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Battery module mechanical development and vibration testing for Strategic Upgrades Testing Satellite (SUTS)

Bachelor’s thesis (12 ECTS)

Computer Engineering

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Abstract

Battery module mechanical development and vibration testing for Strategic Upgrades Testing Satellite (SUTS)

Strategic Upgrades Testing Satellite (SUTS) is a PocketQube developed by Estonian Student Satellite Foundation. One of the main modules on any satellite is the battery module. The battery module is used to store energy, and without it being operational, the whole mission is put at risk or fails completely.

The goal of this Bachelor's thesis was to develop the mechanical design of the battery module for SUTS. While numerous battery modules are commercially available for CubeSats, the PocketQubes market currently lacks dedicated battery modules, which prompted the SUTS team to develop one themselves. The main goal of the mechanical design is to make sure the battery module is operational after the rocket launch and deployment to low-Earth orbit. Before design, market research was conducted on CubeSat battery modules, and based on the information gained, a design outline was created that was used to design the battery module. A design of the battery module was done with the use of static analysis and topology optimization to remove excess weight from the module without losing structural integrity. A structural prototype was created to be tested, by measuring the resonance frequencies and performing high sine and random vibration tests to ensure the quality of the battery module's structural design. The tests were conducted in the Tartu Observatory laboratory of the University of Tartu.

CERCS: T320 Space technology

Keywords: PocketQube, picosatellite, battery module, topology optimization, vibration testing

Lühikokkuvõte

Akumooduli arendus ja testimine Strateegiliste Uuenduste Testimise Satelliidi (SUTS) jaoks

Strateegiliste Uuenduste Testimise Satelliit (SUTS) on 2024. aasta juunis välja kuulutatud Eesti Tudengisatelliidi Sihtasutus ehitatud miniatuurne kuupsatelliit [1]. Üks satelliidi kriitilistest alammoodulitest või lastidest on akumoodul. Akumoodulit kasutatakse, et hoiustada satelliidi energiat ning ilma selle toimimiseta on terve satelliidimissioon tugevalt raskendatud või isegi täielikult rikutud.

Bakalaureusetöö eesmärk on arendada SUTSu jaoks akumooduli mehaanika disain. Kuna SUTS on miniatuurne kuupsatelliit ning turul pole ühtegi SUTSu missioonile sobivat akumoodulit, peab SUTSu tiim selle ise arendama ja seda testima. Mehaanilise disaini eesmärk on hoida akusid turvalisena nii teel kosmosesse, kanderaketilt eemaldumisel kui ka Maa-lähedasel orbiidil missiooni läbi viies. Enne disainimist viiakse läbi turuanalüüs turul olevatele kuupsatelliitide akumoodulitele ning vormistatakse teada saadud info kaudu aku mooduli nõuded. Nõuete põhjal teostati akumooduli disain, mille käigus kasutati staatilist analüüsi ja topoloogia optimiseeringut, et kinnitada disaini struktuuri tugevust ja eemaldada liigne mass ilma struktuuri tugevust kaotamata. Enne täieliku kvalifikatsioonimudeli testimist, toodeti akumooduli struktuuriline prototüüp, mille peal viidi läbi resonantssageduste kaardistamine, siinusvibratsioonide katsed ja paljude juhuslike sagedustega vibratsioonikatsed. Testid viidi läbi Tartu Ülikooli Tartu Observatooriumi laboris.

CERCS: T320 Kosmosetehnoloogia

Märksõnad: PocketQube, miniatuurne kuupsatelliit, akumoodul, topoloogia optimisatsioon, vibratsioonikatsed

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Acronyms

SUTS	Strategic Upgrades Testing Satellite
PCB	Printed Circuit Board
COTS	Commercial-off-the-shelf
EPS	electrical power system
FEA	Finite Element Analysis
DUT	Device Under Test
CAD	Computer-Aided Design

1 Introduction

1.1 Strategic Upgrades Test Satellite

Strategic Upgrades Test Satellite (SUTS) is an Estonian student satellite project. SUTS is the first Estonian satellite that brings together teams from the University of Tartu and Taltech under a single foundational banner - Estonian Student Satellite Foundation. Both universities have a heritage in developing CubeSat satellites, with the University of Tartu developing ESTCube-1 and ESTCube-2 and TalTech developing Koit and Hämarik. CubeSats have been developed since 1999 and are popular in student satellite teams, attributable to standardised form factors called “units”. “One unit” or 1U corresponds to 10 x 10 x 10 cm in measurement but is also extendable to bigger units like 3U, 6U, and even 12U. ESTCube-1, the first Estonian satellite, and both TalTech satellites were 1U while ESTCube-2 was a 3U satellite with dimensions of 10 x 10 x 30 cm. [2, 3, 4]

With CubeSats being a standard of nanosatellites, SUTS is a 3P PocketQube satellite, which is a standard of picosatellites. The PocketQube standard was first started in 2009 by professor Robert J. Twiggs, who wanted to make a satellite that could fit in your pocket. Today, PocketQube is a picosatellite standard developed by Alba Orbital, Delft University of Technology, and GAUSS Srl. PocketQubes can be developed into three form factors - 1P, 2P, and 3P. The three different form factors refer to its dimensions and mass, which are defined in the PocketQube standard. With a form factor of 1P, a satellite would have dimensions of 50 x 50 x 50 mm with a maximum mass of 250 grams, but with 3P, the SUTS satellite has dimensions of 50 x 50 x 178 mm with a maximum mass of 750 grams [5, 6].

The two scientific payloads onboard SUTS are an encrypted optical communication payload, which will use a laser to shoot encrypted data at a ground station, and solar cells made out of lunar regolith, which are made from materials found on the moon [7, 8]. Other than these two, there are additional modules on the satellite to keep the system functional. SUTS has a communication board which will use a radio antenna to both receive and transfer data between the satellite and the ground station, attitude determination and control system with the task to control the orientation of the spacecraft, an electrical power system (EPS) to power all the components on the satellite, and command and data handling system that collects and processes data. The battery module, including its cells, forms a key subsystem under the battery management system which itself is a core component of the EPS.

1.2 Purpose of the Work

The main objectives of the work are to design, simulate, manufacture, and test the structural prototype of the battery module for SUTS. The battery module is an assembly that integrates multiple individual battery cells into a single cohesive functional unit. It could be called the heart of the satellite, as it provides a storage of energy for all onboard modules, and thus the module needs to be of great quality, as failure would be critical to the whole mission [9].

During the design of an effective battery module, multiple factors need to be considered. The first is the batteries themselves, which make up the module. From a materials perspective, the selection of battery chemistry, like lithium-ion and lithium-polymer, directly impacts available capacity, discharge characteristics, and operational temperature ranges. In orbit, thermal management will be the most critical factor to hold the temperature of the batteries within a certain range. Mechanically, the design must address structural integrity, which is the most critical factor during launch as the module needs to survive vibrations and shocks present in the rocket during the launch. To ensure the quality of the physical prototype before manufacturing, finite element analysis simulations are often used in aerospace engineering designs [10].

To verify flight readiness of satellite components or payloads, a series of qualification tests is conducted on qualification models that are identical to the flight model. Every requirement and testing level is determined by the launch provider. For CubeSats, these tests include random vibration tests to simulate launch vehicle dynamics, shock tests which simulate separations in multiple launch stages and separation into space from the deployer, and thermal vacuum cycles and bakeout to reduce outgassing from flight-ready hardware [11].

1.3 Organization of the Thesis

The thesis consists of 7 chapters. The outline of each of the chapters is described in the following paragraphs.

In Chapter 2, a market analysis is conducted to understand how space-flown battery modules have been designed and engineered.

Chapter 3 lists the design outline for the battery module structure. It is based on the information gathered from the market analysis.

Chapter 4 discusses the main design of the battery module and the usage of FEA simulations in the frame design process.

Chapter 5 defines the test procedure plan that will be run on the structural prototype of the battery module.

Chapter 6 focuses on the analysis of both the high sine and random vibration test results.

Chapter 7 gives an overview of the future work that will be done on the battery module to make a successful flight model.

2 Market Research

The first phase in the design process was to conduct a market analysis. This research stage is fundamental in developing our own product for multiple reasons. Primarily, it enables us to identify commercial-off-the-shelf (COTS) solutions with proven space flight heritage, which, if suitable for our mission, would render in-house development a waste of funding and time. However, when COTS products fail to meet our needs, examining existing designs provides valuable insight into established design practices. Understanding how others manufacture battery modules is particularly important to this thesis, due to other Estonian satellites, like ESTCube-1 and ESTCube-2, having their batteries attached to the EPS boards and not as a separate module, like our mission will [12].

For market analysis, existing CubeSat battery modules were studied to understand common design approaches and implementation methods for battery systems in small satellites. It was found out that there are no available COTS PocketQube battery modules, and thus the CubeSat battery modules were chosen due to nanosatellites being the next bigger standard compared to PocketQube picosatellite. CubeSats are also more popular compared to PocketQubes since there have been 2596 CubeSats launched compared to 83 PocketQubes as of Dec 31st, 2024 [13].

During the market analysis, the focus was on understanding how the batteries were constructed. More specifically, attention was given to the electrical and mechanical interfaces, the standards applied, materials used, sizing, mass, thermal characteristics, and the tests conducted on battery modules. Most of the battery module datasheets only included basic battery parameters, but a few provided additional information about the construction.

2.1 NanoPower BP4

NanoPower BP4 is a battery module developed by GOMSpace. The module holds 4 18650 lithium-ion cells, 3000 mAh per cell, and the weight is 270 grams. It also fits the PC-104 standard, with the board dimensions being 87.4 x 93.4 x 22.9 mm [14].

The datasheet also has an explanation of how the mechanical assembly takes place: “The batteries are attached to a PCB following the CubeSat Kit standard (modified PC-104 plus) and are repacked with Kapton insulation and fitted to the board with Scotch-Weld 2216 epoxy. In addition, aluminum brackets are glued to the batteries and screwed to the PCB for added mechanical and thermal stability. The inter-cell connections are made with strips spot-welded to the cell terminals” [14].

From Figure 1 it can be seen that the other side of the strips that get spot-welded to the cell terminals are soldered to the PCB pads. The heaters have also been glued to the battery shells to increase thermal conductivity.

Figure 1: Screenshot of NanoPower BP4 [14]

2.2 Intelligent Protected Lithium Battery Module with SoC Reporting (BM2)

The Battery Module 2 (BM2) represents a robust power solution similar to the NanoPower BP4. It features an aluminum core designed to secure up to eight 18650 cells, complete with integrated battery heaters and temperature sensors. The cells are securely clamped with AL6061-T6 hard-anodized black mounting brackets, which provide maximum emissivity for efficient cooling as seen in Figure 2 [15].

BM2's electrical connections are established through spot-welding of cell terminals to create series or parallel configurations. The module incorporates a multi-level PCB housing all necessary electronics, connectors, and connections to battery terminals, heaters, and temperature sensors. Each cell is individually wrapped with a conformal Kapton heater, and most are instrumented with thermistors for temperature telemetry [15].

Figure 2: Image of BM 2 [15]

2.3 PicoEPS Daughterboard Battery Module

The PicoEPS daughterboard stands out as one of the most promising COTS battery modules for missions with extremely tight mass budgets, such as ours, due to it having the lowest mass of all COTS found battery modules, with only 80 grams. Specifically designed for 1U and 2U CubeSats using the PC104 standard, it integrates 1400 mAh lithium-polymer batteries. However, a downside exists, as seen in Figure 3, the daughterboard can not work without the EPS motherboard, which has the same capacity of 1400 mAh but a mass of 110 grams [16].

This dependency effectively increases the minimum practical mass to 110 grams for 1400 mAh of capacity, as the motherboard is essential for system functionality. When both components are combined, the total capacity increases to 2800 mAh, but the mass also rises to 190 grams. Additionally, an optional radiation shielding case can add another 100 grams to the system [16].

While the PicoEPS datasheet lacks detailed assembly information compared to BP4 and BM2, its extremely light weight makes it particularly valuable for small satellite missions where mass constraints are critical. The use of lithium polymer batteries rather than the 18650 cells found in other modules validates our consideration of this battery chemistry. However, final battery selection must carefully balance these technological advantages against the stringent safety requirements and environmental constraints imposed by launch vehicle providers.

Figure 3: Image of PicoEPS daughterboard (top) and motherboard (bottom) [15]

2.4 Lessons Learnt From Market Research

The last three battery modules were brought up due to their uniqueness and ability to offer great insight into battery modules for CubeSats. Both NanoPower BP4 and BM2 have extensive flight history, which shows us their products are of quality and their ideas of design are to be trusted [17, 18]. There are a few main takeaways for our own battery module model construction.

The use of polyimide tape to electrically and thermally isolate batteries was found on both NanoPower BP4 and BM2. Space grade polyimide is used due to its wide operating temperature range, withstanding vacuum, high electrical resistance, and radiation properties, but it has been said that “atomic oxygen in low orbit can attack polymer tapes” [19, 20]. For both of the mentioned battery modules, Kapton tape was used as an electrical isolator to prevent short circuits and as a flexible heater or thermal manager.

Epoxy glue would be used to attach batteries directly to the battery management board. This will give us more confidence in batteries staying in their mandated area. Extreme precision is required during the choice of epoxy glue. Normal glue compared to space grade glue can start outgassing, which means that in vacuum conditions glue will start boiling due to releasing bubbles that have stayed inside the glue. This is a great concern for our mission because the optical communication payload has lenses that might, in the end, become foggy and thus inoperable. The curing temperature is also a problematic point due to some glues curing at room temperature, others needing ovens, which would mean heat treating our batteries [21, 22].

Aluminum alloy brackets made from alloys like 6061-T6 were used on flight heritage modules to help with structural integrity and thermal management. Making brackets with fastening holes out of aluminium for our battery module is one way to integrate our module into the satellite bus and help hold batteries together at the same time. In thermal management, the bracket might be connected to some thermally affected electronics components that need heat during operation. The usage of aluminium brackets comes at a cost in addition to mass.

The usage of metal strips to spot weld interconnect battery terminals. This configuration will allow us to connect multiple cells together to form a bigger cell with more capacity, just like electric vehicles' battery packs are made. Spot welds, when done correctly, will form a strong welded connection without heat damage to the battery [23].

Additional information was found from multiple battery modules. The EXA BA01 High Energy Density Battery Array stating "[...] BA01 employs an advanced containment technique designed to reduce the normal LiPo cell swelling in vacuum to a minimum and yet not increasing the mass of the device by using bulky metal containers, however a minimum amount of swelling is to be expected, which is a rise of about 1 to 1.3 millimeters in the surface of the array [...]" giving insight into the problems that lithium polymer might experience in vacuum due to their gel like inside with pouch structure. Furthermore, the same documentation reveals that the module's composition and architectural structure contribute to its effectiveness as a radiation shield. This insight is valuable for determining optimal battery placement within the satellite. It suggests the potential for dual functionality of the battery module as both a power source and a protective element for sensitive components, but since our mission orbit will be low-Earth orbit (LEO), the need to protect components from radiation is not critical [24].

3 Design Outline

The two main outlines of any design are dimensions and mass. The battery module dimensions will be defined by the PocketQube form factor standard and the satellite bus. With the 3P form factor, the satellite dimensions are 50 x 50 x 178 mm with a mass of 750 grams. Based on the first design iteration of the satellite bus as shown in Figure 4, which has 2 mm side walls, the battery module dimensions are limited to 46 x 48 mm. It is not 46 x 46 mm due to the deployer plate, which is the plate where the satellite will slide off from inside the deployer, being outside of the 50 x 50 mm allocation. The third dimension of the battery module will be determined in the design process. For mass, 20% of the whole mass of the satellite would be allocated for the battery module, meaning that out of the 750 grams, 150 grams is to be used by the battery module [5].

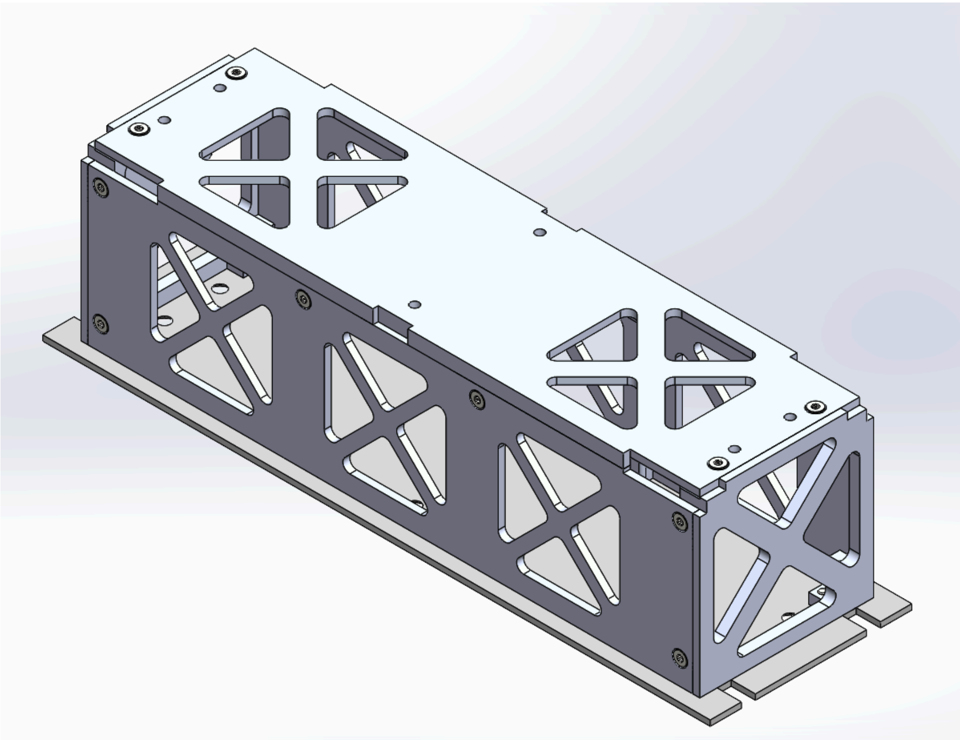


Figure 4: Isometric view of the first iteration design of the SUTS satellite bus

The two most promising battery candidates identified were CELLEVIA BATTERIES ACCU-LP103740/CL lithium polymer batteries and the Panasonic UF553443ZU lithium-ion batteries. The market research to identify suitable batteries was conducted by Kristin Kandelin from the SUTS electronics team. The chosen battery candidate parameters are shown in Table 1. A vacuum bucket test was run in collaboration with the electronics team on both battery candidates to see how both batteries react in low-pressure conditions. The conditions reached -0.76 bar when -1 bar is considered vacuum. Due to its pouch casing, the lithium-polymer battery will expand under vacuum conditions and thus create internal pressures on the battery module assembly. The lithium-ion battery has a metal shell casing, which will considerably reduce the expansion of the battery in vacuum conditions. Both batteries returned to their original dimensions under 1 atmospheric pressure condition [25, 26].

Table 1: Comparison Of The Two Chosen Batteries [25, 26]

Battery model/name	CELLEVIA BATTERIES ACCU-LP103740/CL	Panasonic UF553443ZU
Battery Chemistry Type	Lithium-polymer	Lithium-ion
Dimensions (mm)	10 x 37 x 40	5.5 x 33.8 x 42.8
Mass (g)	29.6	18.7
Typical capacity (mAh)	1580	1040
Operable working temperature (°C)	Charge: 0 ~ +45 Discharge: -20 ~ +60	Charge: 0 to +40 Discharge: -20 to +60
Additional info	Pouch shell	Metal shell

The lessons learnt from the market research were the use of polyimide tape to isolate and heat batteries, spot welding to connect multiple cells into a bigger one without heat damaging the cells, epoxy glue to mount batteries to the battery manager board, and aluminium alloys as brackets to integrate battery module to the satellite bus.

The battery module will also be modular. With modularity, the module will be a singular unit. With this configuration, every satellite payload or instrument is a separate unit. This way, the satellite will form a singular system if every unit is available and in working condition. This also means that the module will need to be easily removable and attachable to the satellite bus. The deployer plate has been chosen by the team as a PCB that will handle communication between different subsystems.

SUTS does not have a definitive launch provider at this stage of development. The team is considering the usage of Alba Orbital deployers, which can accommodate 1P, 1.5P, 2P, and 3P form factor PocketQubes to space. To ensure compatibility with the broadest range of launch providers, we have chosen the launch provider with the harshest launch profile. Igor Kuzmin from the mechanics team analysed all available rocket launch providers, and it was identified that the rocket Vega-C developed by Arianespace has the roughest launch profile [27].

Resonance in a structure is a phenomenon that occurs at certain frequencies where the structural body naturally amplifies forced vibrations to their maximum amplitude [28]. In our design, resonance must not be found under 115 Hz as required by the Vega-C frequency requirements shown in Table 2.

Table 2: Vega-C Frequency Requirements [29]

Direction	Minimum frequency (Hz)	Reference
Lateral frequency	> 115	Section 4.2.4
Longitudinal frequency	> 115	Section 4.2.4

Table 3: Vega-C Sine Sweep Requirements [29]

Sine environment (0-peak) g[1]			
Longitudinal direction			
Frequency band (Hz)	5-70	70-110	110-125
Qualification levels (0-peak) (g)	2.5	1.25	1.25
Acceptance levels (0-peak) (g)	2.0	1.0	1.0
Lateral direction			
Frequency band (Hz)	5-70	70-110	110-125
Qualification levels (0-peak) (g)	2.5	1.25	1.25
Acceptance levels (0-peak) (g)	2.0	1.0	1.0

[1] The non-standard unit "g" is used to represent an acceleration with a magnitude of ~9.81 m/s^2 (i.e. the Earth's gravitational acceleration).

