relatively simple and straightforward. For the third version the assembly is partly complicated by the need for precise alignment when mounting the frame.

The modularity is mainly related to the number of parts that can be used for different configurations and the simplicity of assembly. The modularity is at a very similar level for all the proposed versions, with only minor differences especially in assembly. In the second version, this difference is due to the rails, which are primarily attached to the side panels, as opposed to the first version where the connection is split between the side and top or bottom panels.

The third version uses the ability to detach entire panels, allowing the best accessibility to the largest possible area of the CubeSat. The difference between the first and second versions lies primarily in the bottom panel, which is the same as the top panel in the second version and allows access to the CubeSat from the bottom side during installation in the BUTPOD. This is not possible with the first version because the bottom panel is made of a single plate without access ports.

The last parameter considered is manufacturing simplicity. In this respect, the first version is the best, which uses only simple plates that have holes, and their production is not a problem. For the second version, the difficulty in manufacturability is mainly represented by the side panels, which have a more complex design and take longer to produce, but on the other hand, the top and bottom panels are the same, which in turn speeds up the production of these parts. The third version uses relatively geometrically complex parts, the production of which represents a considerable difficulty and increase in production time compared to the first two versions.

4.6 Summary

By comparing the different versions, it is necessary to determine which version will represent the best solution for the detailed design. Parameters such as simplicity of assembly, manufacturing, as well as modularity and efficiency of the solution must be considered. Of the presented variants, the second version represents a solution that combines a conventional solution (the first variant) and an innovative solution that is not currently on the market. At the same time, when comparing the evaluated parameters in Table 20, the second version comes out as the best.

For this reason, it was decided to develop a second variant in the detailed design. The design will be mainly focused on the development of the design of the internal parts of the BUTPOD, but also on the optimization of the individual parts of the external structure to achieve the most optimal solution that will meet all the objectives set for the test fixture.

5. Detailed design

After deciding which design is best, the detailed design of the BUTPOD can be completed. It is necessary to define how the individual parts will be held together, i.e., the choice of the type of connection of the individual panels. Next, the system of rails on which the CubeSat is placed needs to be specified in more detail. Similarly, for a precise fit, the Pusher Plate, which is used to hold the satellite inside the fixture during the test, needs to be designed. As the last part of the detailed design, a system for mounting on the Shaker needs to be developed.

After detailed design of individual parts, optimization of some parts will be carried out to achieve the best possible manufacturability, reliability, and simplicity of assembly. The final design must represent a solution that can compete with commercial solutions and in some respects surpass them, especially the capabilities of the BUTPOD modular solution.

5.1 Assembly solution

It was decided to use a blind hole bolted connection as a method of assembling the individual panels together. This is the standard method of connection used by all commercial solutions. To simplify assembly, the same screws were used for the entire BUTPOD, which greatly simplifies assembly and avoids any confusion during installation. Specifically, these are hexagon socket head cap screws CSN 02 1143 (DIN 912) M4×12. These screws meet the length limitations and allow them to be "countersunk" so that no screw overhangs the surface of the individual plates.

This connection can be seen in Figure 38. 12 screws each are used to attach the front and rear panels to the rest of the structure. 24 screws are used to attach the side panels, top and bottom plates along with the rail at each corner of the BUTPOD. The total number of screws to connect the outer structure and the rails is therefore 120 screws. In addition to this number, 24 screws must be added to attach the middle rail in the 6U configuration to test two smaller CubeSats. In this case, the total number of screws rises to 168. For the 3U configuration, 8 screws each are used to attach the front and rear panels, the same number of screws are used to attach the rails as for the larger configuration due to the modularity and the fact that this part of the BUTPOD is the same for both configurations.