Table 4: Random Vibration Tests [29]

Random levels (SSMS Top and Towers positions)	
Frequency Band (Hz)	**PSD, Power Spectral Density** ($10^{-3} g^2/Hz$)
20 - 150	7.1
150 - 200	7.1 – 56.3
200 - 270	56.3
270 - 300	56.3 - 100
300 - 400	100
400 - 450	100 – 56.3
450 - 1000	56.3 – 34.0
1000 - 2000	34.0 – 29.3
GRMS (g)	8.8
Duration (s)	60

Table 5: Vega-C Quasi-Static Loads [28]

Direction	Flight load (g)	Qualification load (g) ($1.25\times$)	Reference
Lateral	± 10	± 12.5	Section 4.2.5
Longitudinal	± 10	± 12.5	Section 4.2.5

4 Mechanical Design

The SUTS battery module design contains everything from the design outline to make a finished engineering model. Positioned between the communications board and avionics stack, the module serves dual functions as both a power source and a passive radiation shield for sensitive electronics.

4.1 Battery Module Mechanical Design Concept

The module utilizes two lithium-ion battery packs consisting of two cells each, rather than lithium-polymer cells as seen in Figure 5. This decision was driven by multiple factors. As mentioned before, the lithium-ion has a metal shell that maintains its dimensions under vacuum. This way, there are no internal forces making the module more structurally intact. The usage of two cells increased the capacity of the whole battery module from 3000 mAh to 4000 mAh, but comes at a cost of the mass also increasing from around 60 grams to 75 grams. The battery cells will be spot-welded together to form a pack, which will be soldered through small cutouts on the holding PCB to the other side of the PCB. To make this configuration possible, one of the battery packs is attached vertically while the other is attached horizontally.

The structural framework consists of two 3 mm thick aluminium brackets, which were both optimized through the usage of topology optimization to achieve maximum rigidity with minimal mass. These brackets serve two essential functions. The first function is securing the battery pack to the side of the management PCB, and the second function is creating mounting interfaces. The team has not analysed the need for a thermal conduction pathway and thus will not be one of the essential functions. Thermal regulation of the batteries is accomplished through flexible heaters adhered to both of the packs on each side. This layout ensures more uniform temperature distribution of both cells in a battery pack and is necessary due to directly impacting the lifetime of a cell.

In the assembly process, polyimide tape will be used to isolate the battery terminals and shell from short-circuiting. The use of epoxy is under question due to there always being some outgassing, even in space-grade epoxies that have undergone thermal vacuum bakeout to reduce outgassing. Outgassing on SUTS could have drastic effects on its optical communication payload as its lenses could get contaminated with condensation and have drastic effects on its working capabilities. As a result, the usage of epoxy to hold the batteries on the management board might not be of help due to spot-welded metal strips being soldered to the plate will already fix the battery, and the bracket has been designed to fit the battery in a small cutout. Thus, there is no need for extra fixturing. The assembly is secured using eight M2.5 × 8 mm countersunk screws with four hex male-female standoffs and four hex female-female standoffs. The module's total mass is approximately 125 grams, which was obtained using SolidWorks mass properties, representing 16.5% of the spacecraft's 750 gram mass budget.

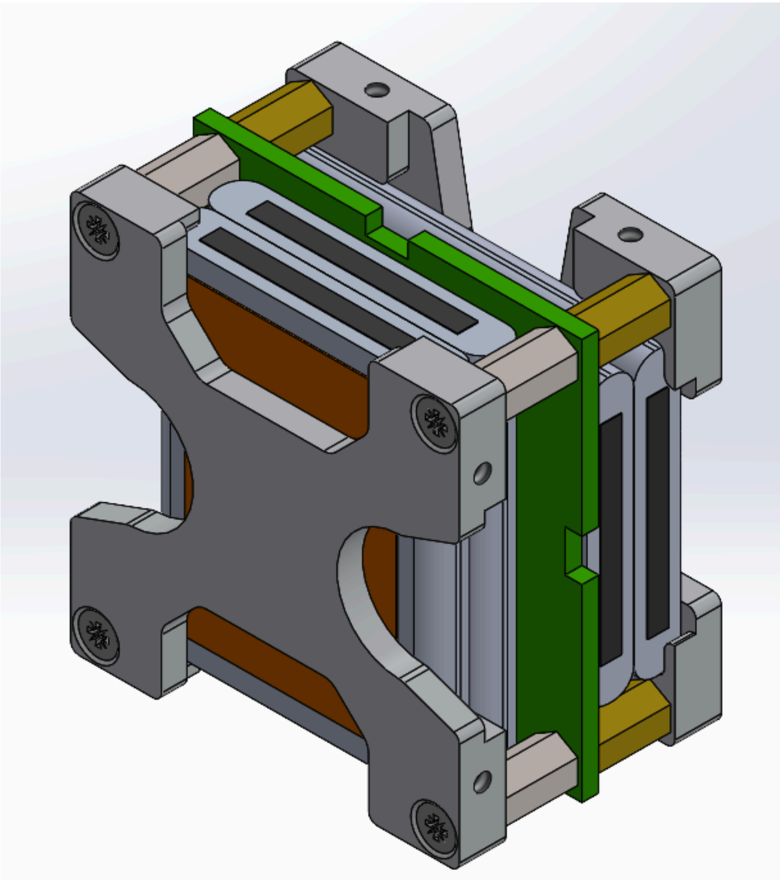


Figure 5: Isometric view of the battery module 3D model

4.2 Usage of SolidWorks Simulation

Finite element analysis (FEA) is a modeling method used to predict how applied loads will act on a chosen model. The model will be broken into smaller discrete parts called elements and nodes, which get assigned material parameters and a mathematical equation that approximates their physical behaviour under the defined loads. Used by engineers in the mechanical, aerospace, automotive, and many other engineering fields, it gives a unique chance to check the quality of a design before any physical prototypes are made, which helps save on manufacturing and testing costs [30].

The goal of the simulations was to find the optimal stiffness-to-weight ratio for the brackets and to ensure the structural integrity of the design. To find the optimal stiffness-to-weight ratio, a study by the name of topology optimization is conducted. With topology optimization, it is possible to simulate the stresses and forces that act on the battery module brackets during launch and find the most optimized geometrical design. It is critical for spacecraft components to optimize the stiffness-to-weight ratio, especially in PocketQube missions where mass budgets are extremely limited, while still maintaining structural integrity. The simulations were run on SolidWorks Student Edition 2024 SP5.0 [31].

4.2.1 Simulation Setup And Methodology

Before any optimization, static analysis was carried out on the assembly model with frames that do not have any cutouts. The goal of this was to see if the brackets in their original state are able to survive the stress exerted on them during launch and therefore undergo weight removal.

During the setup of the simulation, each part of the assembly had to have a material assigned. The brackets were defined as aluminium alloy 6063-T6, while the PCB and flexible heaters were modeled as FR4 material. Alloy 6063-T6 is used due to its great yield and tensile strength values at a low price. The battery cells, which are metal shells, were simplified to be single material with properties of aluminium alloy 6061-T6. Fastener connection interfaces were added as countersunk for the fasteners and counterbore for the standoffs, with a preload of 0.4 Nm applied to each. The batteries and flexible heaters were bonded together with the management board to be a unified group that reflects the real-life physical attachment through spot-welded and soldered strips and adhesive. Fixed fixture points were holes that are used to mount the module to the satellite bus through fasteners. The external load of 10 g gravitational force or $98.1\, m/s^2$ was applied in the simulation to represent the maximum quasi-static loads experienced during launch, as specified by the Vega-C requirements in Table 5. Quasi-static load was chosen due to the highest acceleration between high sine, random vibration, and quasi-static loads, and because the fact that Tartu Observatory laboratory is not able to perform quasi-static tests. Each axis was separately simulated as SolidWorks requires a single load to an individual axis per simulation. The mesh was set to the finest detail to ensure the most accurate results to determine the quality of the module structure, as shown in Figure 6.

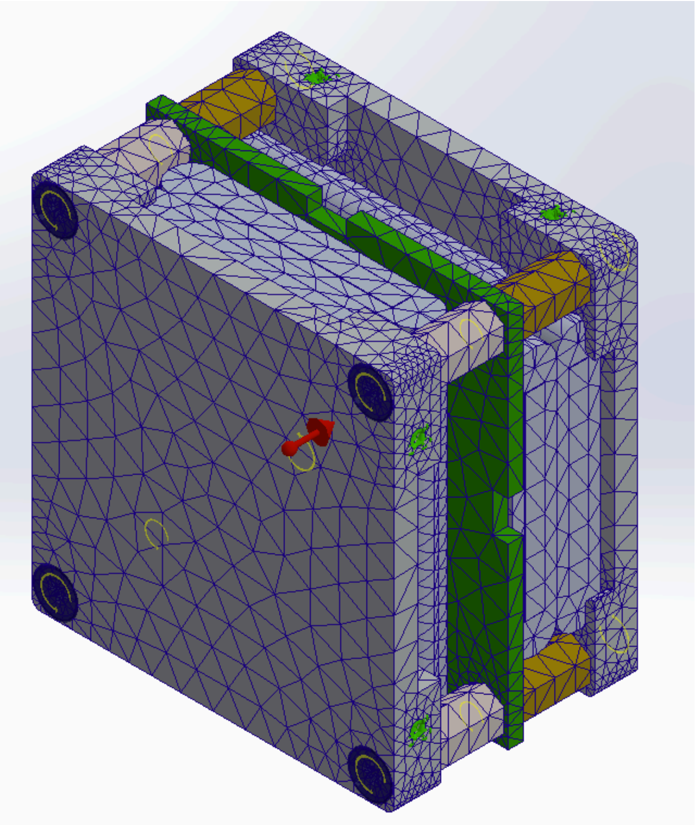


Figure 6: Battery module with a mesh that is ready to be studied in the Z-axis

4.2.2 Static Analysis Results

The initial static analysis revealed that under a 10 g load, the maximum stress concentration reached approximately 223 MPa, as shown in Figure 7, primarily localized at the fastener and standoff connection points. With the maximum stress, the theoretical safety factor will be 0.964 based on the material's yield strength of 214 MPa. However, this calculation only shows safety factors on very certain areas, as iso clipping analysis demonstrated that the vast majority of the bracket structure experiences significantly lower stresses below 22.2 MPa, corresponding to a more representative safety factor of 9.64. Displacement analysis showed a maximum deflection of only 4.44×10^{-3}mm, indicating exceptional rigidity in the assembly. The strain analysis revealed a maximum equivalent strain of 1.093×10^{-3}%, well within the elastic deformation range of the aluminium alloy. The predominantly low stress distribution throughout the brackets confirmed that the basic design was structurally sound and suitable for topology optimization to reduce mass while maintaining adequate strength.

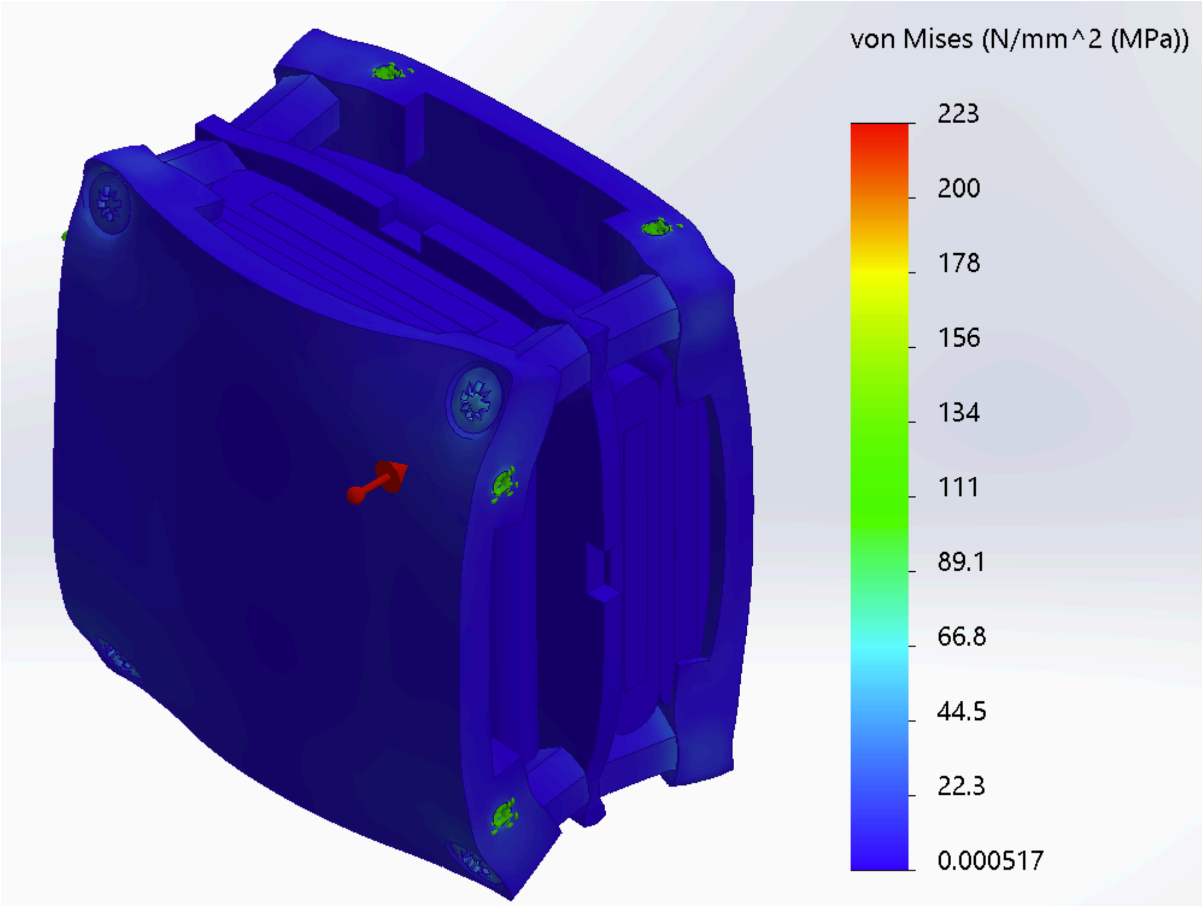


Figure 7: Battery module assembly stress results visualized

4.2.3 Topology Optimization Studies

The topology optimization was configured to achieve the best stiffness-to-weight ratio while adhering to several critical constraints. A mass reduction target of 60% was established after initial testing showed that a 70% reduction produced geometries that were impractical to manufacture. The frequency constraint was set to ensure the first natural frequency remained above 115 Hz, in compliance with Vega-C launch vehicle requirements. A stress constraint limiting maximum stress to 40% or 86 MPa of the material's yield strength was implemented, providing a safety factor of 2.5. Manufacturing considerations were also integrated through several parameters to make sure that the end product is easily manufacturable. Preserved regions were defined around fastening holes and battery contact areas, a minimum thickness of 3 mm was specified to prevent the generation of non-machinable web-like structures, and quarter symmetry planes were utilized to reduce computation time. The optimization was performed on both brackets separately due to subtle differences in their geometries, with particular attention to maintaining flat mating surfaces where the brackets interface with other components. Figure 8 shows one of the two bracket optimizations results.

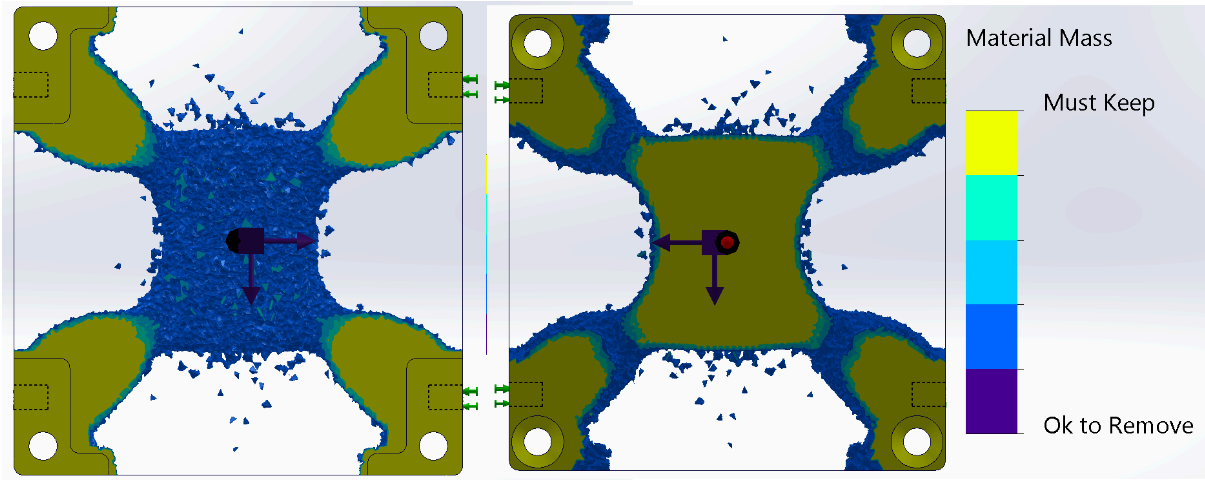


Figure 8: Topology results on a single bracket from front and back

4.2.4 Optimized Design Validation

Post-optimization static analysis confirmed the structural integrity of the redesigned brackets under identical 10 g loading conditions. The maximum stress in the optimized assembly, as seen in Figure 9, decreased to 99.2 MPa from the original 223 MPa, resulting in an improved safety factor of 2.15. The topology optimization yielded brackets with a mass of approximately 11.5 grams each, compared to the original 19.7 grams, representing a 41.6% mass reduction. While the optimization algorithm, as seen in Figure 8, suggested more aggressive material removal in some areas, particularly at the battery and heater interface surfaces, practical manufacturing and assembly considerations necessitated maintaining flat mating surfaces in these regions. This pragmatic approach balanced theoretical optimization with real-world implementation requirements, resulting in a design that is both manufacturable and structurally sound while achieving significant mass savings. It was decided to manufacture the battery module structural prototype and the mounting fixture according to the technical drawings in Appendix A (Figures 19-27)

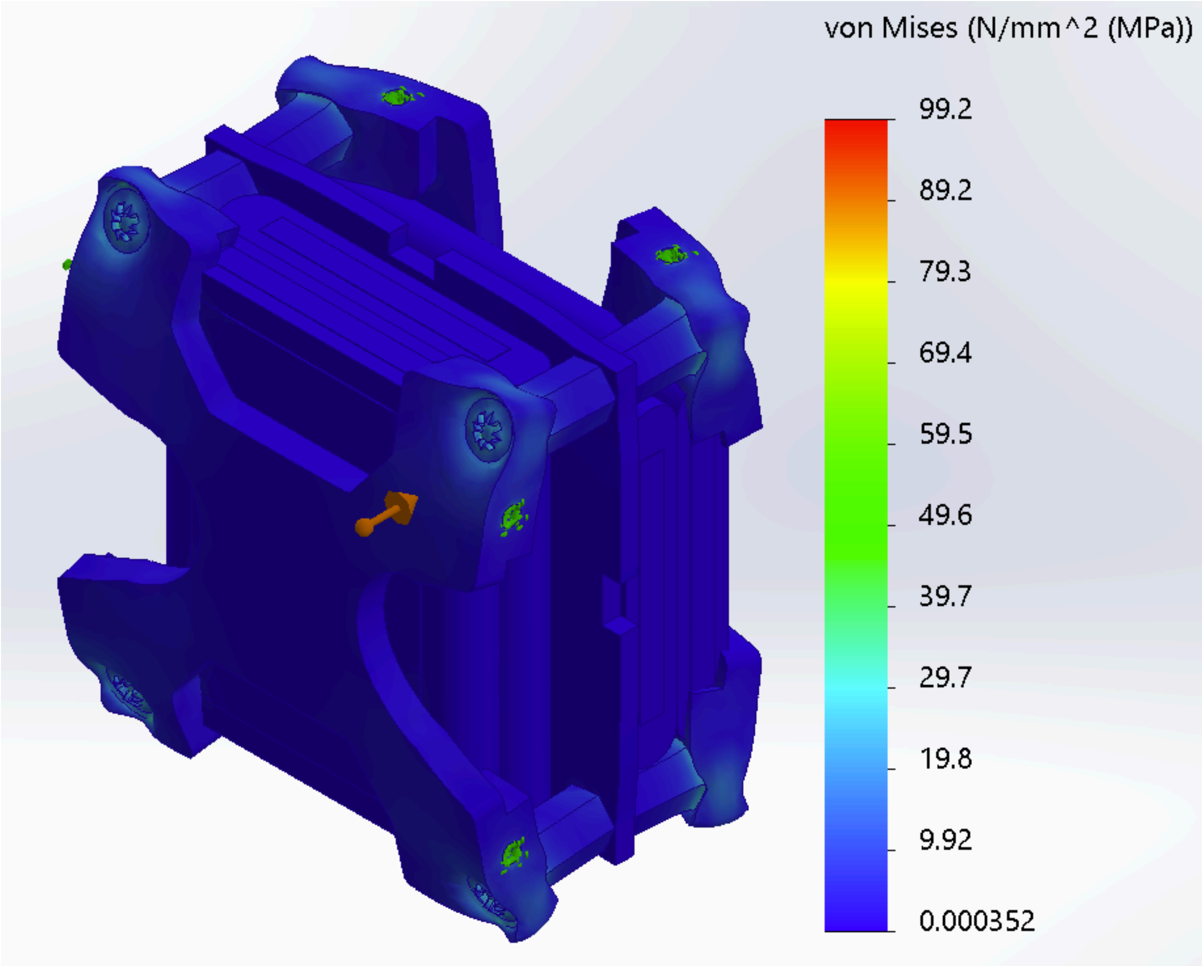


Figure 9: Static analysis test results with optimized brackets

The author also tried using COMSOL Multiphysics to run another topology optimization on the brackets to compare the results between the two simulations. COMSOL Multiphysics 5.2 was used with an optimization license included. Due to no experience using COMSOL before and the version being so old that it was missing the topology optimization study, with the author being unsure of how to fully set up topology simulations, the analysis was discontinued due to software limitations [31].