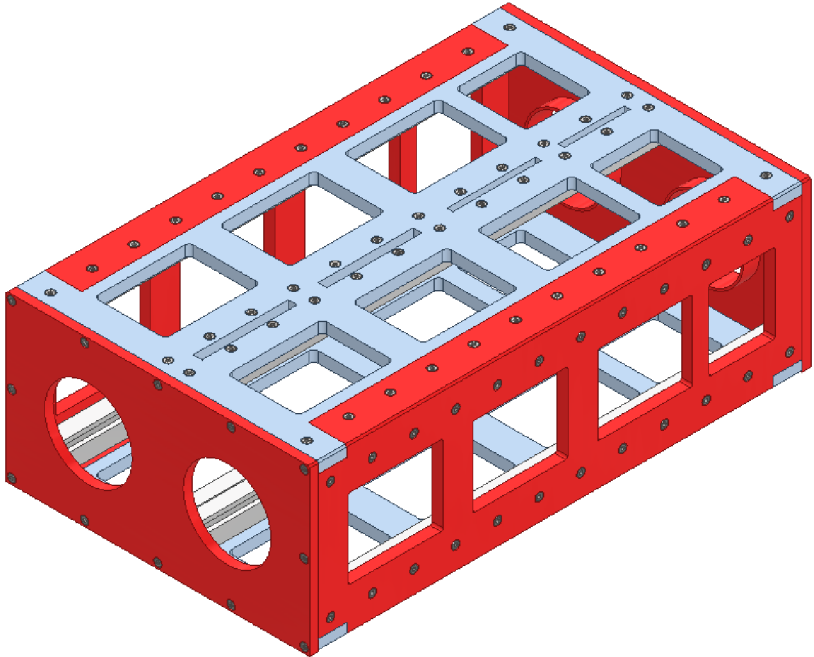


Figure 38 Positioning of the mounting screws

5.2 Rails system

The rails system in which the CubeSat is housed is designed with rods that are installed into the BUTPOD using screws and attachment to the side panels. This connection can be seen in Figure 39. This method, as opposed to the case where the rails directly form part of the side panels, allows for easier surface treatment on these rails as required. At the same time, the structure is lightened, and the material is removed where no threaded holes need to be drilled.

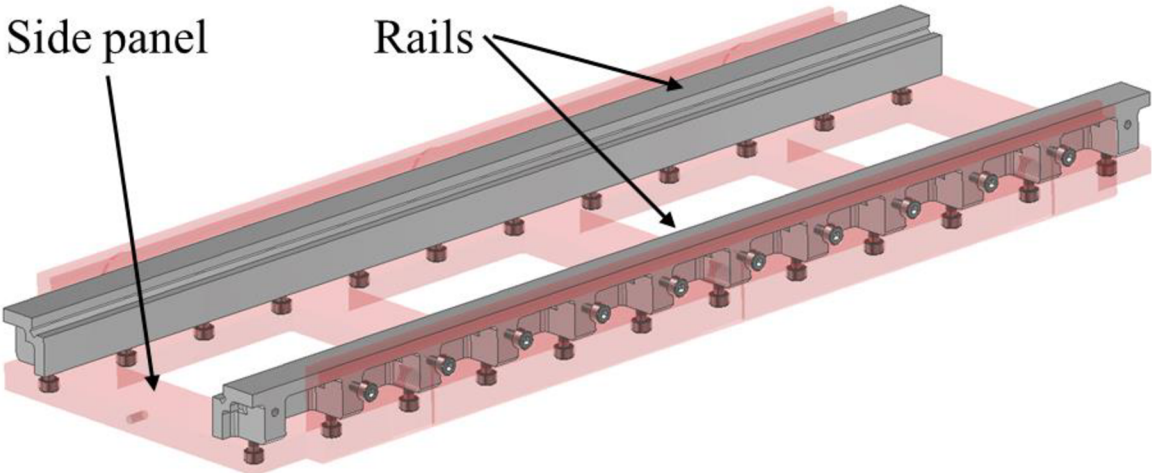


Figure 39 Rails system

5.3 Pusher plate design

Pusher plate which is used for fixing the CubeSat in the Z axis consists of the Pusher plate itself, rails for guiding and a spring or screw connection for alignment. One of the basic tasks is its optimal design to secure the satellite as safely as possible inside the BUTPOD to avoid damage during vibration tests.

5.3.1 Pusher plate

As already mentioned, the basis of the Pusher plate (Figure 40) design is a plate with a hole, which serves for the possibility of having the CubeSat fitted with a so-called tuna can. For this reason, the Pusher plate continues with a cylindrical extension that serves as a protection for the satellites against possible contact with the spring. Four short rails are used for the guiding, which are attached to the plate with DIN 912 M3×8 screws, while at the same time a groove is created on the Pusher plate for the guiding of these rails.

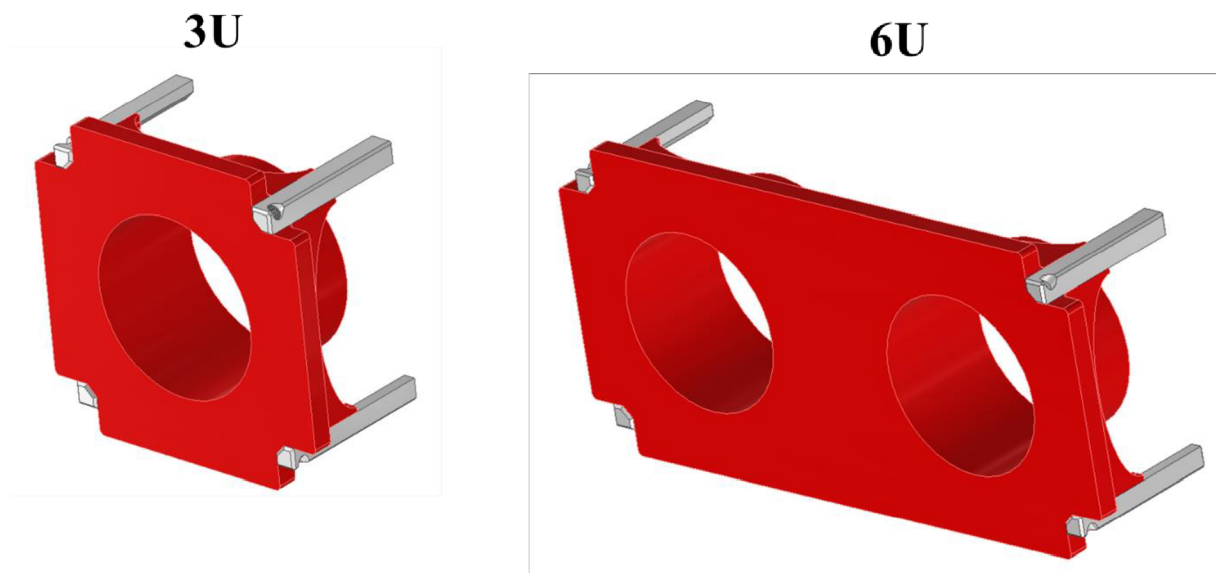


Figure 40 Pusher Plate design

Two configurations had to be created for the design. One for 3U size BUTPOD and one for 6U size. In principle it is the same Pusher Plate, which is only "doubled" and has two holes for the tuna can. A representation of the location of the Pusher Plate in the BUTPOD is shown in Figure 41.

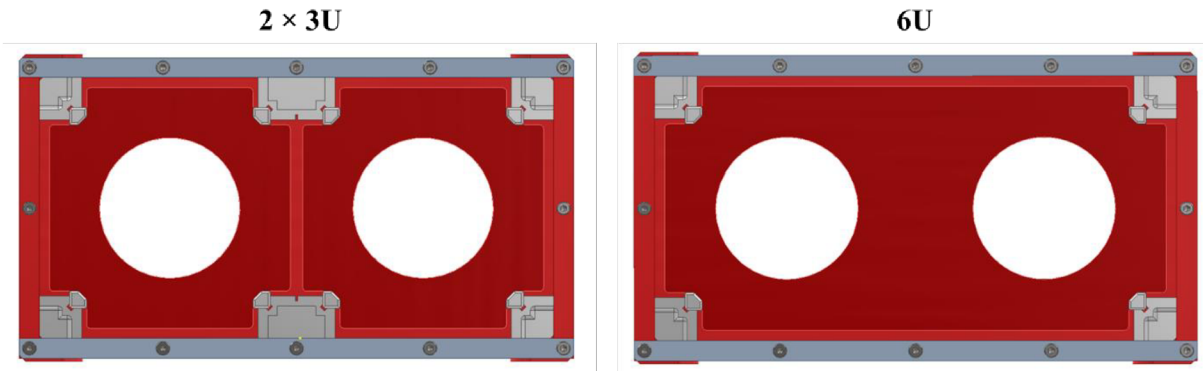


Figure 41 Internal configuration of pusher plate in BUTPOD

5.3.2 Pusher Plate fixation

There are several solutions for fixing the CubeSat. However, they are all based on the same principle, the main task in Deployer is to launch and speed up CubeSat. However, this role is not fulfilled in the case of the test fixture and the main purpose is to fix the satellites in the fixture. The most common system, especially for 6U size CubeSats, is the use of springs. Such use is shown in Figure 42, where the spring can be seen in a compressed state, which corresponds to the case where the CubeSat is installed inside. The other half shows the spring in an empty BUTPOD. The main parameters affecting the choice of spring are the maximum diameter of the tuna can and the maximum required length of the spring in the loaded and unloaded state.