5 Test Procedure

5.1 Test Scope

The scope of this test is to validate the structural integrity of the designed battery module as defined under Vega-C high sine and random vibration loads.

5.2 Device Under Test

The device under test (DUT) is the SUTS battery module. The tested battery module, as shown in Figure 10, will consist of two frames, four male-female standoffs, four male-male standoffs, a 48 x 46 x 2 mm FR4 plate, and eight fasteners ISO 7046 A4 TX M2.5 x 8 mm. The frames were manufactured with aluminium alloy 6082-T651, which, compared to the alloy 6063-T6 that was used in SolidWorks simulations, is stronger in the shear, yield, and ultimate strength values [32]. The change in frame material was carried out by the suggestion of the manufacturer. Both the male-female (M-F) and the female-female (F-F) standoffs are 9mm in length, but the M-F is made of steel while the F-F is made of brass. The FR4 plates are used to replace the PCB that holds the batteries, as a precaution to ensure the structural integrity of the module before any tests with batteries are run. The same dimensions of the final PCB will be used for the FR4 replacement. The mass of DUT is 44 grams but with the vibration jig the total mass comes to 1200 grams. The flight model of the battery module will use titanium Ti 6Al-4V standoffs and titanium fasteners due to great mechanical properties, corrosion resistance, and lightweight [33].

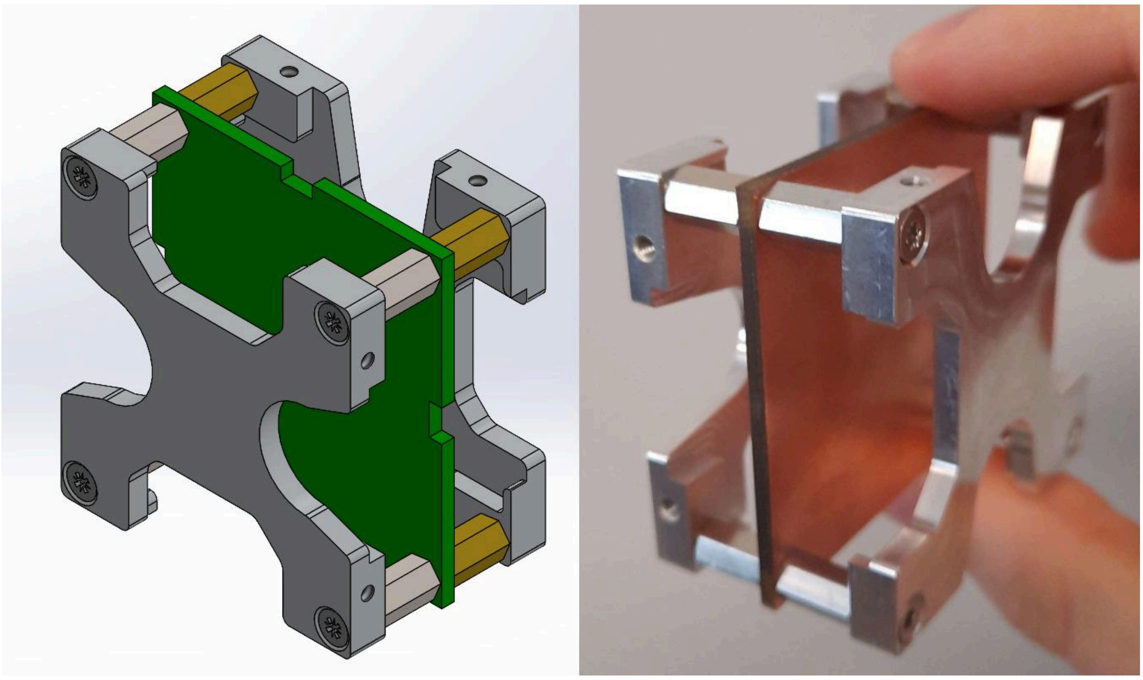


Figure 10: Overview of the primary DUT, seen in CAD (left) and real life (right) configuration

5.3 Test Definition

5.3.1 Vibration Tests

Random vibration tests and high sine tests will be conducted according to the SSRS Vega-C 4.3.3 Spacecraft compatibility tests for Small S/C document [29]. Both tests are discussed in Chapter 3. The design outline and the test profiles are shown in Tables 1 and 2.

5.3.2 Vibration Test Profiles

The Vega-C vibration test profiles are shown in Figures 11-13. The high sine profile has been modified in the frequency range 5 Hz to 15 Hz due to the limitations of the vibration shaker at Tartu Observatory laboratory. Instead of reaching 2.5 g at 5 Hz, 2.5 g is reached at 15 Hz, as shown in Figure 12.

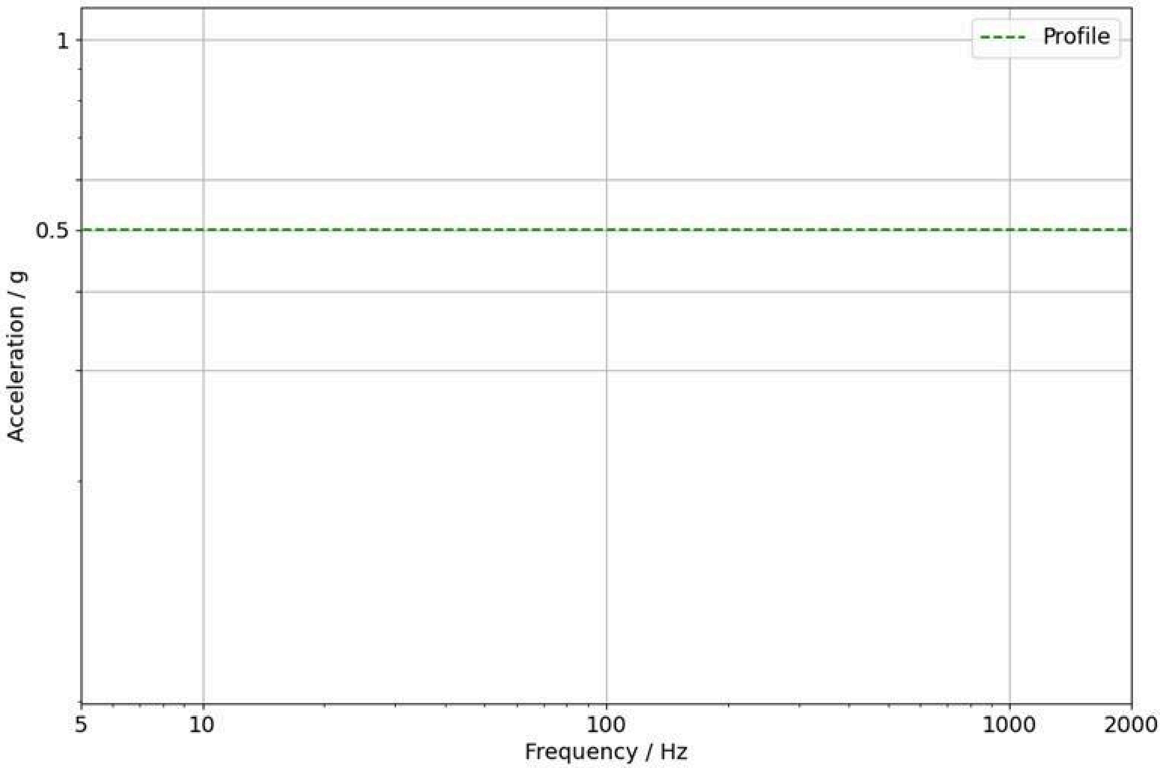


Figure 11: Resonance search test profile

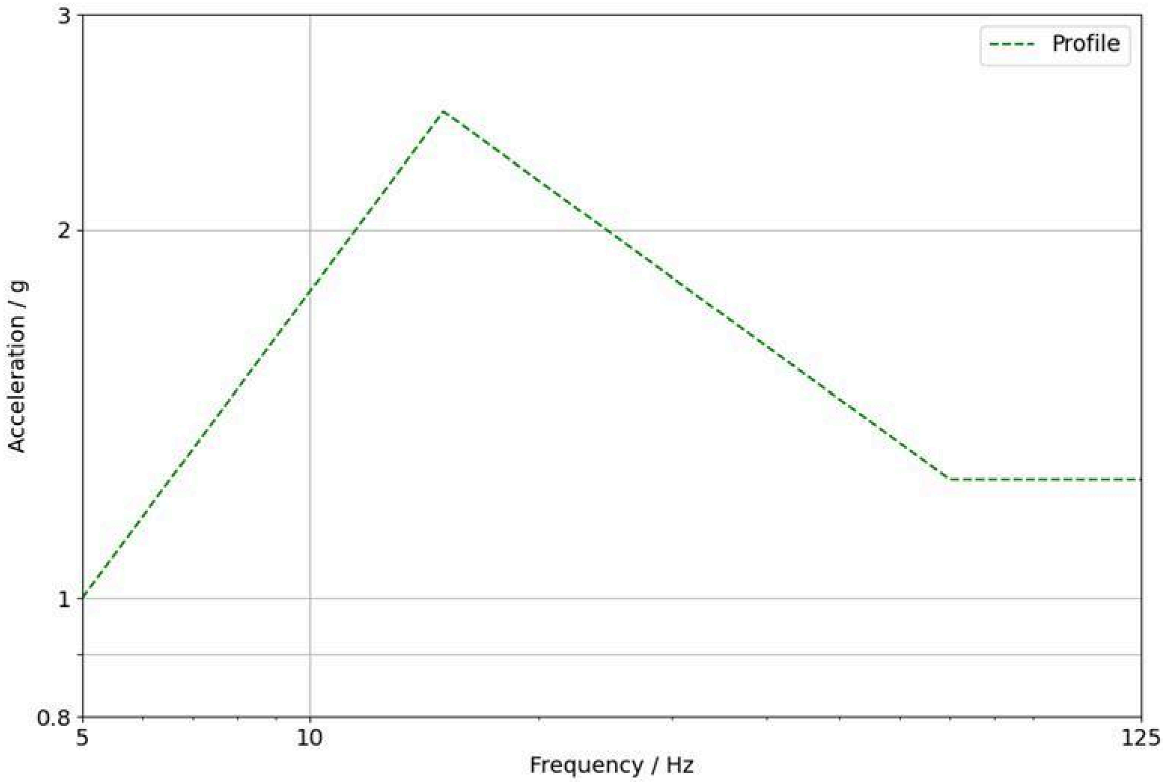


Figure 12: High sine test profile

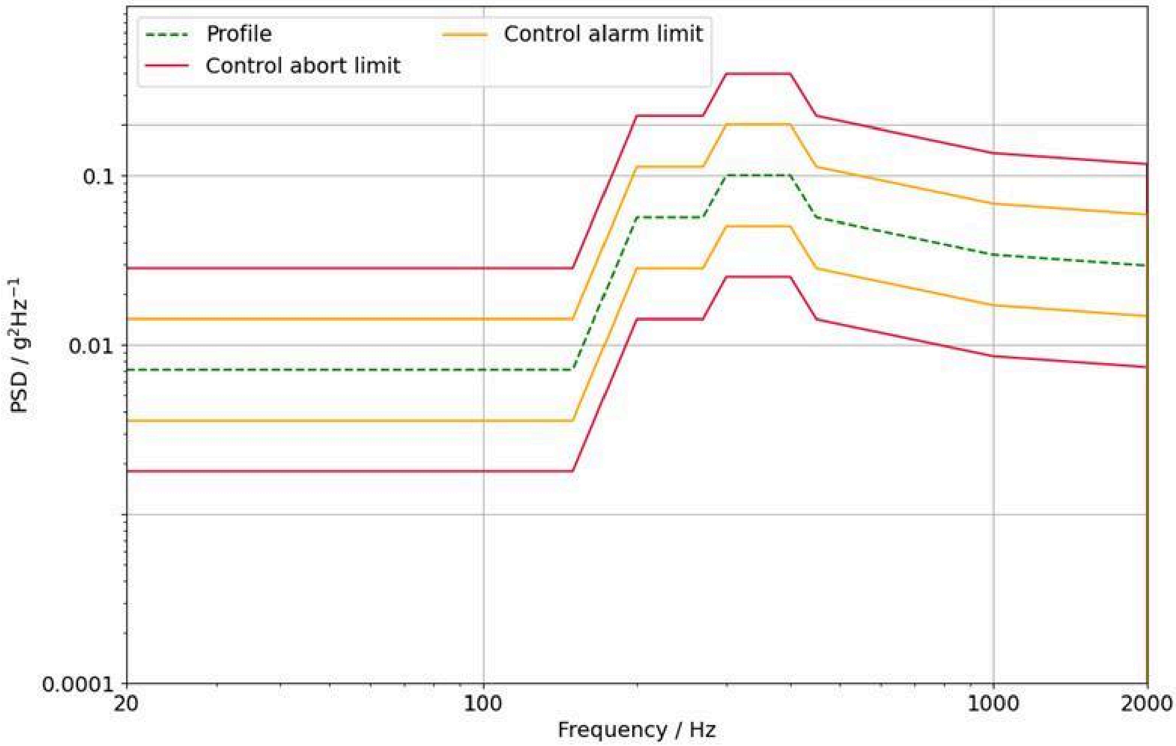


Figure 13: Random vibration test profile

5.3.3 Test Axis

The test axis of the DUT is shown in Figure 14.

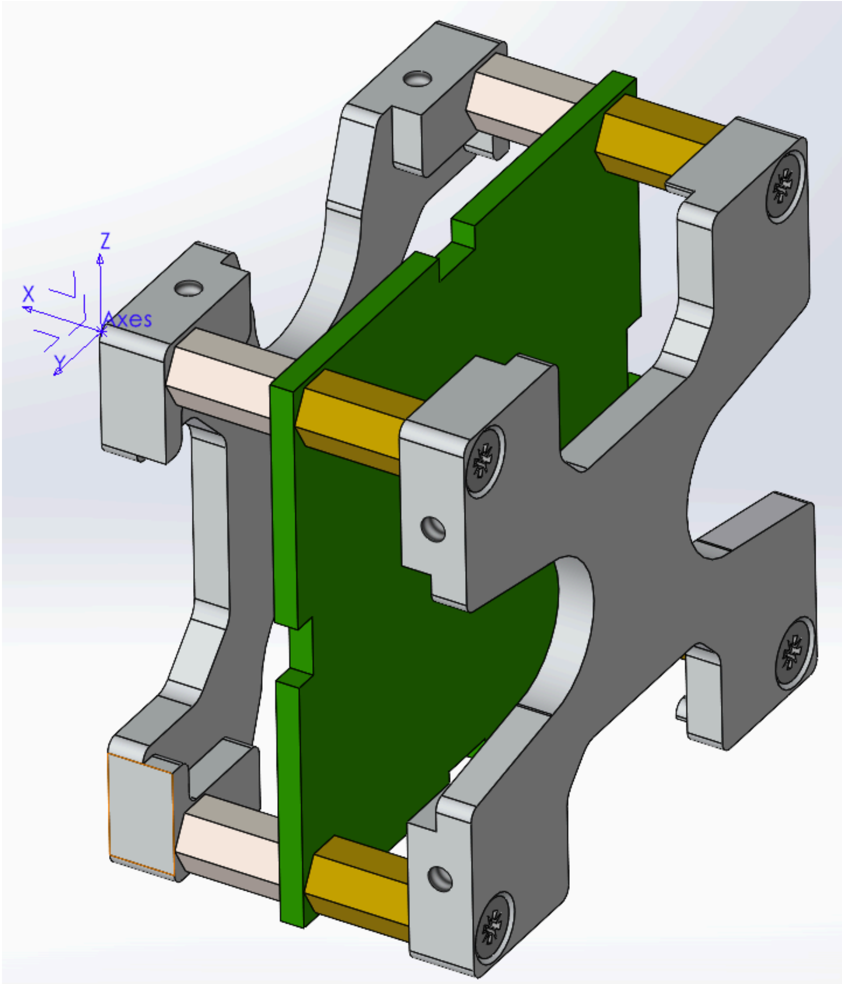


Figure 14: Test axes of the DUT

5.4 Test Plan

5.4.1 Mounting of the DUT to the Mounting Fixture

The module should be mounted to the mounting fixture 09.13-P01-SUTS prior to the testing. The vibration fixture needs to be assembled according to drawing 09.13-P01-SUTS-A, with all mounting torques for the jig found there. The following steps are for reference for easier assembly of the fixture.

5.4.2 Vibration Jig Mounting

In the Y-axis and Z-axis, the mounting order of the vibration jig is as ordered.

1. 09.09-P01-SUTS plate will get fastened to the vibration bench plate that is already mounted to the vibration shaker.

2. The vibration jig will be assembled, as seen on Figure 15, with one of the two 09.10-P01-SUTS and the 09.12-P01-SUTS plates missing.
3. The jig will be fastened to the vibration shaker via 3 DIN 912 12.9 M4 x 10 mm fasteners.
4. DUT will be placed into the open jig.
5. The 09.10-P01-SUTS plate will be added to the jig and fastened.
6. The 09.12-P01-SUTS plate will be added to the jig and fastened.
7. The mounting holes for the DUT will be fastened.

   For the X-axis, the only point that is different between the Y-axis is in point 2 where the jig will be assembled with one of the two 09.11-P01-SUTS and the 09.12-P01-SUTS plates missing.

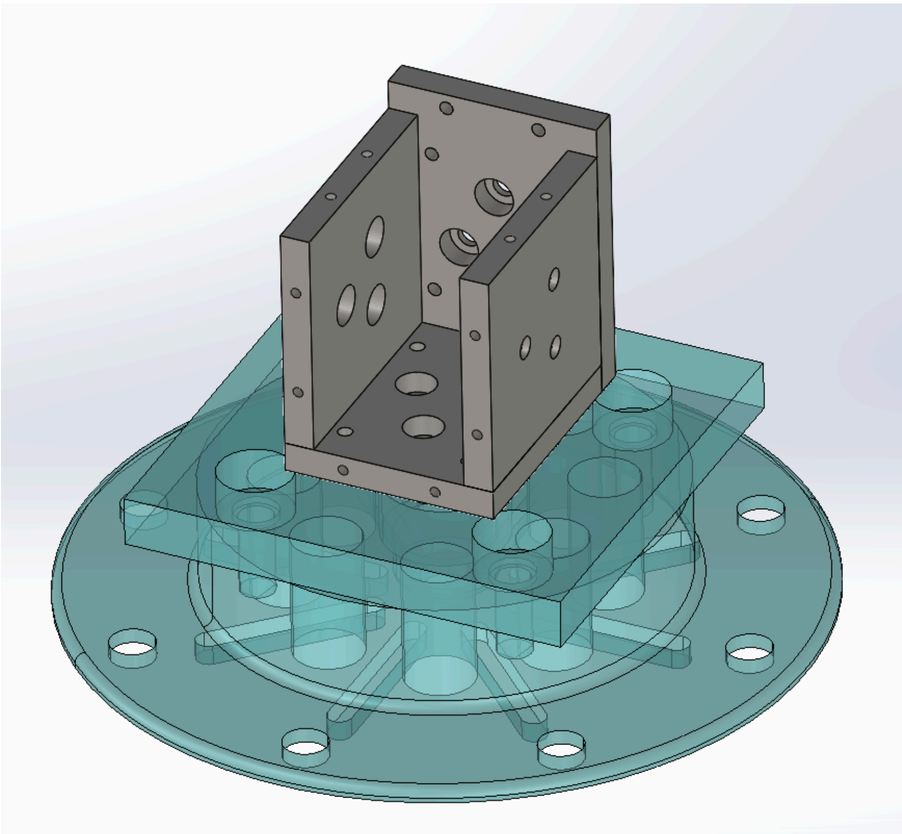


Figure 15: Vibration jig mounted in Z-axis with one 09.10-P01-SUTS and 09.12-P01-SUTS plates missing

5.4.3 Tests to be Conducted

Tests will be conducted based on Tables 3 and 4. Tests will be conducted on a single DUT in all three axes.