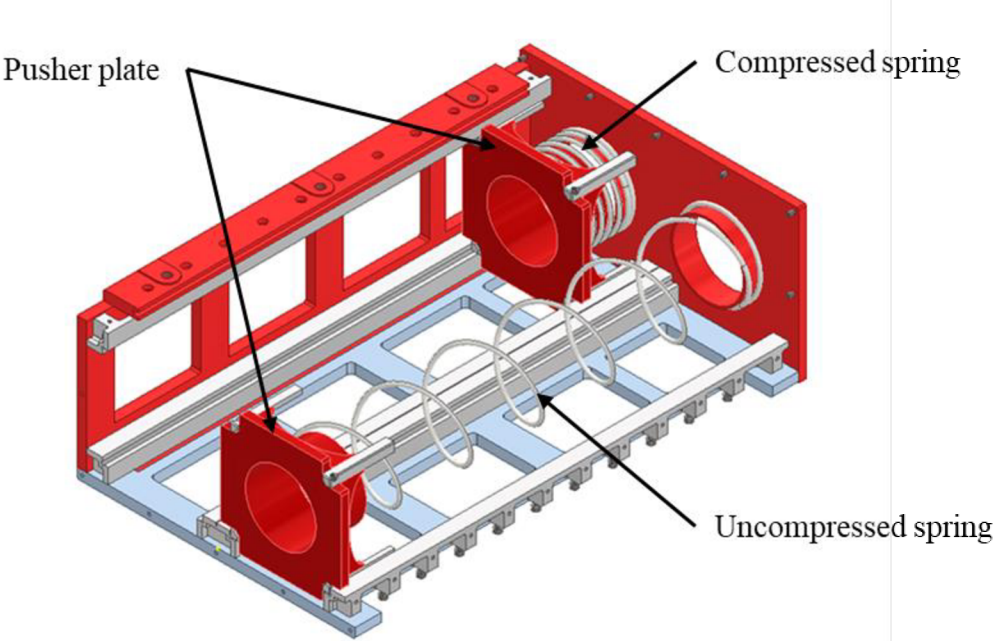


Figure 42 Compressed and uncompressed Pusher plate spring

However, this solution is not always required. Especially for smaller Deployer sizes 3U and smaller, it is possible to use a spring plunger instead of a spring. This plunger essentially fulfils the same role and ensures a precise fit with some overload during installation in the BUTPOD. There are also solutions where the spring plunger is replaced by a screw only, where any movement during testing is eliminated. A solution using M6×30 spring plungers is shown in Figure 43. When this solution is used, the ends of the rails on the Pusher plate are provided with holes into which the spring plungers can fit.

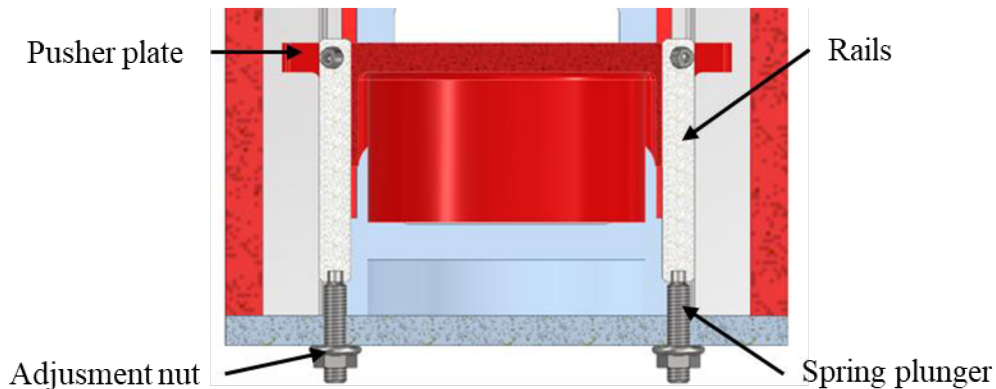


Figure 43 Pusher plate fixing with spring plungers

5.4 Shaker attachment system

As for the mounting system to the Shaker, the BUTPOD is equipped with six mounting points on the bottom and top panels. These holes are provided with M10 size threads. An additional feature of these holes is the possibility of installing a device for easier carrying of the whole BUTPOD. This system of holes directly on the side panels provides a simple effective solution that does not require complicated installation. The position of these points can be seen in Figure 44.

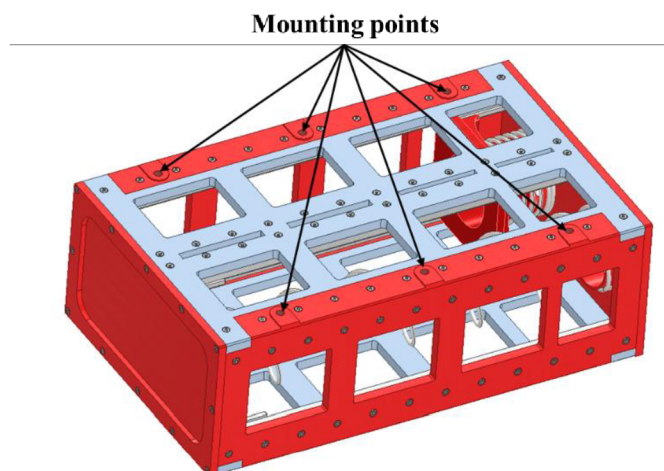


Figure 44 BUTPOD mounting points

5.5 Optimization

After the successful detailed design, several optimizations need to be made to improve the BUTPOD performance. The most significant change was made to the top and bottom panels. Due to the mounting method and from the results of the modal analysis, it is evident that these panels can bend considerably. Therefore, the panels have been upgraded with protrusions and the side panels have been upgraded with grooves to better connect the side panels to the top and bottom panels. As a result, the stiffness of the entire BUTPOD is increased and unwanted deflections are avoided. This change and the new fit in the groove are shown in Figure 45.