5.4.4 Testing Sequence

The testing procedure is performed in each axis of the DUT according to the following steps:

1. The vibration jig is mounted to the vibration shaker.
2. Acceleration sensors are installed on the mounting fixture to monitor vibration levels.
3. A resonance search is performed to map the resonance frequencies and amplitudes of the mounting jig.
4. The DUT is mounted to the mounting fixture and to the vibration shaker.
5. Acceleration sensors are installed on the mounting fixture and DUT if possible to control and monitor the vibration levels during the tests.
6. A resonance search is performed to map the resonance frequencies and amplitudes of the DUT and mounting fixture.
7. A high sine vibration test is conducted with the required test profile as seen on Figure 12.
8. A resonance search is performed again after the high sine vibration test.
9. After completion of the high sine vibration test, a visual inspection of the DUT and mounting fixture is to be done and documented – a photo is taken from each side of the DUT, which is still mounted to the vibration shaker.
10. A random vibration test is conducted with the required test profile as seen in Table 4 and on Figure 13.
11. A resonance search is performed after the random vibration test.
12. After completion of the random vibration test, a visual inspection of the DUT and mounting fixture is to be done and documented – a photo is taken from each side of the DUT, which is still mounted to the vibration shaker.
13. The DUT is removed from the vibration shaker, and photos are taken from each side.
14. If the DUT or mounting fixture is damaged, it must be documented with detailed photos and information.
15. The above steps will be repeated for all three axes of the DUT.

After all of the vibration tests, the resonance search results are plotted separately for all three axes. The resonance search plots from before and after the high sine and random vibration tests are compared. If shifts in frequency or amplitude occur, it means that the vibration tests have caused damage to the DUT or mounting fixture [34].

6 Validation

Vibration tests according to the test plan in Chapter 5 were carried out on the structural prototype of the battery module on 13 May 2025 at the Space Technology Laboratories of Tartu Observatory, University of Tartu. The results of the vibration tests are presented in Appendix B.

Prior to the vibration tests, a resonance search was performed on the empty mounting fixture to ensure that no internal resonances would interfere with the test results. In the Y-axis configuration as seen in Figure 16, no significant resonances were observed, as illustrated in Figure 17. Given the structural rigidity and symmetric design of the fixture, and in the interest of time, further resonance searches on the empty fixture in the X- and Z-axis orientations were considered unnecessary. The resonance search plots from accelerometers E8-55 and E8-62, mounted at different positions on the jig, showed minor differences due to their placement. However, these differences were consistent with expectations and did not indicate any structural issues in the fixture

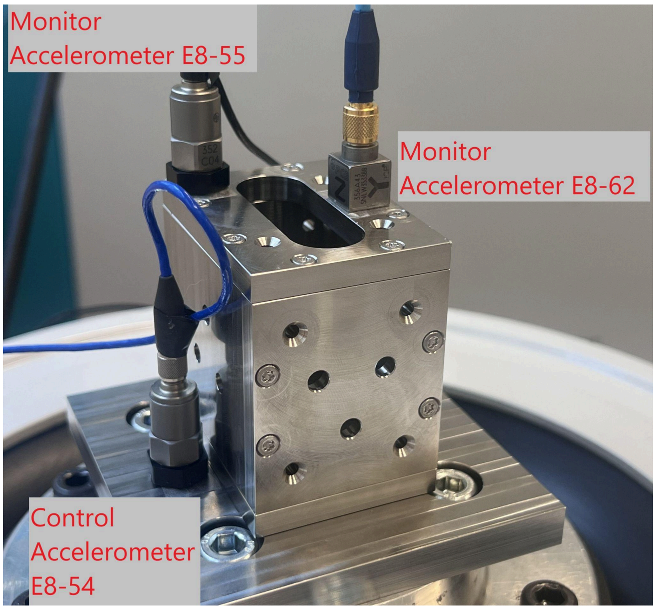


Figure 16: Empty vibration fixture mounted in Y-axis, ready for resonance search

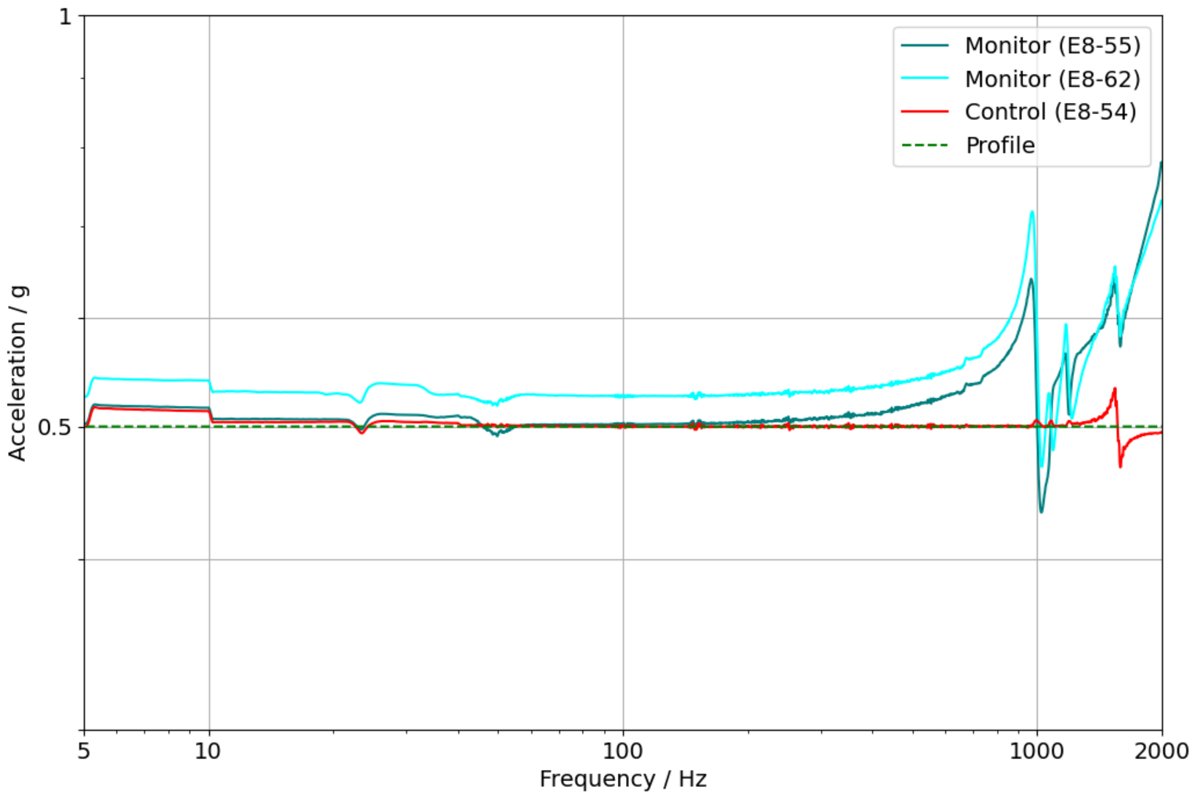


Figure 17: Results of the mounting fixture resonance search in the Y-axis

Subsequently, the battery module structural prototype was mounted to the vibration fixture, and a full resonance search was conducted for all three axes of excitation. The resonance search confirmed that:

- No resonances were detected below 125 Hz, satisfying the Vega-C launcher requirement of a minimum natural frequency of 115 Hz.
- A minor amplification was observed only in the Y-axis configuration, where a 0.5 g input was amplified to 1.0 g by the DUT. This amplification is minimal and not considered critical for structural integrity.

High sine and random vibration tests were then performed using the modified Vega-C profiles, as presented in Chapter 5. Following each test, a visual inspection of the DUT was performed while still mounted on the shaker, with photographs taken from each side. No visible signs of mechanical degradation, deformation, or fastener loosening were observed..

After completing the full test sequence in all three axes:

- Post-test resonance searches confirmed no significant frequency shifts when compared to the pre-test values. This indicates that the structure did not experience plastic deformation or joint loosening.
- The DUT maintained its integrity, suggesting that the prototype meets mechanical qualification standards for this stage of development.

It's important to remember that these tests were only done on the structural prototype, which did not include real batteries or electronics. Once the full version of the battery module is built, with the actual battery cells, heaters, electronics, and wiring, more tests will be performed. Adding around 80 to 85 grams of extra weight from the batteries is expected to make the module even more rigid, since the batteries have a strong metal casing. This could also help reduce vibrations

7 Conclusions and Future Work

This bachelor's thesis aimed to develop the structural prototype of the battery module for the SUTS mission and ensure its structural integrity by performing simulations and vibration testing. To achieve this goal, a market analysis was carried out on CubeSat standard battery modules to understand the engineering principles behind them. With the knowledge gathered from the market research, a design outline was formed to address the important design criteria.

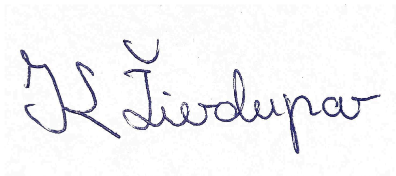
During the design process, static analysis and topology optimization techniques were used to create brackets that could survive the harshest launch conditions of the Vega-C launch vehicle. High sine and random vibration tests were conducted based on the SSMS Vega-C user manual at the Tartu Observatory laboratory of the University of Tartu, on the battery module’s structural prototype, to ensure the quality of the design. The structural prototype of the battery module successfully passed all the required vibration tests, demonstrating sufficient structural integrity for further development..

In future work, the battery module will be assembled in its entirety. To achieve that goal, additional research and testing will be conducted in spot welding to ensure high-quality welds. A separate market research will be conducted on flexible heaters to find a suitable candidate for our mission. The chosen batteries, heaters, and other electronic parts will be added to the tested battery module structural prototype.

Once the full qualification model is built, it will undergo a more comprehensive testing campaign. This will include high sine and random vibration tests, quasi-static load tests, shock testing, and thermal vacuum testing. Due to the constraints of the PocketQube standard, a modified version of the designed brackets will be used in the qualification model of the avionics stack.

Acknowledgements

The author of this thesis would like to deeply thank both of his supervisors. Thank you, Mari Allik, for always being positive, finding time when I came to bother, helping me with thesis writing, and giving me the opportunity to understand environmental tests in more depth. Thank you, Sergei Kuzmin, for giving me this opportunity to be part of the Student Satellite team, having great engineering insight to my questions and keeping me focused on the thesis.



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Appendix A: Technical Drawings

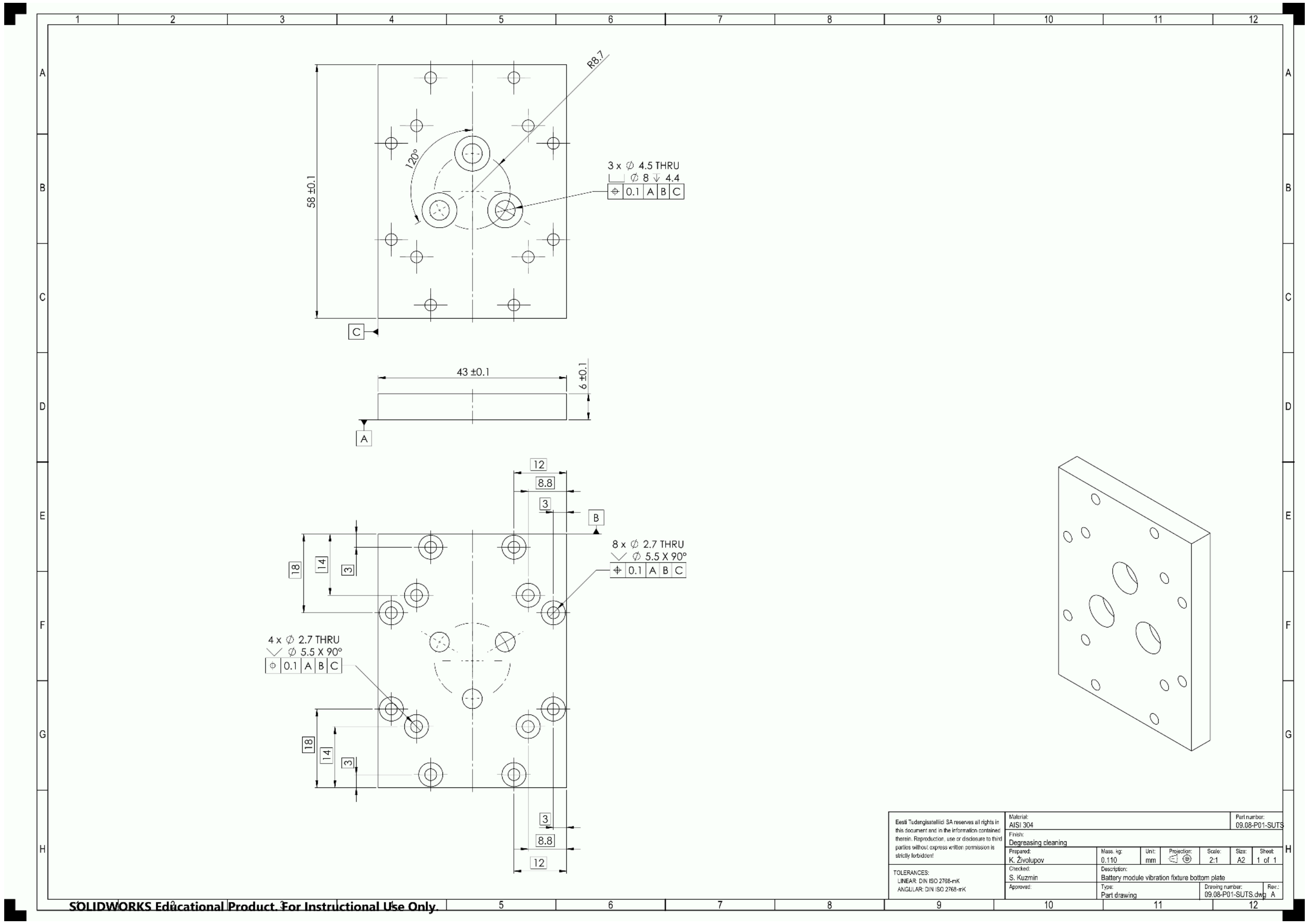

Figure 17: Technical drawing of part 09.08-P01-SUTS

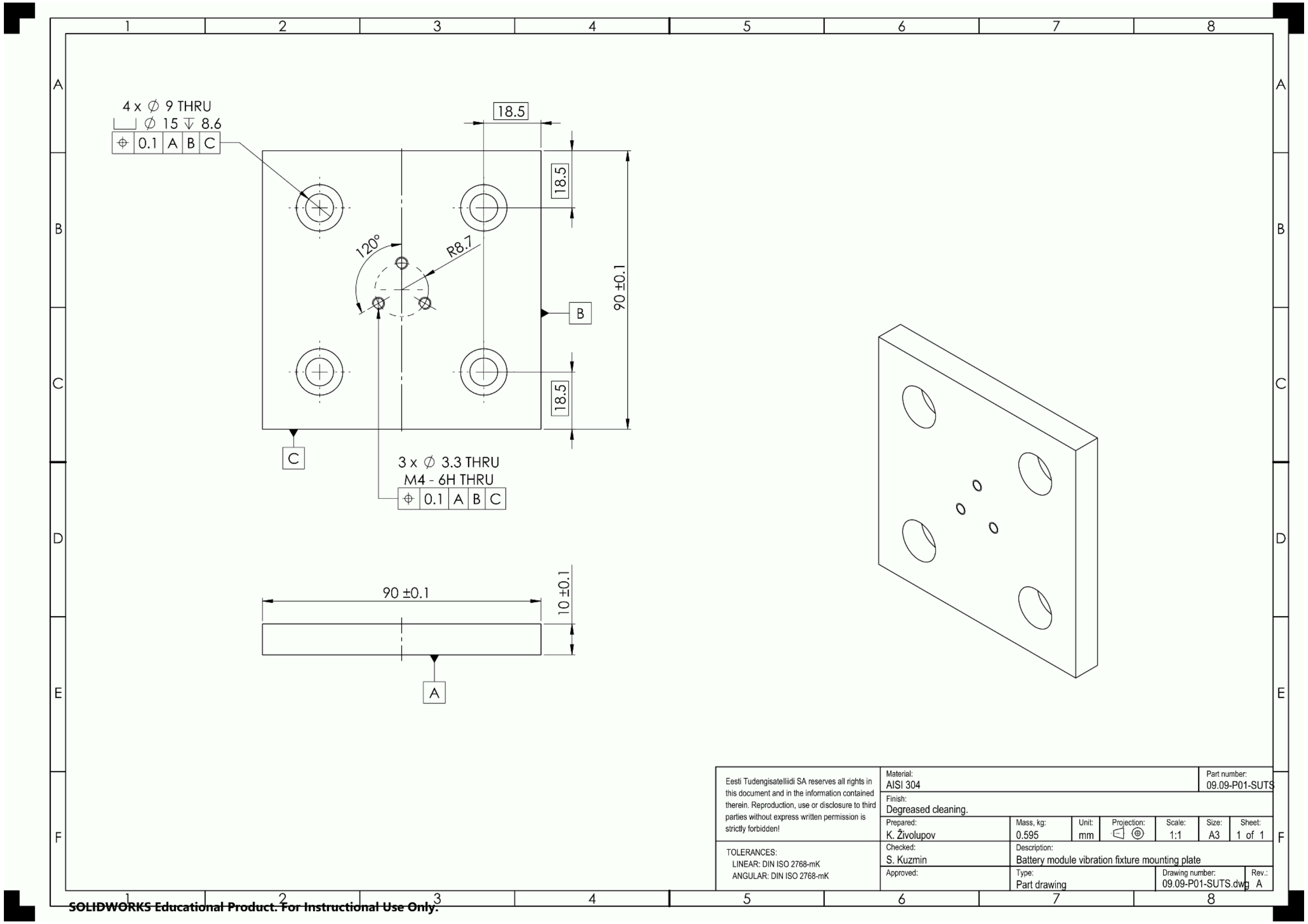

Figure 18: Technical drawing of part 09.09-P01-SUTS

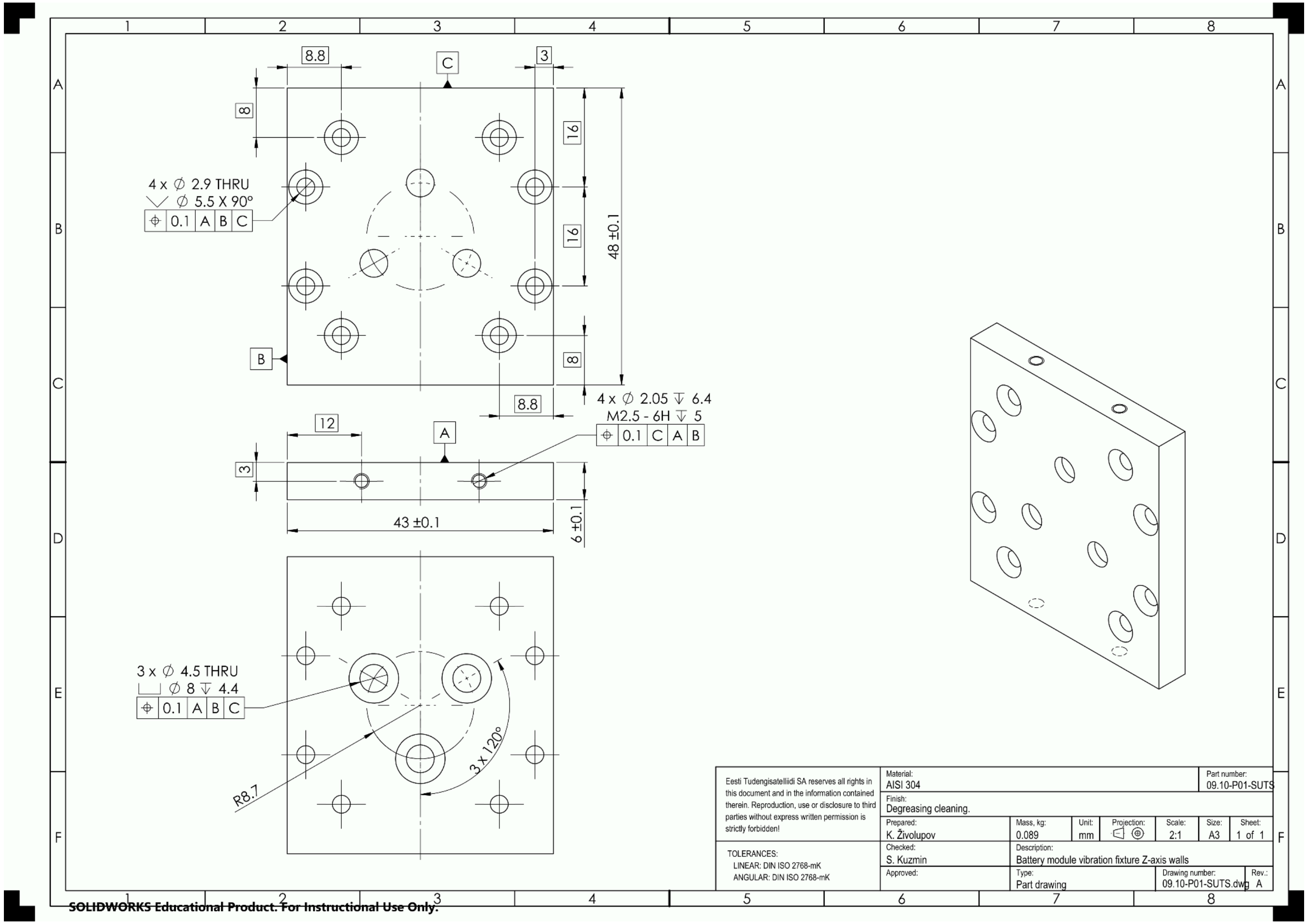

Figure 19: Technical drawing of part 09.10-P01-SUTS

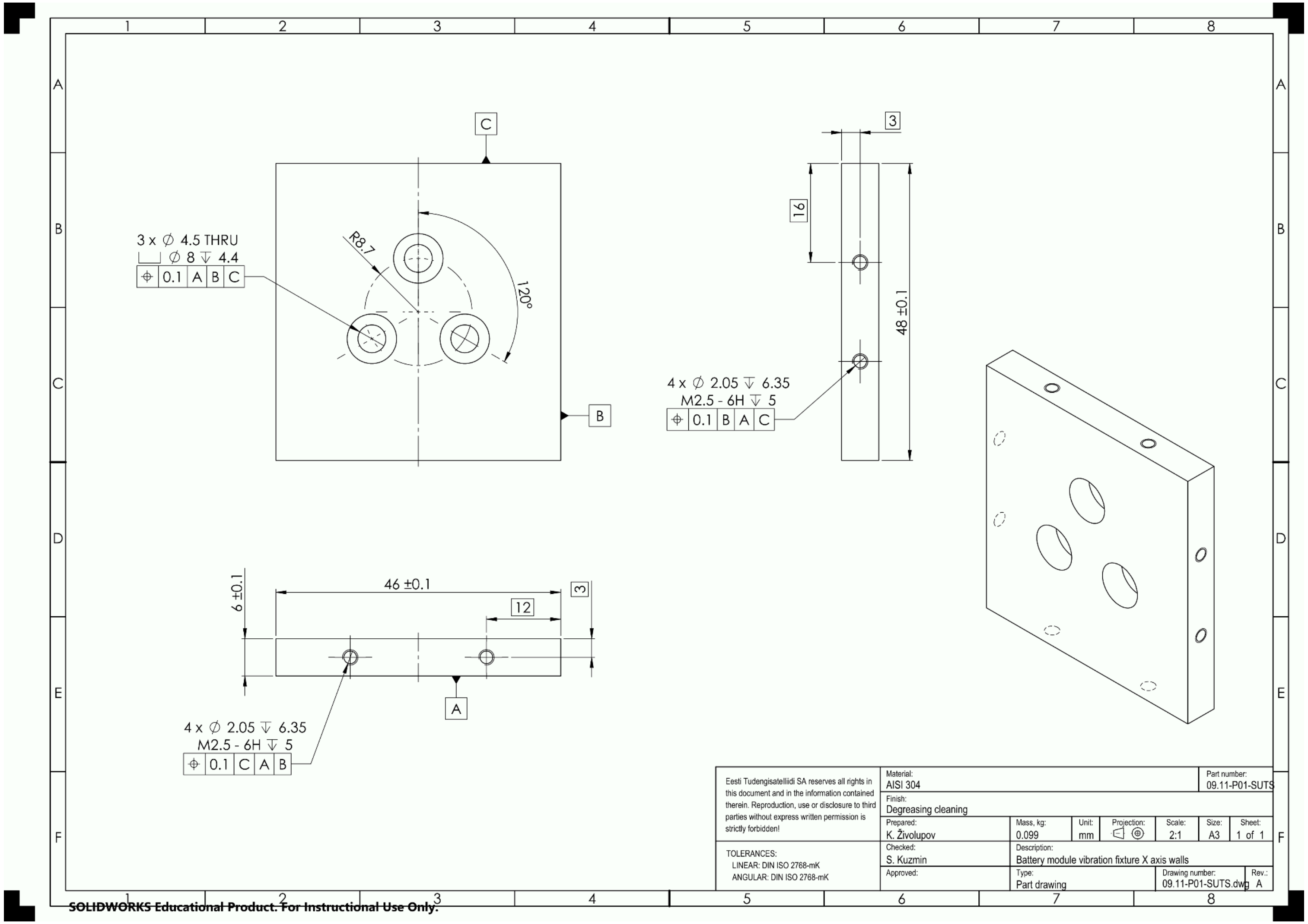

Figure 20: Technical drawing of part 09.11-P01-SUTS

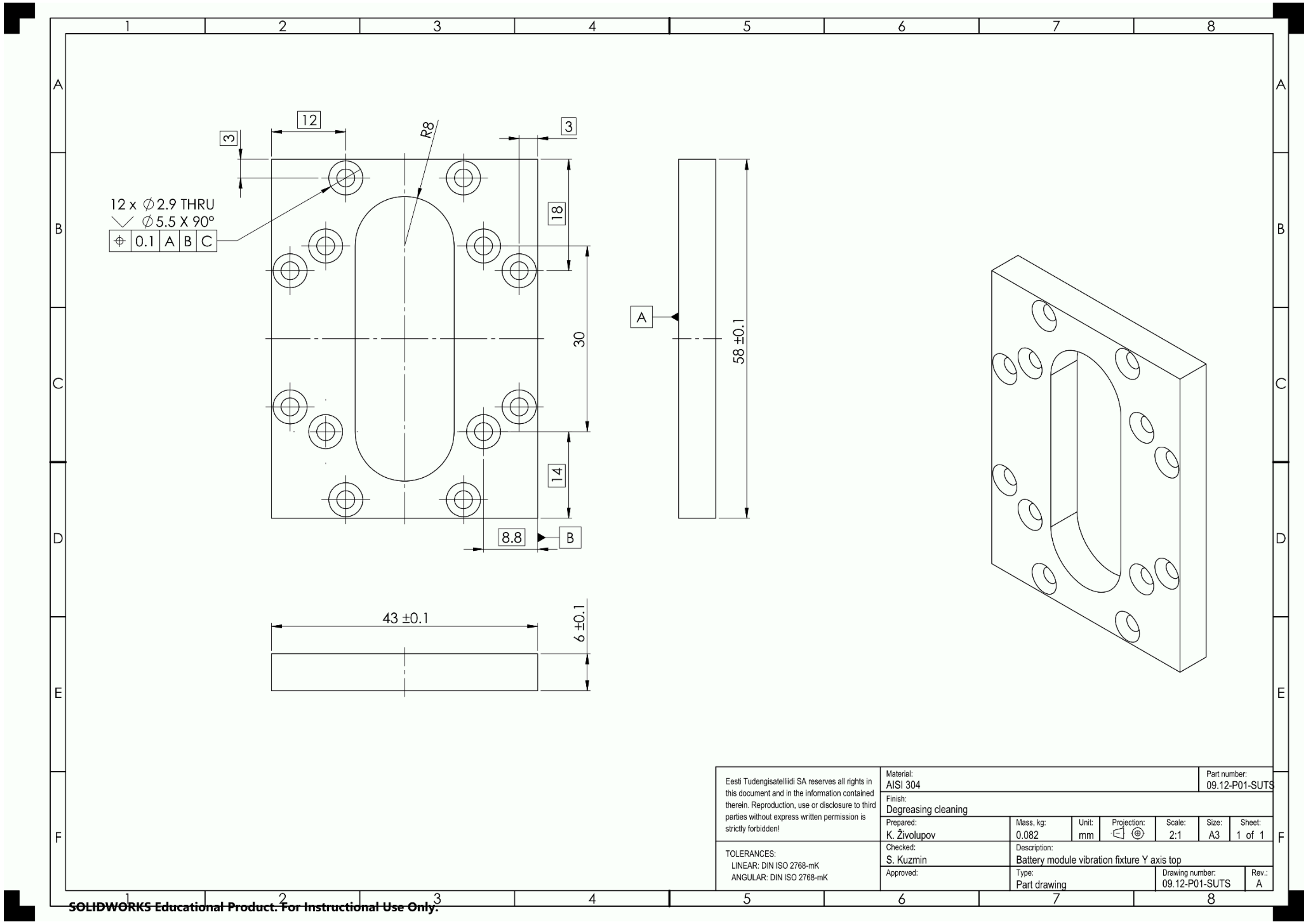

Figure 21: Technical drawing of part 09.12-P01-SUTS

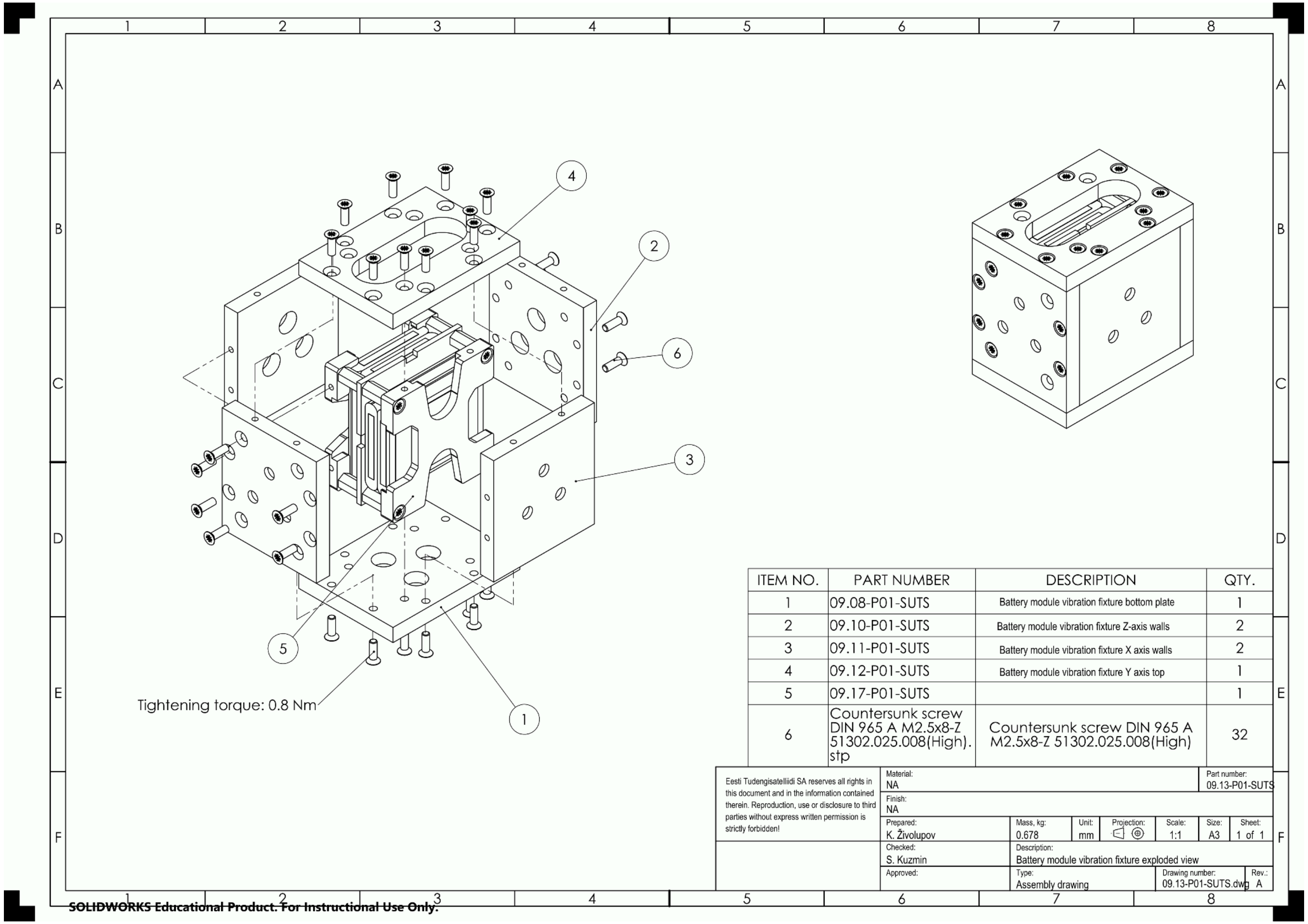

Figure 22: Technical drawing of vibration jig assembly 09.13-P01-SUTS

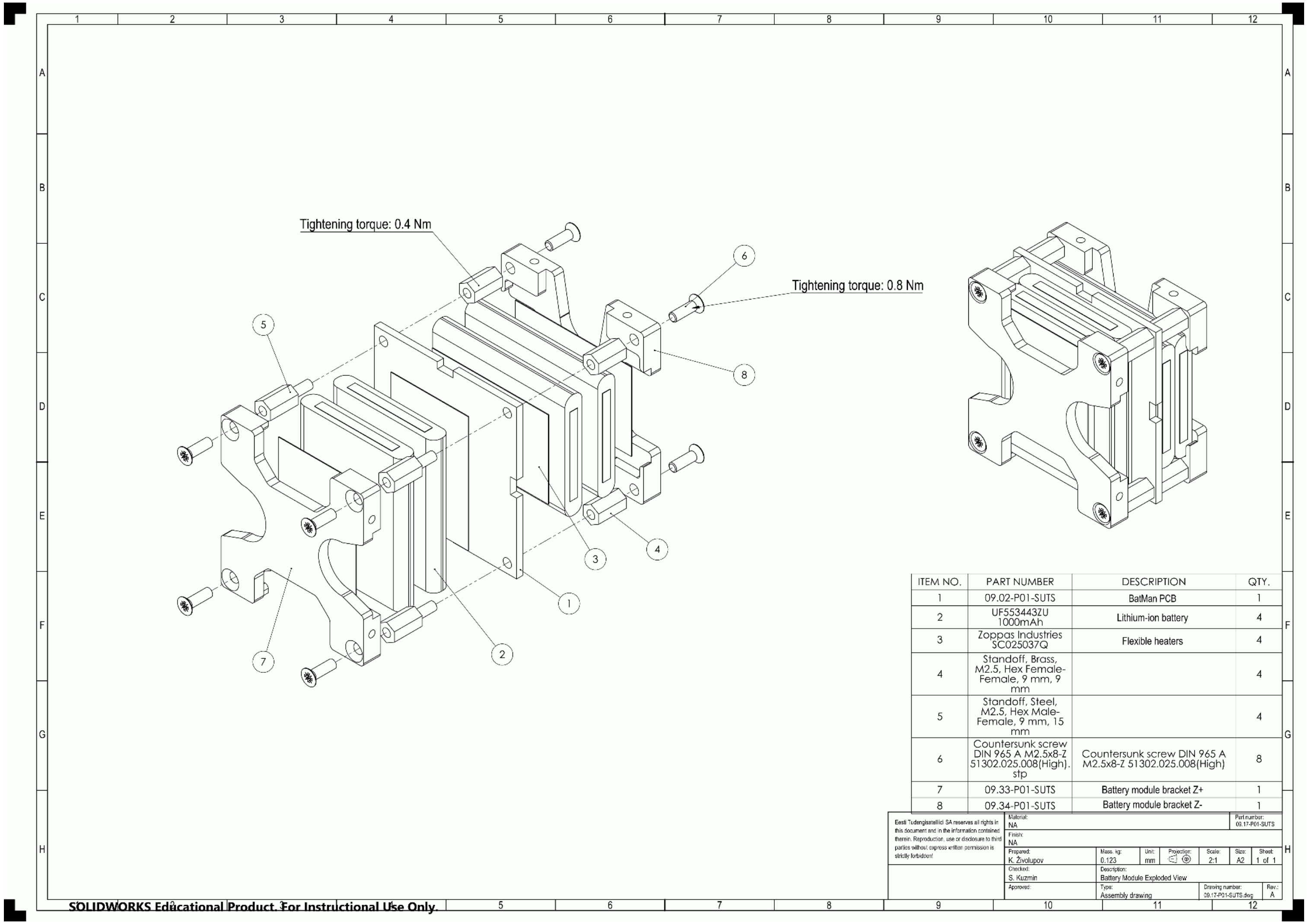

Figure 23: Technical drawing of battery module assembly 09.17-P01-SUTS

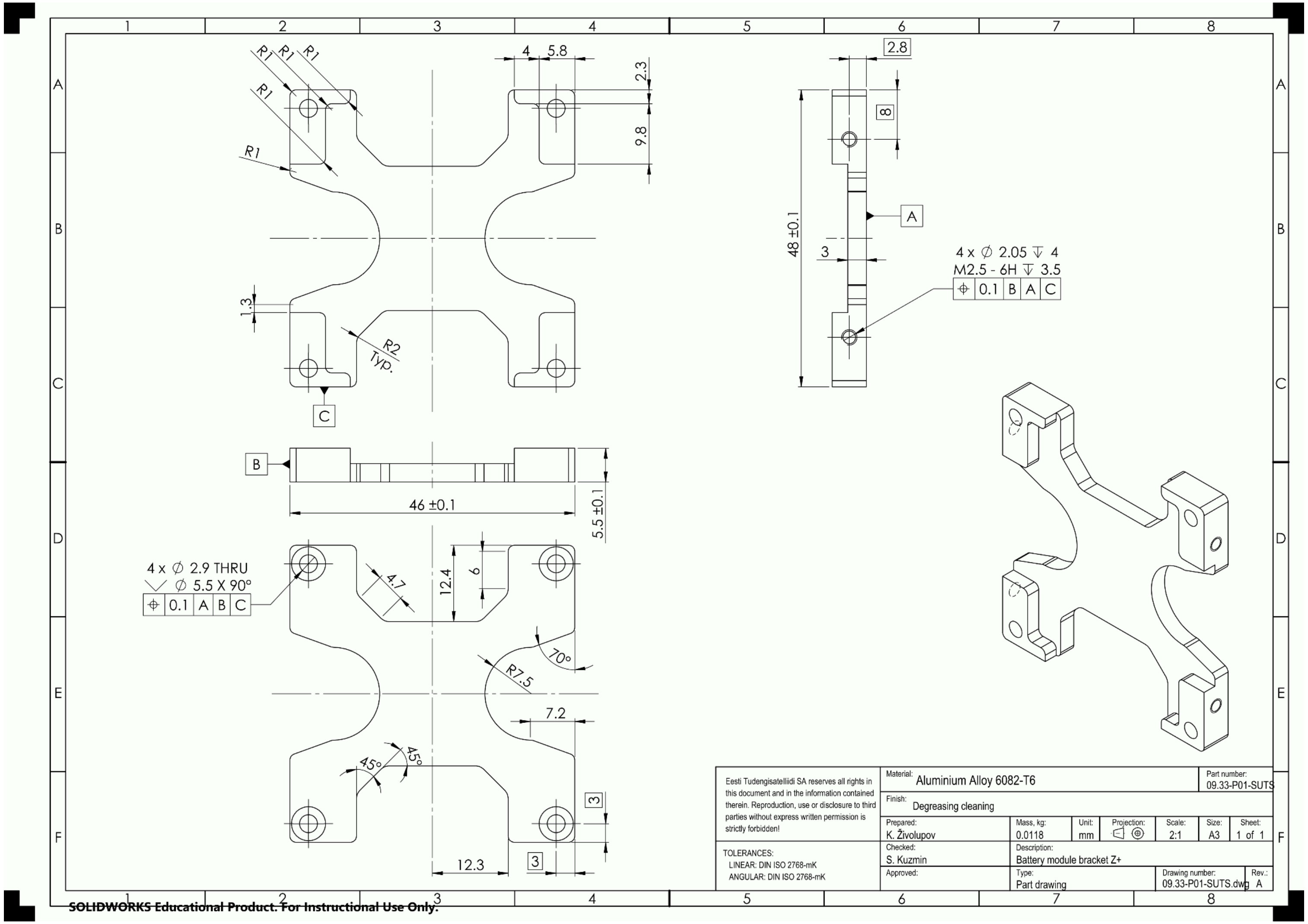

Figure 24: Technical drawing of part 09.33-P01-SUTS

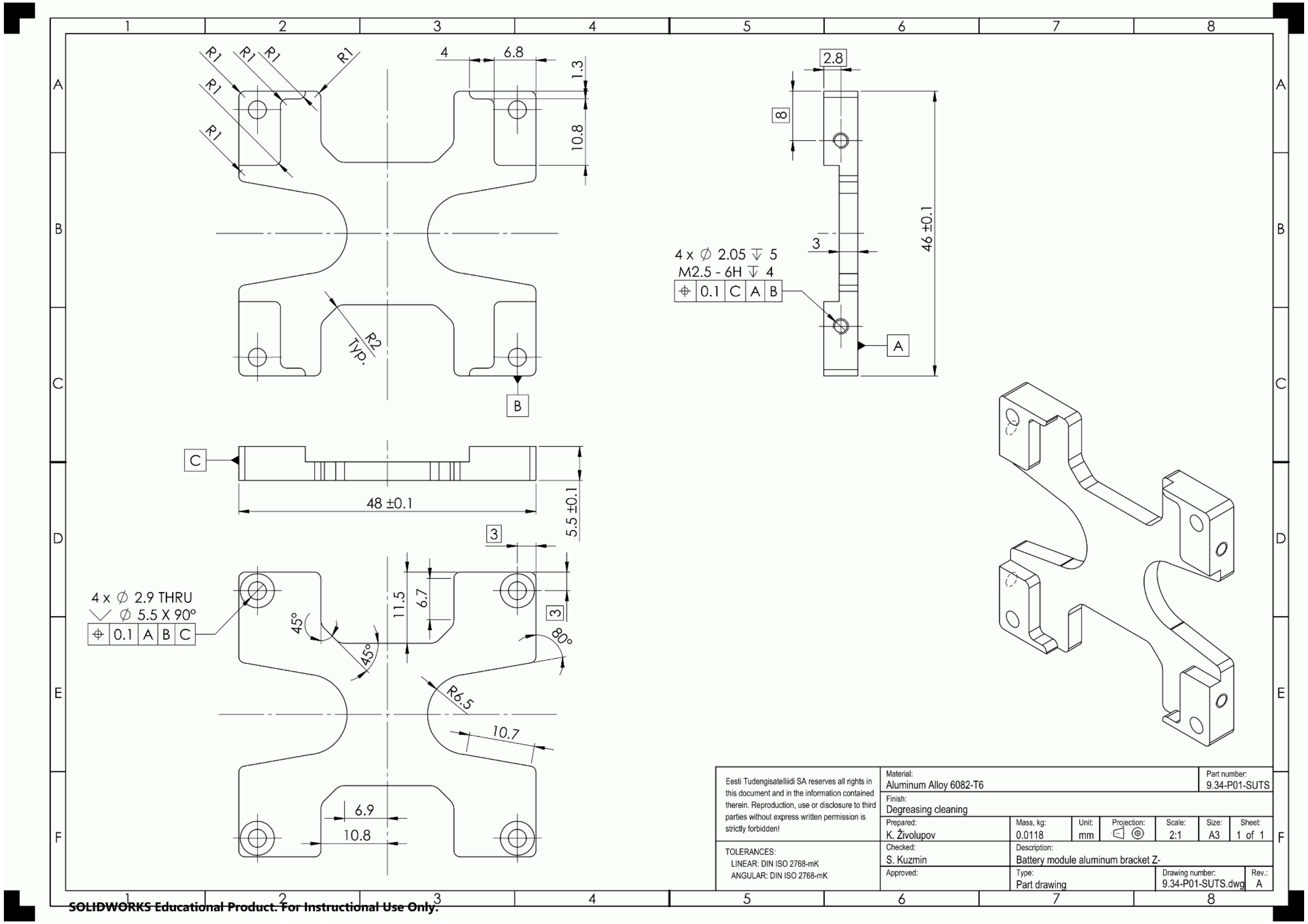

Figure 25: Technical drawing of part 09.34-P01-SUTS

Appendix B: Vibration Testing Certificate for the SUTS Battery Module Structural Prototype

KATSETUSTUNNISTUS

TESTING CERTIFICATE

EN ISO/IEC 17025
L151

Tunnistuse nr ja kuupäev: Certificate No and Date:	8-138-25 / 13.05.2025
Tellimuse nr ja kuupäev: Order No and Date:	8-011-25 / 05.05.2025
Tellija: Customer:	Eesti Tudengisatelliidi Sihtasutus, W. Ostwaldi tn1, 50411 Tartu
Objekt: Object:	SUTS Battery Module Structural Prototype
Katseobjekti(de) saabumine laborisse: Test object arrival:	13.05.2025
Katse(te) teostamise ajavahemik: Date of Tests:	13.05.2025
Kasutatud metoodika: Method used:	M801:15.10.2024 Vibration testing

Allkirjad:
Signatures:

Riho Vendt Kosmosetehnoloogia labori juhataja Head of Space Technology Laboratory	Mari Allik Koostaja(d) Compiled by

Dokument koosneb katsetustunnistusest ja – tulemuste kokkuvõttest 15 lehel ning on välja antud ühes (1) allkirjastatud eksemplaris.