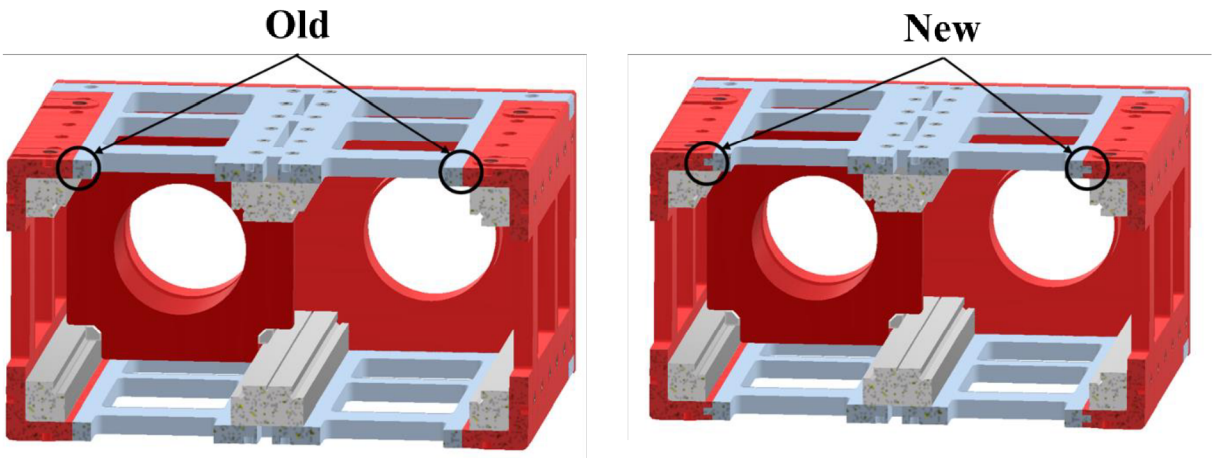


Figure 45 Upper and lower panel mounting adjustments

Several minor adjustments and optimizations were made during the detailed design process. The aim was mainly to simplify the production of some parts, improve the simplicity of assembly and better weight distribution in the BUTPOD. One such modification was the modification of the front panel by one large recess instead of two-cylinder holes. The final form of the BUTPOD after all the previous steps are completed is shown in Figure 46.

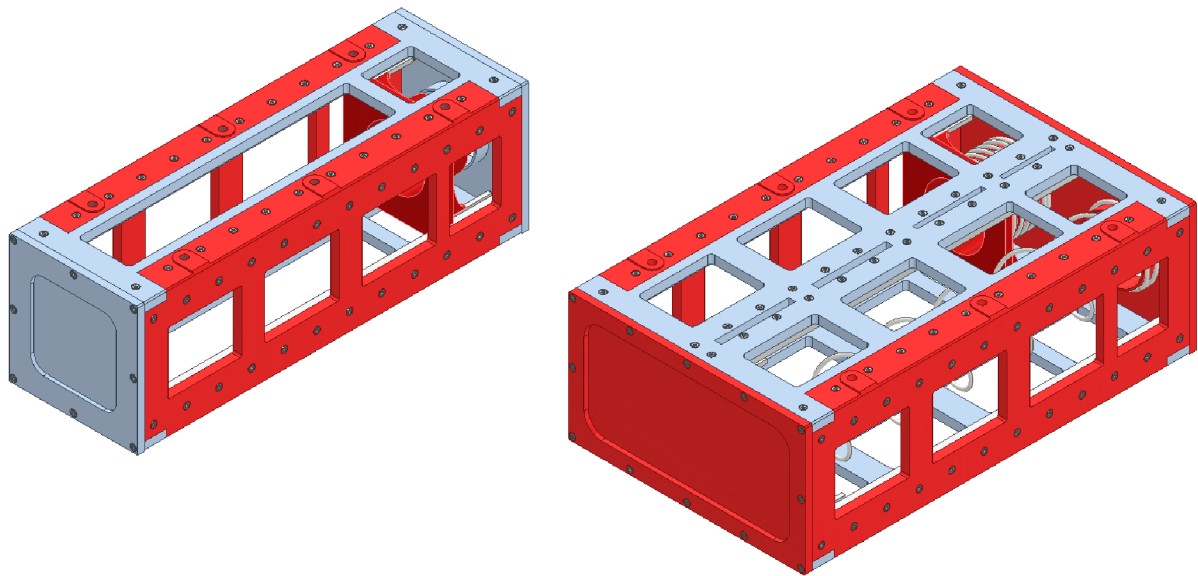


Figure 46 Final design of BUTPOD 3U (left) and 6U (right)

5.6 Summary

In this chapter, a detailed design of the BUTPOD was made. After the modal analysis of the previous chapter and verification that the proposed structure meets the required parameters, the design of the internal CubeSat storage system was carried out. The system uses rails, a pusher plate and a spring or spring plunger. The geometry underwent minor modifications to create the Shaker mounting system. Finally, some parts were optimized to achieve the best possible design.