The document consists of a Testing Certificate with a Summary of Results on 15 pages in one (1) signed copy

Kontakt/Contact: Mari Allik, +372 737 4501, mari.allik@ut.ee
TÜ katsekoja kosmosetehnoloogia labor / Testing Centre of UT, Laboratory of Space Technology
Tartu Ülikooli Tartu observatoorium / Tartu Observatory of University of Tartu
Observatooriumi 1, 61602 Tõravere, Estonia

1. Testing equipment

1. Vibration controller Brüel & Kjær Type 7541 S/N 1302400 (E8-04), calibrated 28.01.2025,
2. PCB Piezotronics ICP accelerometer 352C04 S/N LW382685 (E8-54), calibrated 19.01.2024,
3. PCB Piezotronics ICP accelerometer 352C04 S/N LW382696 (E8-55), calibrated 19.01.2024,
4. PCB Piezotronics triaxial accelerometer 356A43 S/N LW353388 (E8-62), calibrated 29.11.2024,
5. Power amplifier LDS PA1000L S/N N1525 6678890,
6. Field power supply LDS FPS 10L-CE S/N N1449,
7. LDS V-650 Air Cooled Vibrator S/N 308257/1.

2. Traceability

The measurement results are traceable to the units of SI through the measurement standards of ISO 17025 accredited laboratories: National Metrology Institute Metrosert, Estonia (voltage), RISE, Sweden (acceleration), and PCB Piezotronics Inc. Laboratory, USA (acceleration).

3. Description of the test object

The device under test (DUT), the Battery Module Structural Prototype, is depicted in Figures 3.1...3.3.

The DUT fixture was attached to the air-cooled vibrator with four M8 bolts. The placement of the controller feedback (E8-54) and monitor accelerometers (E8-62 and E8-55) for the different axis vibration tests can be seen in Figures 3.1...3.3.

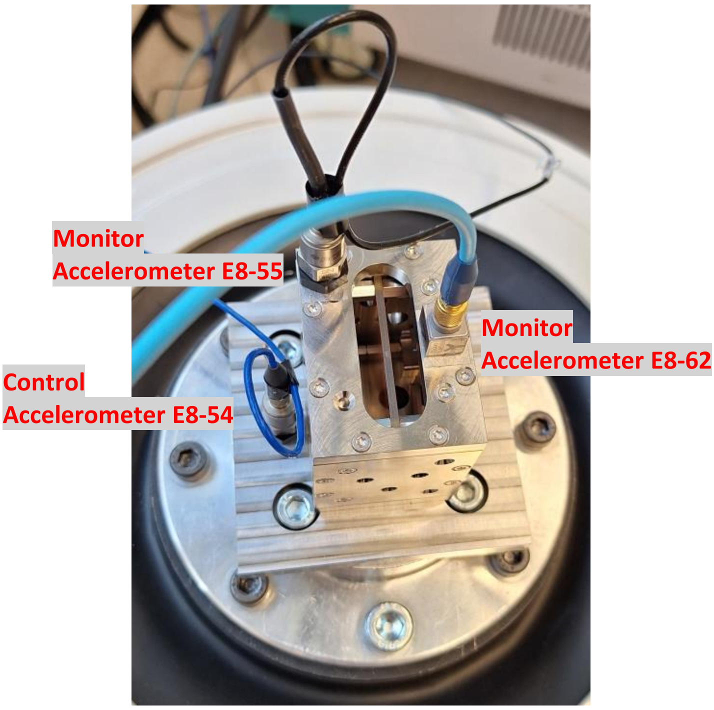

Figure 3.1. Setup for the Y-axis vibration tests.

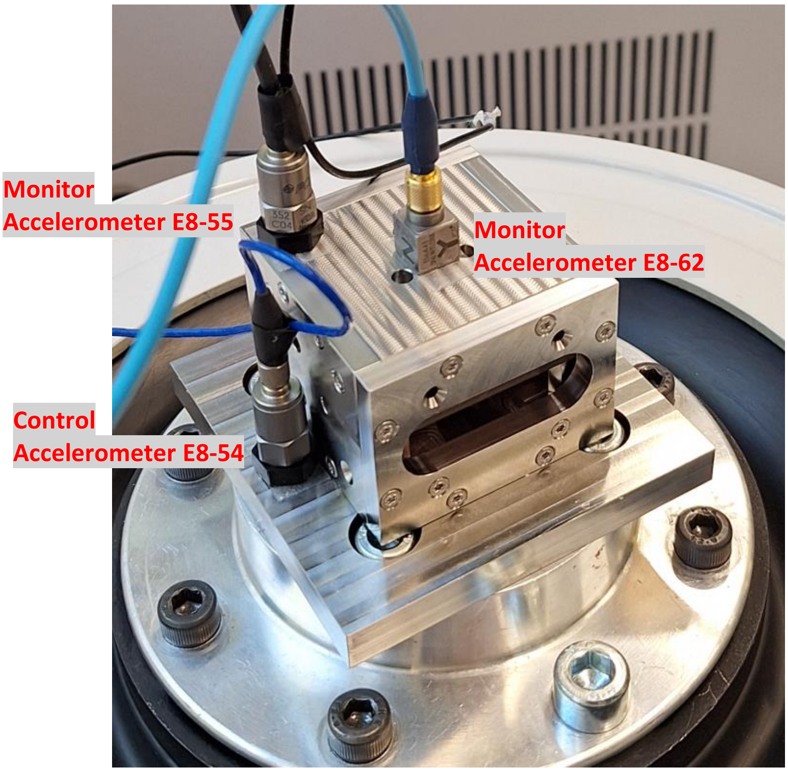

Figure 3.2. Setup for the X-axis vibration tests.

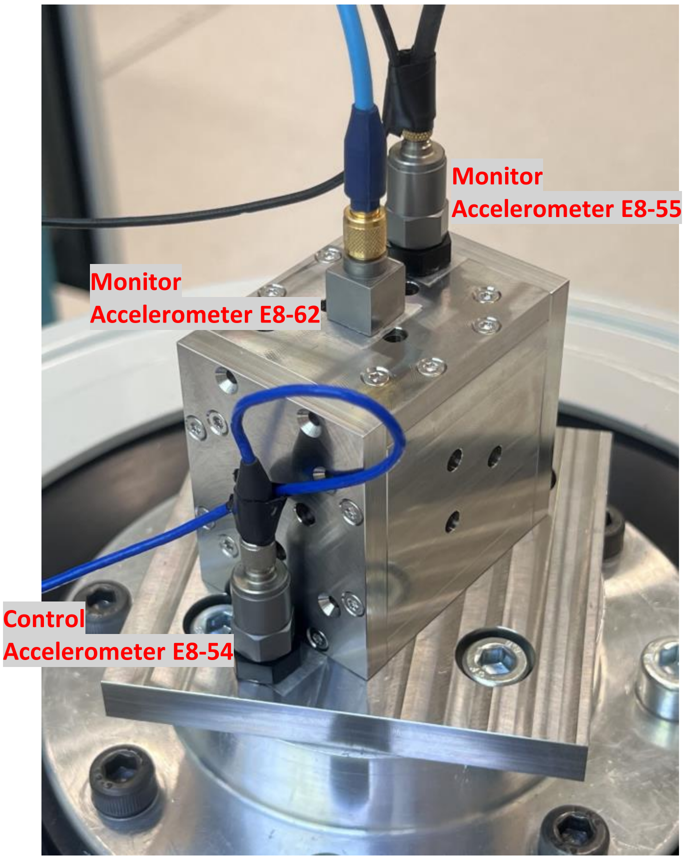

Figure 3.3. Setup for the Z-axis vibration tests.

4. Test method

Vibration testing was performed according to the test procedure M801:15.10.2024 Vibration testing, following the standard ECSS-E-ST-10-03C (2022).

4.1 Control method and strategy

The vibration tests were performed using a single-channel control strategy. The signal from the control accelerometer at the reference points (see Figures 3.1 to 3.3) is used to maintain the specified vibration levels.

The parameters used for the reference sine and high sine vibration tests are presented in Table 4.1. The parameters used for the random vibration tests are presented in Table 4.2.

Table 4.1. Parameters set for the sinusoidal vibration tests.

Parameter	Value
Control strategy	Single channel, closed loop
Measurement strategy	Proportional filter
Bandwidth	25%

Table 4.2. Parameters set for the random vibration tests.

Parameter	Value
Control strategy	Single channel, closed loop
Number of frequency lines	400
Degrees of freedom	64
Sigma clipping (crest factor)	5
Frequency resolution	2.5 Hz

4.2 Test severities

The vibration profiles and test severities are presented in Tables 4.3 to 4.5. The frequency resolution is 2.5 Hz for the random vibration tests.

PSD (power spectral density) describes the random vibration profile and test results. G_{RMS} (root mean square acceleration) describes the average power distributed across the frequency spectrum.

Table 4.3. Reference sine sweep profile.

Frequency / Hz	Acceleration / g*	High Abort / dB	Low Abort / dB
5	0.5	6	-6
2000	0.5	6	-6

* In this report, the non-standard unit “g” is used to represent an acceleration with a magnitude of ~9.81 m/s^2 (i.e. the Earth’s gravitational acceleration).

Table 4.4. High sine vibration profile.

Frequency / Hz	Acceleration / g*
5	1
15	2.5
70	1.25
110	1.25
125	1.25

Table 4.5. Random vibration profile.

Frequency / Hz	PSD / g^{*2} / Hz	High Abort / dB	Low Abort / dB
20	0.071	3	-3
150	0.071		
200	0.0563		
270	0.0563		
300	0.1		
400	0.1		
450	0.0563		
1000	0.034		
2000	0.0293		
G_{RMS}	8.8 g*		

5. Results

The test log of the vibration tests is presented in Table 5.1. The results, measurements from the controller feedback (E8-54), and monitor (E8-55 and E8-62) accelerometers are presented in Figures 5.1…5.18.

The alarm limits included in Figures 5.6, 5.12, and 5.18 are applied to the controller feedback (E8-54) accelerometer and are not limits of the monitor accelerometers' (E8-55 and E8-62) measurements.

Table 5.1 Test log of the vibration tests

Run No.	Frequency range / Hz	Test description	Test duration	Comments
1	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine before the Y-axis high sine vibration test
2	5…125	High sine	2 oct / min	Y-axis high sine vibration test
3	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine after the Y-axis high sine/before random vibration test
4	20…2000	Random vibration	1 min	Y-axis random vibration test
5	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine after the Y-axis random vibration test
6	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine before the X-axis high sine vibration test

7	5…125	High sine	2 oct / min	X-axis high sine vibration test
8	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine after the X-axis high sine/before random vibration test
9	20…2000	Random vibration	1 min	X-axis random vibration test
10	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine after the X-axis random vibration test
11	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine before the Z-axis high sine vibration test
12	5…125	High sine	2 oct / min	Z-axis high sine vibration test
13	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine after the Z-axis high sine/before random vibration test
14	20…2000	Random vibration	1 min	Z-axis random vibration test
15	5…2000	Reference sine (0.5 g* load)	2 oct / min	Reference sine after the Z-axis random vibration test

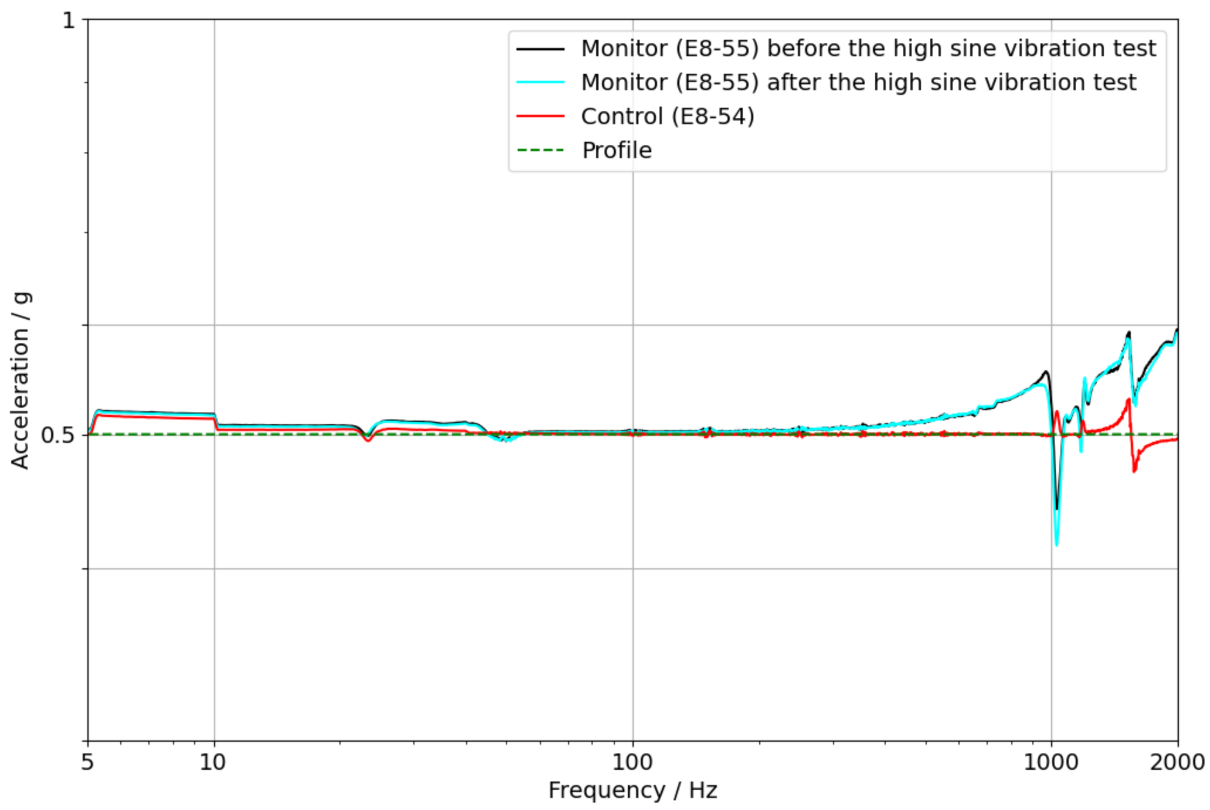

Figure 5.1. E8-55 reference sine vibration tests before and after the Y-axis high sine vibration test (runs 1 & 3).

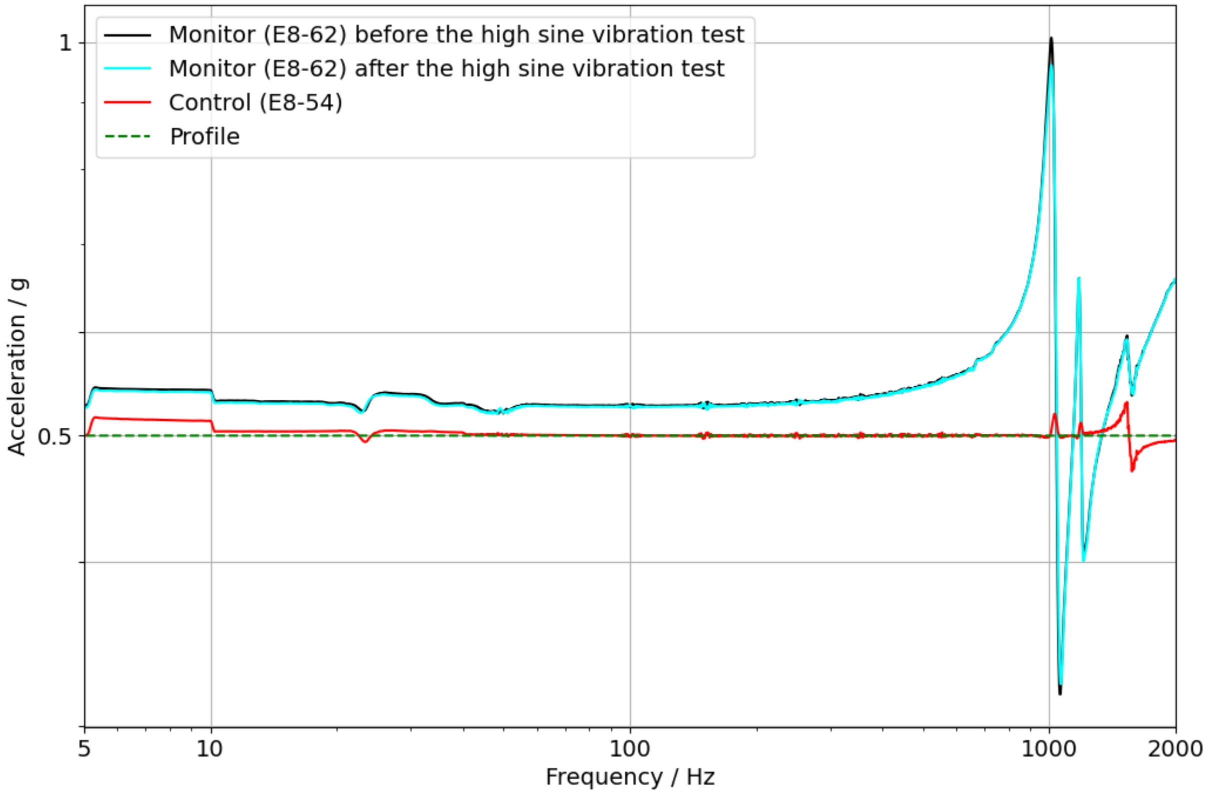

Figure 5.2. E8-62 reference sine vibration tests before and after the Y-axis high sine vibration test (runs 1 & 3).