Throughout the design, the focus was on the ability to be modular. In particular, the ability to use the same parts for BUTPOD 3U and 6U configurations. Both configurations share the same side panels, rails, and pusher plate system. By swapping out the six parts (front, back, top, and bottom panels), it is possible to rebuild the BUTPOD to the desired size as opposed to a conventional solution where two unique TestPods would be required.

BUTPOD is a simple solution for vibration testing. Its main advantage lies in its modularity and the ability to in-house adjust any parameter to test a specific CubeSat. At the same time, it acts as a summary and guide regarding the functionality and requirements for Deployers.

6. Manufacture and requirements verification

The last thing that needs to be specified is how the individual parts are manufactured and verification that the BUTPOD meets the basic requirements that are placed on Deployers in general and must be met by the test fixtures.

6.1 Manufacturing process proposal

The choice of the method of manufacturing of individual parts can greatly influence the final price of the entire BUTPOD. In this case, the main production method is milling, by which all parts can be milled from aluminium blanks thanks to their convenient design. All parts of the 6U BUTPOD that need to be manufactured are shown in Figure 47.

The simplest parts are the front, rear, top and bottom panels. These panels are essentially just plates with a relief recess and are not a problem to manufacture. The most complex shapes to manufacture are the side panels and pusher plate. Due to the many functions that the side panels perform, their geometry is somewhat more complex compared to the other parts. However, these are not shapes that cannot be created by milling. The milling itself will be followed by drilling and creating all the necessary holes. The situation is similar for the pusher plate, which also has a more complex shape. The procedure for its manufacture will be similar.

As far as the main rails are concerned, the emphasis here must be on precision manufacturing, because the correct fit of the CubeSat inside the BUTPOD depends on it. The basic method of manufacturing is again milling and drilling. After the rails are made, hard anodizing must take place to ensure the surface meets the requirements. In the case of using a middle rail for a 2×3U configuration, the manufacture of the middle rail is similar. The last major part on the BUTPOD is the spring due to the requirements for its properties it does not make sense to manufacture this part and some commercial solution will be used and springs will be purchased.

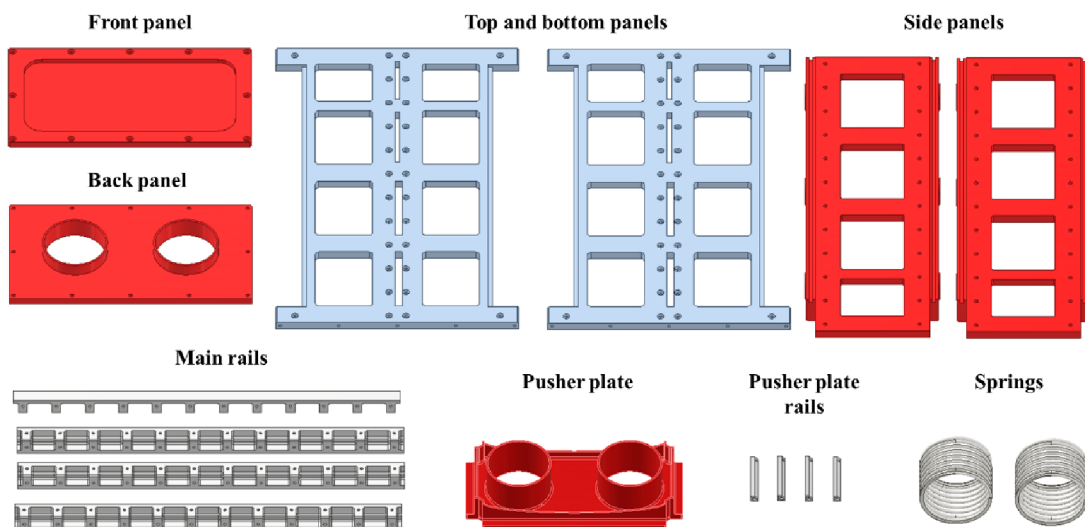


Figure 47 Parts of the 6U size BUTPOD

6.2 Requirements verification

In general, there are technical requirements for Deployers that have already been discussed in this thesis. Some of them can and must be applied to TestPods to ensure that the environment in these products simulates well the environment in a real Deployer. The main points that according to the technical requirements have been met are as follows:

- BUTPOD was designed according to the environmental requirements in [4]
- In BUTPOD it is possible to test CubeSats that have dimension limits according to [4].
- The materials used on the BUTPOD are in accordance with NASA-STD-6016
- BUTPOD has a natural base frequency higher than 120 Hz

6.3 Summary

This chapter served mainly to introduce how the individual parts can be manufactured. Due to the simplicity of the parts, most are made by milling and drilling from blanks. Using the same bolts for the entire BUTPOD also simplifies the production and tooling requirements when not as many are needed.

This was followed by a summary of the technical requirements that exist and verification that the proposed design meets them. This concludes the whole design of the BUTPOD.

7. Evaluation of structure's marketability




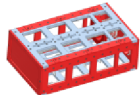
The final step after the complete design of the BUTPOD is to compare it with commercially available TestPods and decide whether the proposed design represents an interesting alternative that equals or even surpasses the other solutions in certain aspects.

7.1 Comparison with competition

For comparison with BUTPOD, a total of three TestPods have been selected that can accommodate a 6U CubeSat and possibly have a version for 3U CubeSats. However, most manufacturers do not publicly disclose detailed information about their products, and it is difficult to find this information.

For comparison, the parameters that can be found in the datasheets available for each TestPod were selected. These are mainly dimensions, mass and configurations. The information for comparison was collected from [28], [38], [39], [40] and their comparison is shown in Table 21. The design proposed in this thesis is the BUTPOD.

Table 21 Comparison of the proposed fixture with competitors

							
	Endurosat	Space Mind		Exo Launch		BUTPOD	
Configuration	6U / 2×3U	6U / 2×3U	3U	8U	3U	6U / 2×3U	3U
Length (Z) [mm]	431.7	382	376.5	526.1	410.6	456	456
Length (X) [mm]	269	267.3	143	440	340	276,3	150
Length (Y) [mm]	144.3	148	141	154.2	149.3	150	150
Mass [kg]	9.5	8.7	5.8	-	-	10.3	6.2
Structural material	Aluminium 6082	-	-	Aluminium Alloy		Aluminium 6061-T6	
Price [€]	11 000	-	3000	-	-	-	-
CubeSat protrusion [mm]	-	-	-	11.2	11.2	12	12
Number of tuna cans	2	0	0	2	1	2	1
Spring system	Yes	No	No	No	No	Yes	Yes
Simplicity ⁽¹⁾	★★	★★★	★★★	★	★	★★	★★
Accessibility ⁽¹⁾	★★	★★★	★★★	★★★	★★★	★★★	★★★

(1) Rating three stars = High, one star = Low

Most companies offer TestPods in both 3U and 6U sizes. Only Exo Launch offers an 8U TestPod that can test extra-long CubeSats. This fact is reflected in the overall dimensions and together with the flange on the bottom, the TestPod from Exo Launch is the largest. In contrast, the TestPod from Space Mind is the smallest in the 6U configuration.

The overall dimensions are mainly affected by the possibility of testing CubeSats that have protrusions and tuna can. It is clear from the comparison that only BUTPOD and ExoLaunch can test these "oversized" CubeSats. Which is one of the key advantages of BUTPOD. But the larger size inevitably leads to an increase in mass, which is higher for BUTPOD than for the others, but this difference is not very significant and since TestPods are generally not designed to fly in space, there is no need to pay extreme attention to the resulting mass.

The materials used for production must meet the technical requirements for Deployers, and despite the minimal information all manufacturers use aluminium alloys. At the same time, some of the manufacturers list a price for their TestPods. This information is only to give an idea of what the price range is for commercial solutions. Since the complete design of the BUTPOD was done in this thesis it can be expected that its manufacturing price would be lower compared to commercial solutions.

The different design philosophies were compared and ranked according to simplicity of design. These are mainly design and assembly simplicity. It is clear from the table that Space Mind represents the simplest solution, but it does not allow the installation of a CubeSat with a tuna can and the satellite locking system does not include a spring. The most complex design is that of Exo Launch, whose design includes several systems that must inevitably increase the final cost (door mechanism, clamping mechanism). The BUTPOD represents a middle ground, where the solution combines simplicity of design and a quality CubeSat securing system using a Pusher Plate and springs.

As far as accessibility is concerned, it is comparable in all TestPods, only in Endurosat the access ports on the side panels have a non-standard layout that does not match the requirements of the CubeSat.

7.2 Summary

The comparison shows that the proposed BUTPOD is on par with commercially available solutions and outperforms the competition in certain aspects, such as the dimensions of the testable CubeSat. However, the main advantage over all solutions is the unique modularity, which is something that is not currently available on the market. The maximum modularity that the current TestPods are capable of is a conversion from a 6U to a 2×3U configuration. BUTPOD, due to its unique design, allows the TestPod to be completely converted from a 6U size to a 3U size, in which even smaller CubeSats can be tested, by replacing some of the parts.