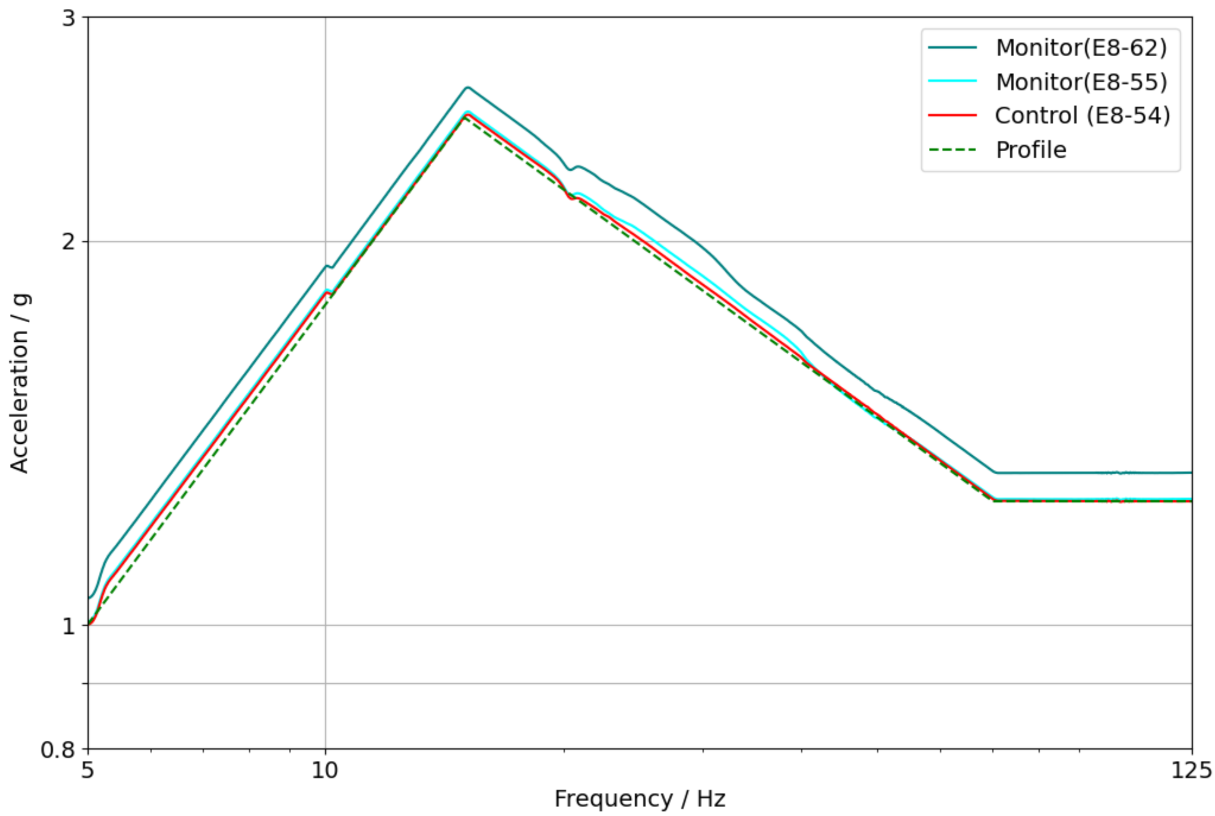

Figure 5.3. Y-axis high sine vibration test (run 2).

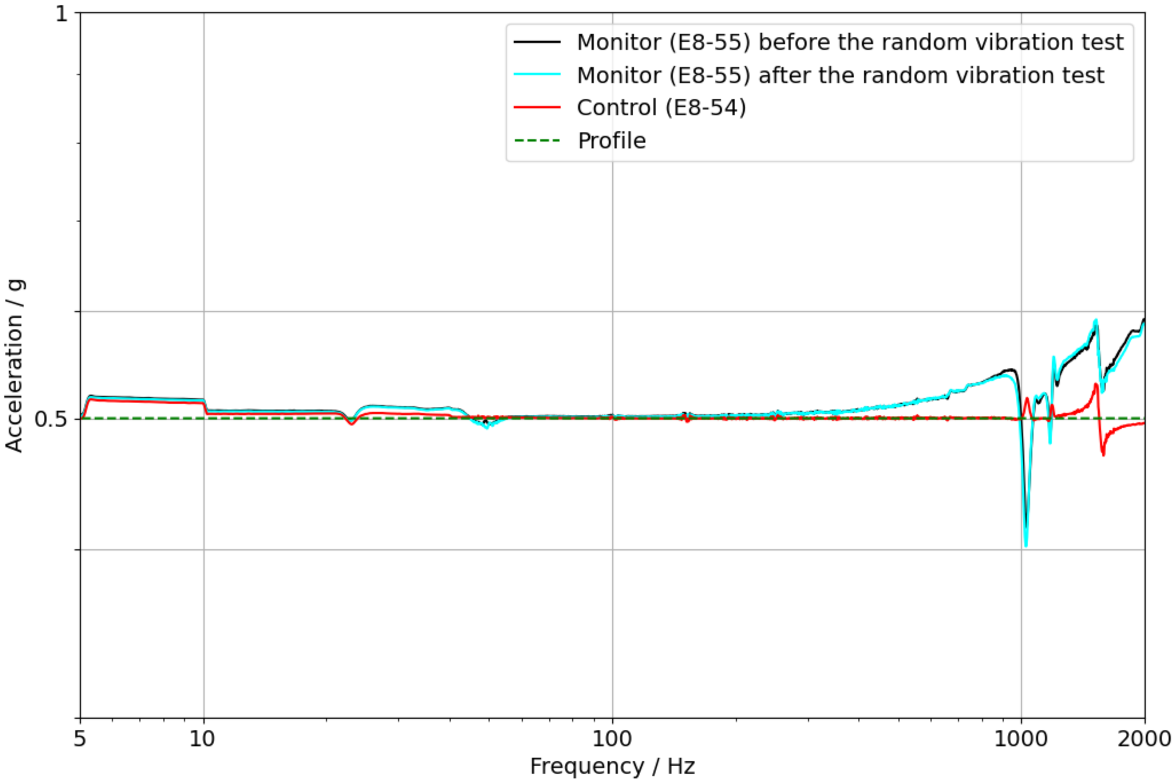

Figure 5.4. E8-55 Reference sine vibration tests before and after the y-axis random vibration test (runs 3 & 5).

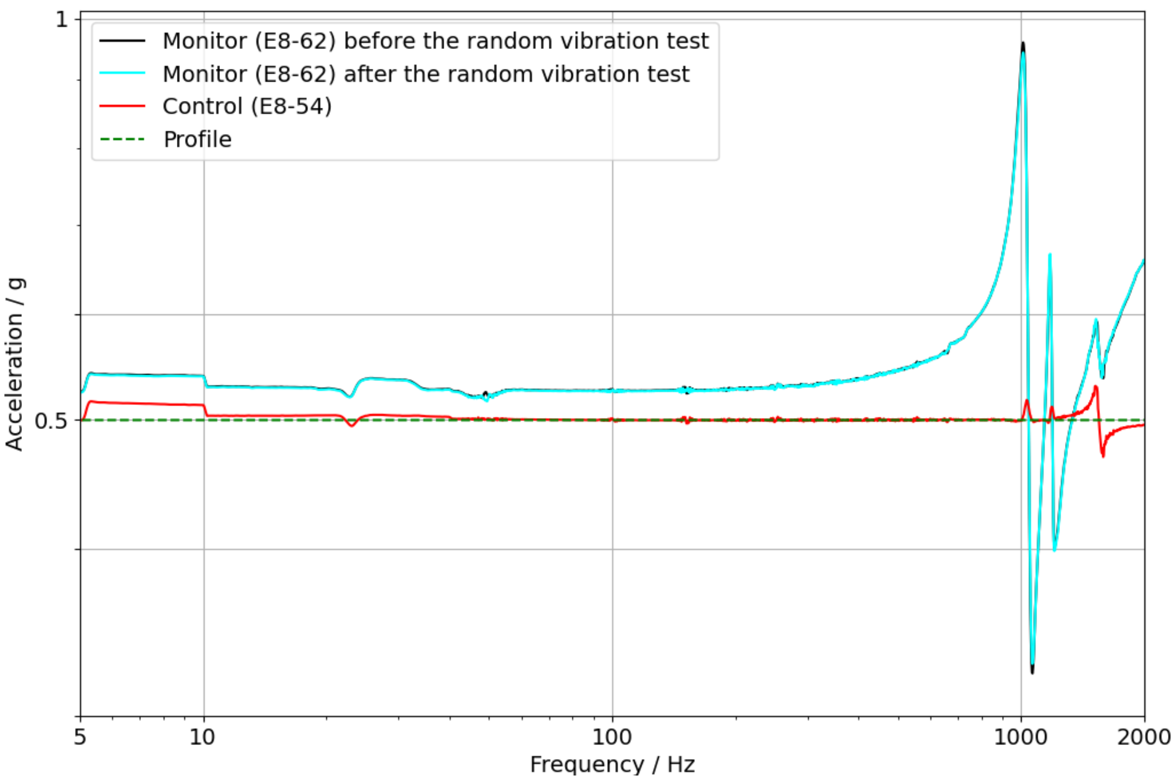

Figure 5.5. E8-62 Reference sine vibration tests before and after the y-axis random vibration test (runs 3 & 5).

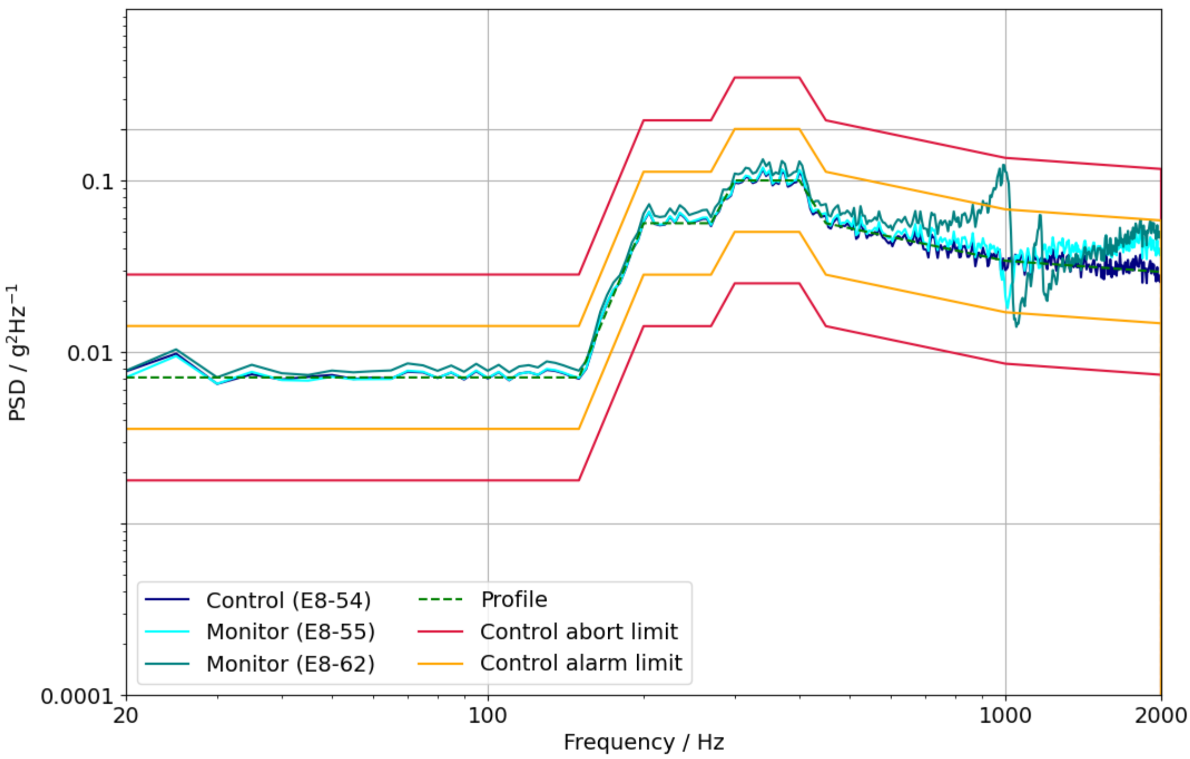

Figure 5.6. Y-axis random vibration test (run 4).

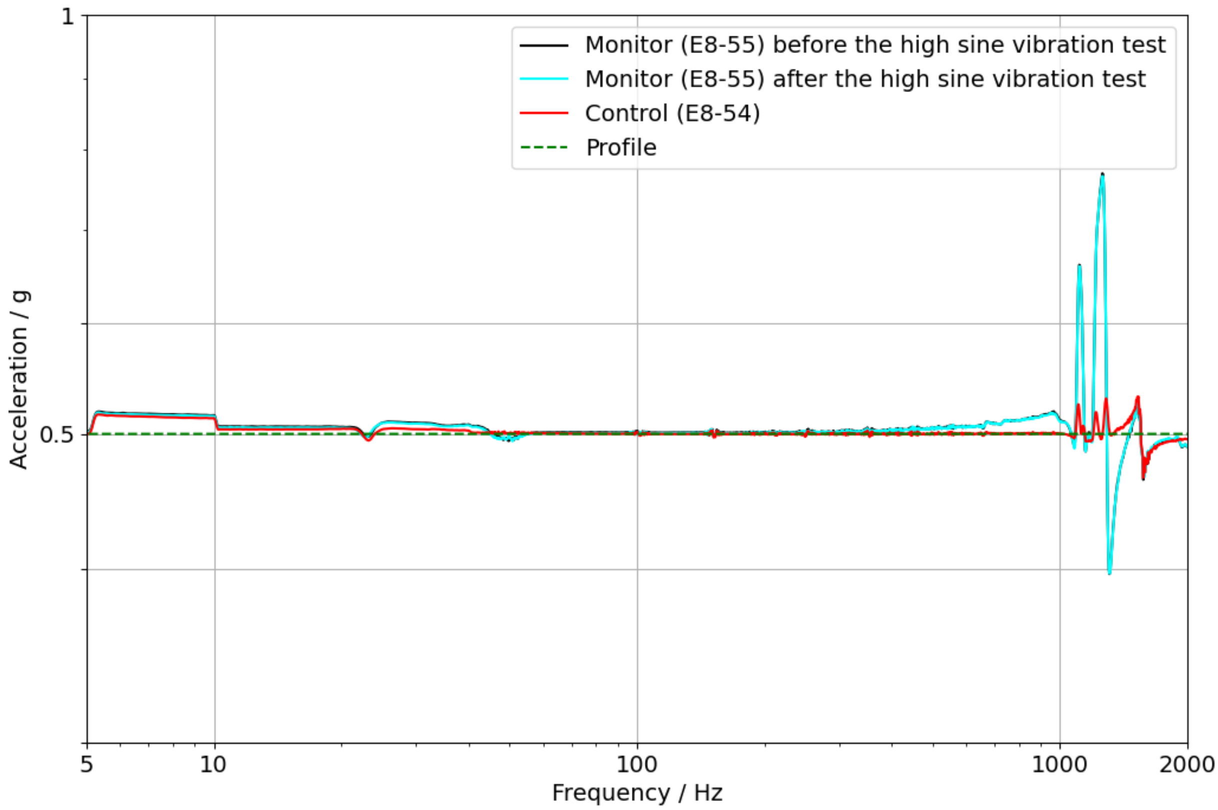

Figure 5.7. E8-55 reference sine vibration tests before and after the X-axis high sine vibration test (runs 6 & 8).

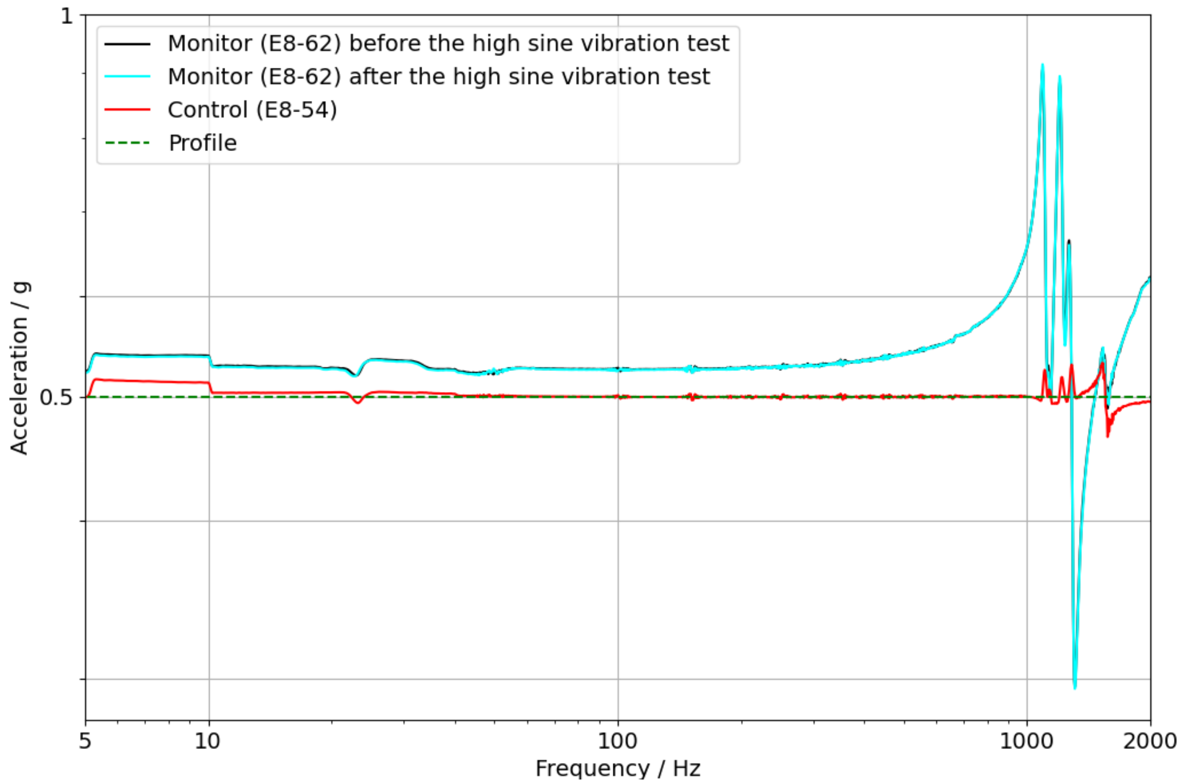

Figure 5.8. E8-62 reference sine vibration tests before and after the X-axis high sine vibration test (runs 6 & 8).

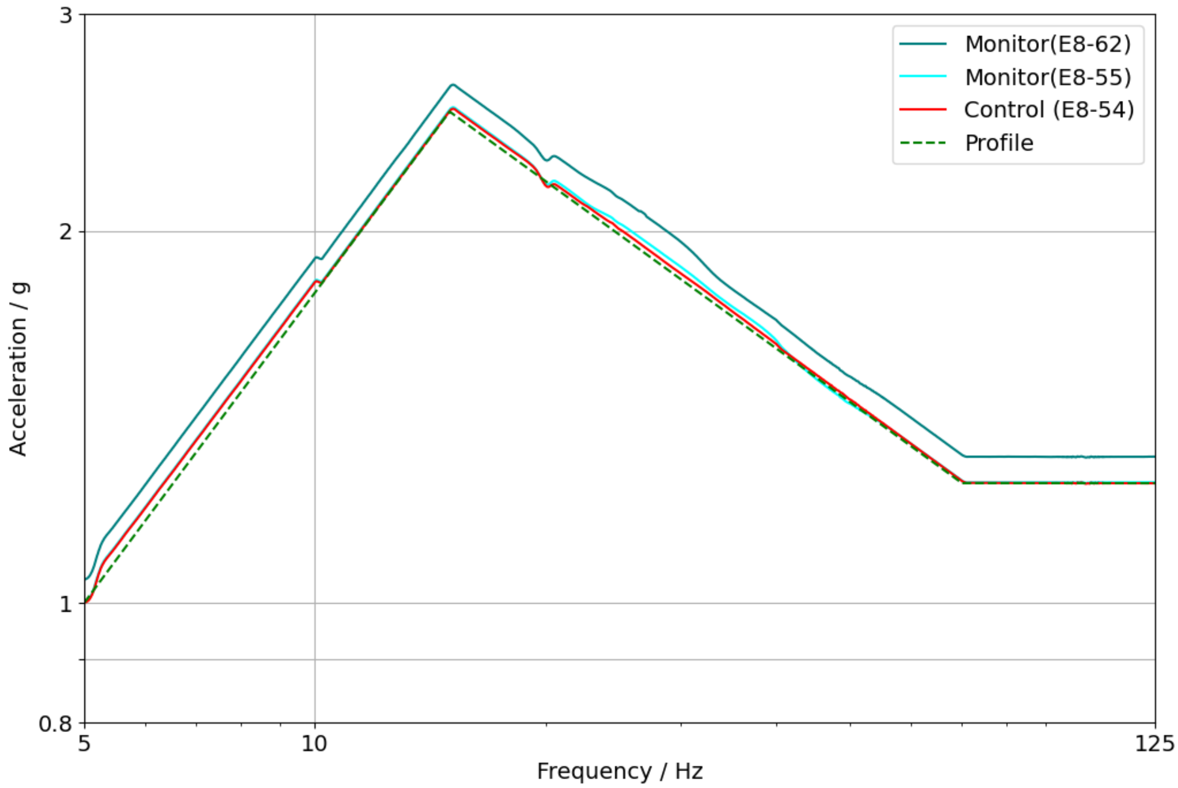

Figure 5.9. X-axis high sine vibration test (run 7).