Discussion and recommendations

Although a complete design of the BUTPOD has been made, including a basic description of how the individual parts are manufactured, there is still room for future modifications and improvements. One possible future innovation is even greater modularity of the fixture. The proposed design utilizes unique front, back, top, and bottom panels, giving room for future modification of these parts to allow for multiple parts to be shared. For example, one such modification may be to modify and split the front panel into two parts, where one will match the front panel of a smaller configuration and can be shared.

Modal analysis was performed for the proposed structure using the finite element method. As this project proceeds, it would be ideal to perform further simulations and verify the behaviour under random and sinusoidal vibrations, so that at a later stage in real testing, it is possible to have the information and ability to adjust the models to match reality as closely as possible.

Currently, new manufacturing technologies such as 3D printing from metal are gaining ground in the industry. An interesting new area of development would be the possibility of creating an entire BUTPOD using 3D printing. This would require customizing the entire structure for printing. Another interesting idea is the use of composite to create the covers on the BUTPOD, such a solution could especially benefit the concept version 3 of the BUTPOD.

The produced version of BUTPOD would help to verify the accuracy of the design and provide invaluable information for the future development of this and all subsequent projects.

The main recommendations arising from this chapter are:

- Focus on even greater modularity by modifying some parts
- Perform more CubeSat mechanical test simulations
- Explore the possibility of using 3D printing methods and composites for BUTPOD production
- Manufacture of the BUTPOD and verification of its properties

Conclusion

The first chapter deals with the requirements for mechanical testing of CubeSats. The different types of these tests are explained here in detail. The focus is particularly on the main group of tests, namely vibration tests. More specifically, random, and sinusoidal vibration tests and their specific patterns. Also included in the chapter are the launching systems from which the requirements for each test are directly derived.

The next chapter is primarily used to introduce the commercially available Deployers that host CubeSat during launch. At the same time, the chapter describes the technical requirements that are placed on the Deployers.

After conducting a search of available Deployers, the basic design assumptions were established. In the introduction of the chapter, the necessary prerequisites that need to be determined before the actual design were specified. These include the size of the BUTPOD, the maximum size of the CubeSat to be tested, the material of construction and the required surface treatment. At the end of the chapter, the approach to the design part of this thesis is presented in graphical form.

The conceptual design chapter of BUTPOD presents three basic versions of the product, each taking a different approach to the solution. Each version is introduced, and the individual parts are described in turn. After the conceptual design, the modal analysis was performed and the natural frequencies and stiffnesses of each design were determined. After the FEM analysis, the different versions were compared to determine which represents the best solution for the detailed design.

The second version emerged from the comparison as the best version. In the next chapter, the detailed design of this version of BUTPOD was therefore carried out. First, the mounting system, the internal rail system and the pusher plate were designed. After the detailed design was done, some parts were optimized to achieve the best possible solution.

After the design was completed, the manufacturability was verified and the best production method for each part was considered. Due to the appropriate design of the individual parts, the same production method is chosen for all parts, using milling and drilling. The chapter also includes the verification of the technical requirements that are set for the Deployers but must also be met by the BUTPOD.

In the second to last chapter, the proposed BUTPOD was compared with commercially available solutions. The comparison shows that the proposed fixture excels in the size of the CubeSat that can be tested and most importantly in modularity. The modularity represents something not currently on the market and represents an innovative solution in this area.

Finally, a discussion of the established results was made and possible further developments beyond the scope of this thesis were presented. This master's thesis has met all the prescribed goals.

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List of abbreviations and symbols

ASD	Acceleration spectral density
Cal Poly	California Polytechnic State University
CDS	CubeSat Design Specifications
CSD	Canisterized Satellite Dispenser
ESA	European Space Agency
FEM	Finite Element Analysis
GEVS	General Environmental Verification Standard
GTO	Geostationary transfer orbit
ISIPOD	ISIS Payload Orbital Dispenser
ISS	International Space Station
LEO	Low Earth orbit
LLS	Low level sine
LSP	Launch Services Program
LV	Launch vehicle
MKP	Metoda konečných prvků
MPE	Maximum Predicted Environment
NASA	National Aeronautics and Space Administration
PCB	Printed Circuit Board
P-POD	Poly Picosatellite Orbital Deployer
PSC	Planetary Systems Corporation
PSD	Power spectral density
RBF	Remove before flight
SRS	Shock response spectrum
SSMS	Small Spacecraft Mission Service
STD	Standartd
TB	Thermal balance
TVC	Thermal vacuum cycling
U	CubeSat unit
3D	Three dimensional

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