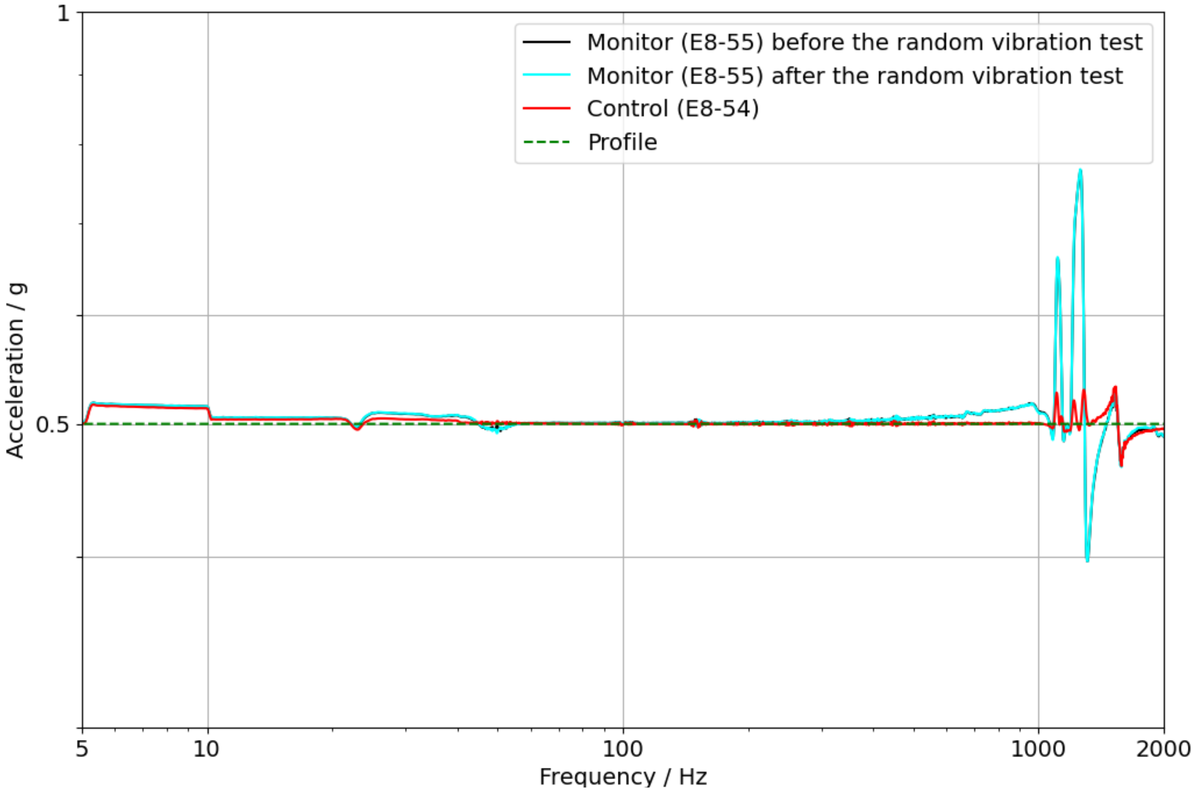

Figure 5.10. E8-55 reference sine vibration tests before and after the X-axis random vibration test (runs 8 & 10).

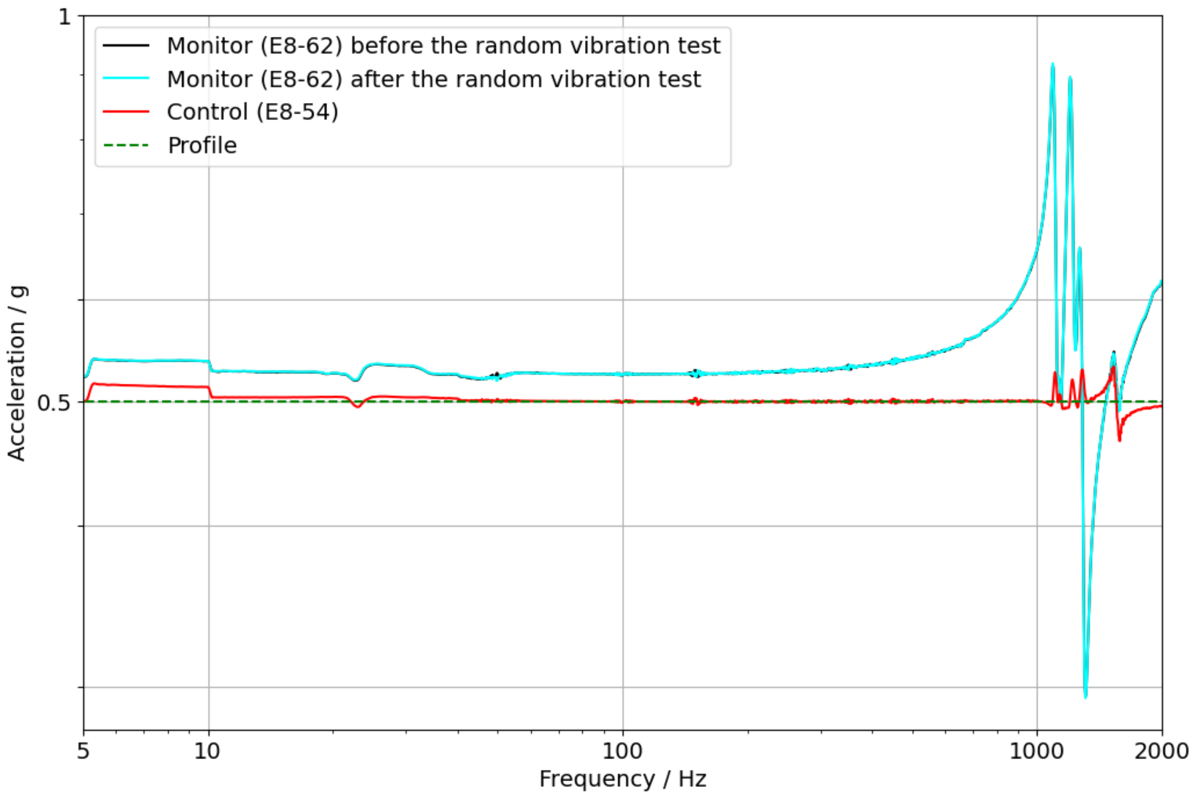

Figure 5.11. E8-62 reference sine vibration tests before and after the X-axis random vibration test (runs 8 & 10).

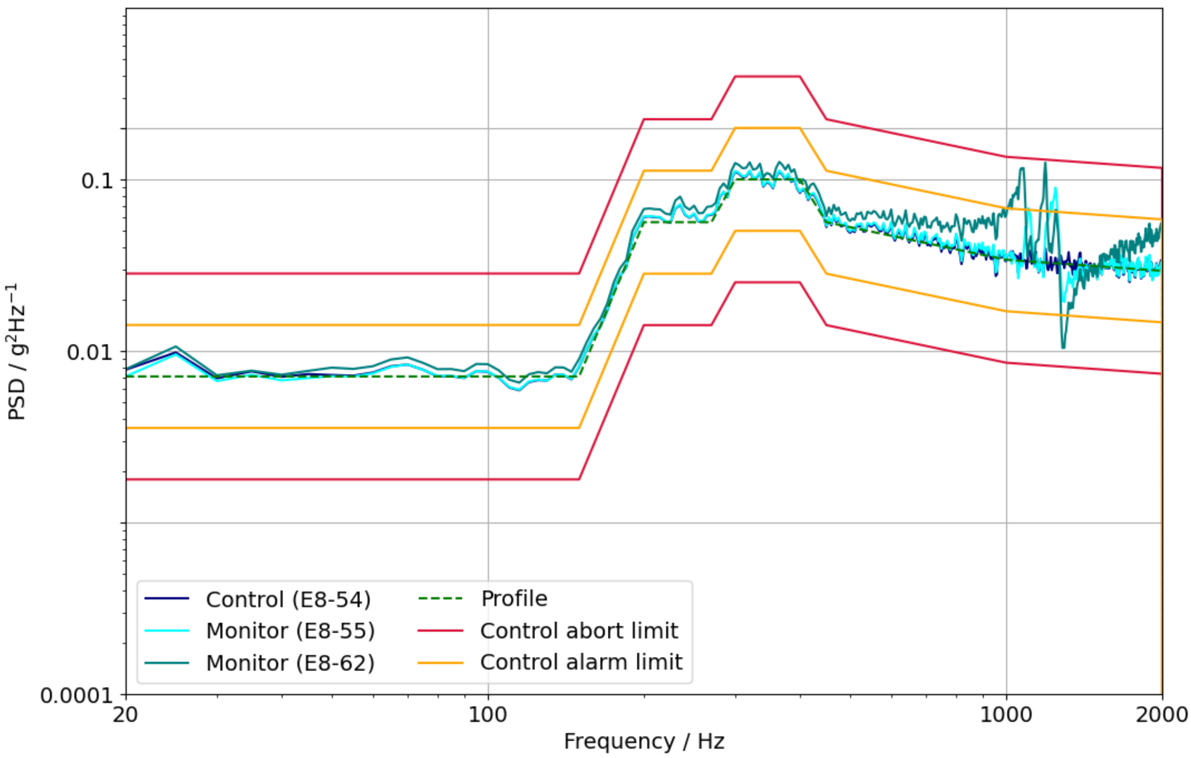

Figure 5.12. X-axis random vibration test (run 9).

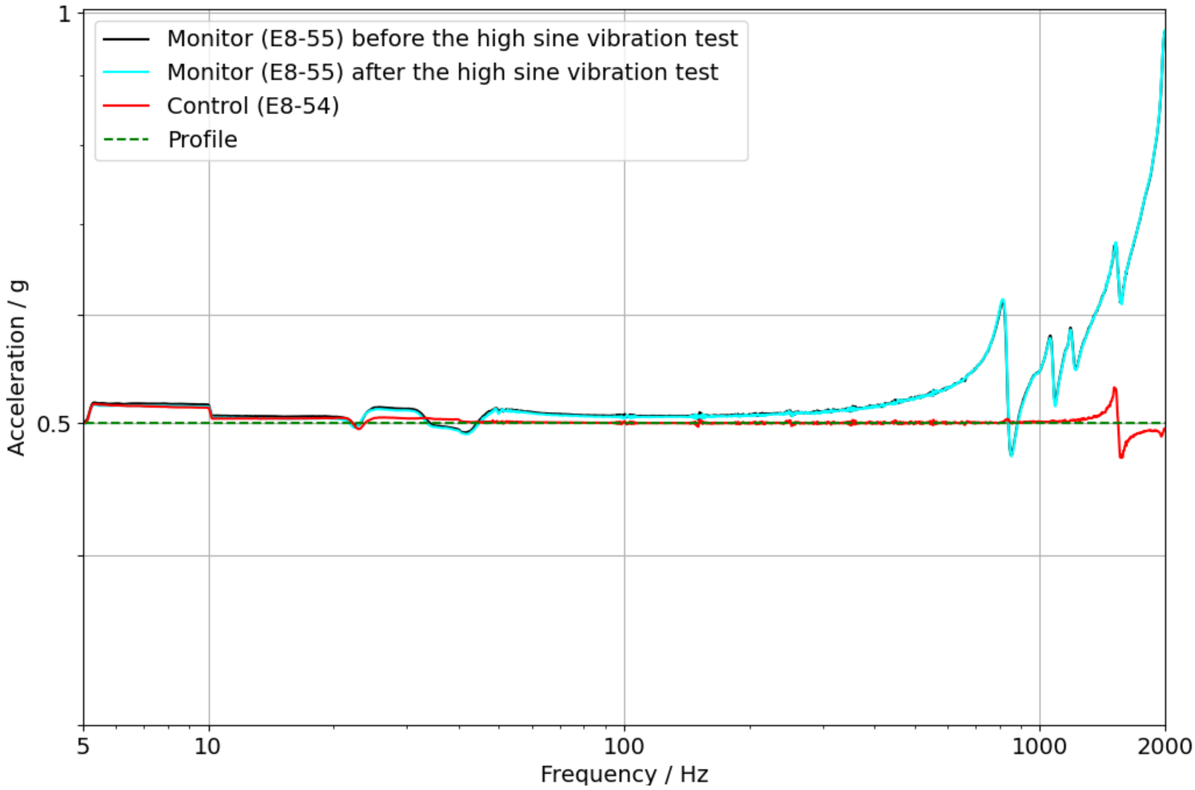

Figure 5.13. E8-55 reference sine vibration tests before and after the Z-axis high sine vibration test (runs 11 & 13).

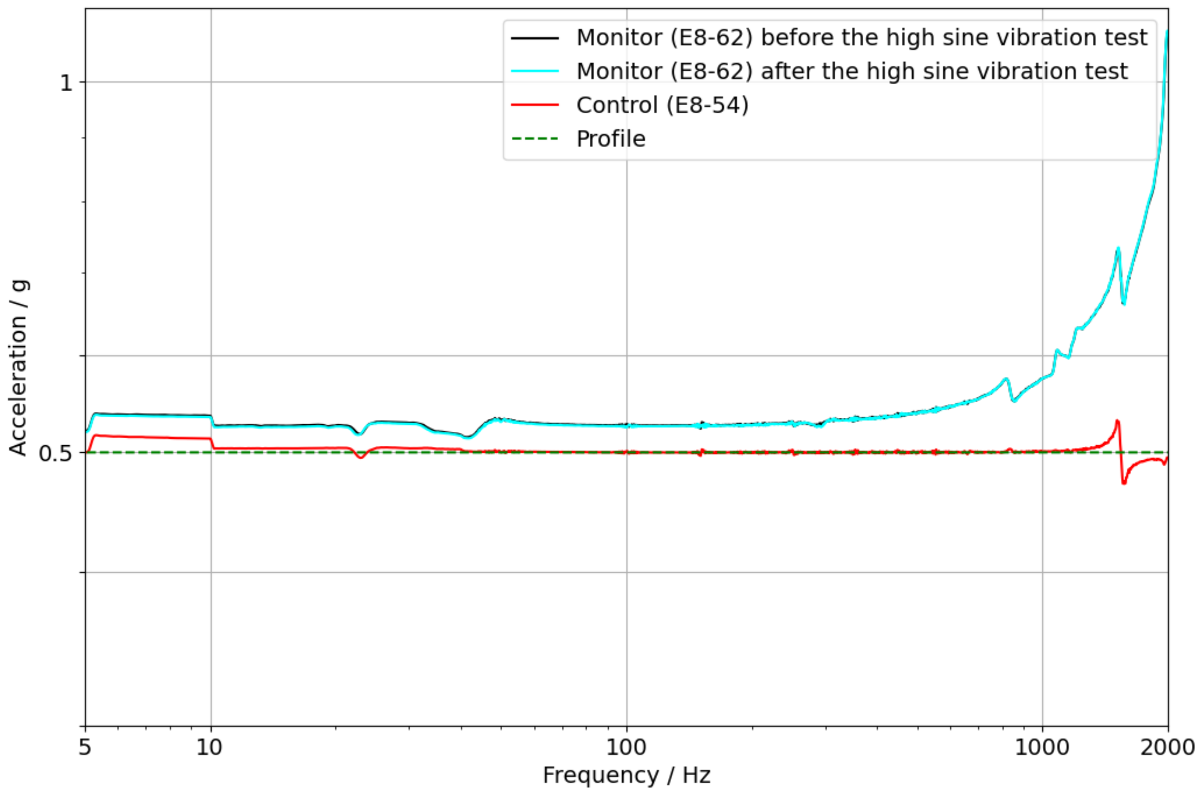

Figure 5.14. E8-62 reference sine vibration tests before and after the Z-axis high sine vibration test (runs 11 & 13).

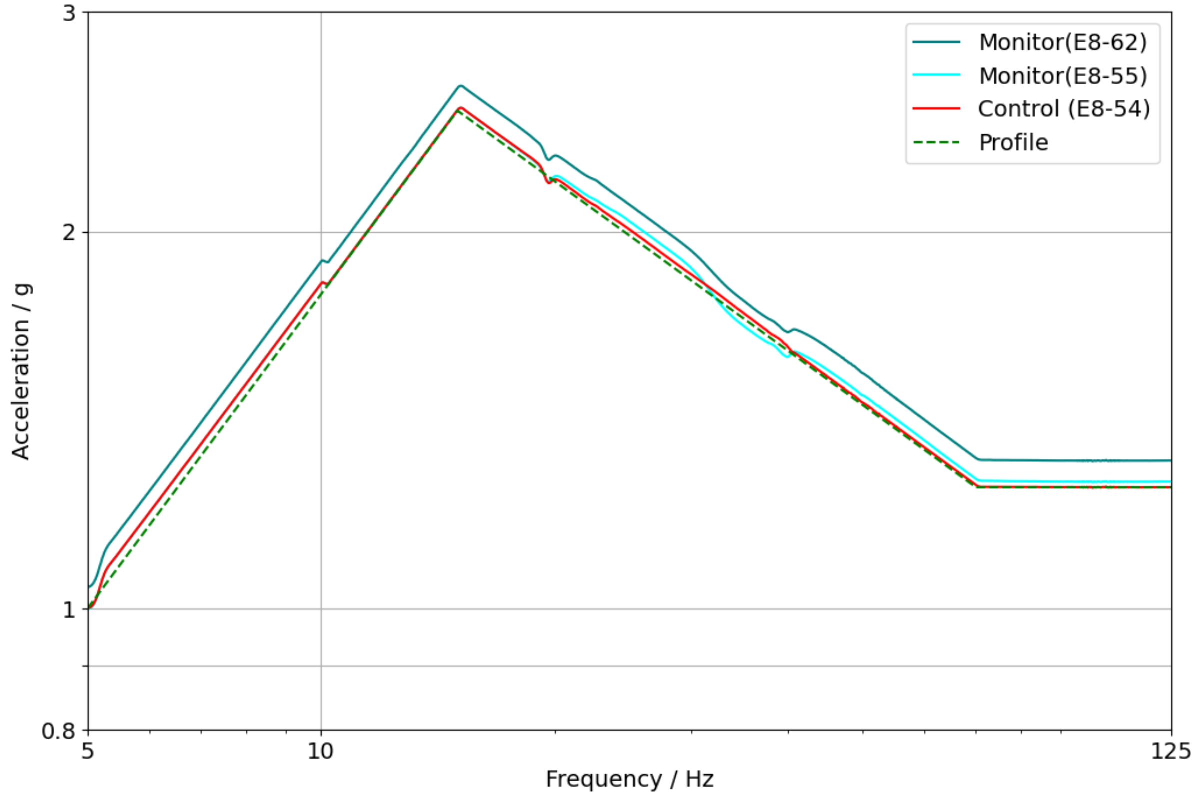

Figure 5.15. Z-axis high sine vibration test (run 12).

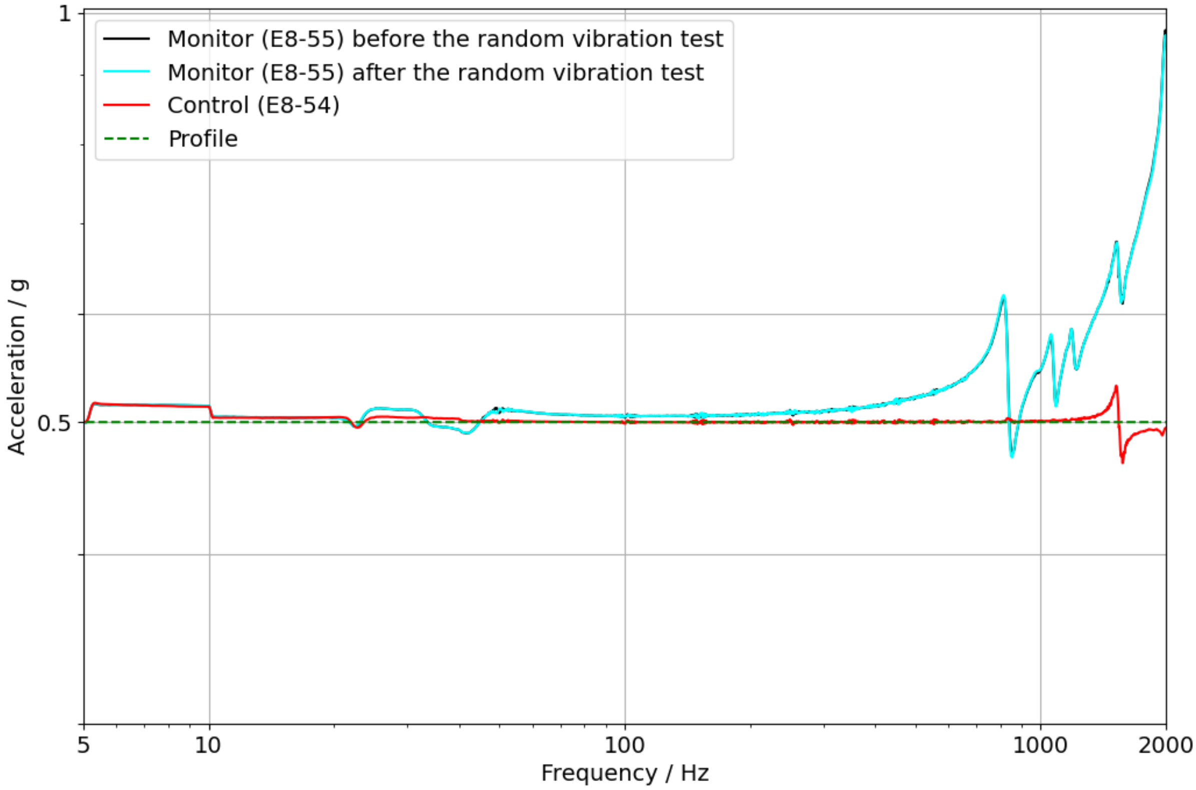

Figure 5.16. E8-55 reference sine vibration tests before and after the Z-axis random vibration test (runs 13 & 15)

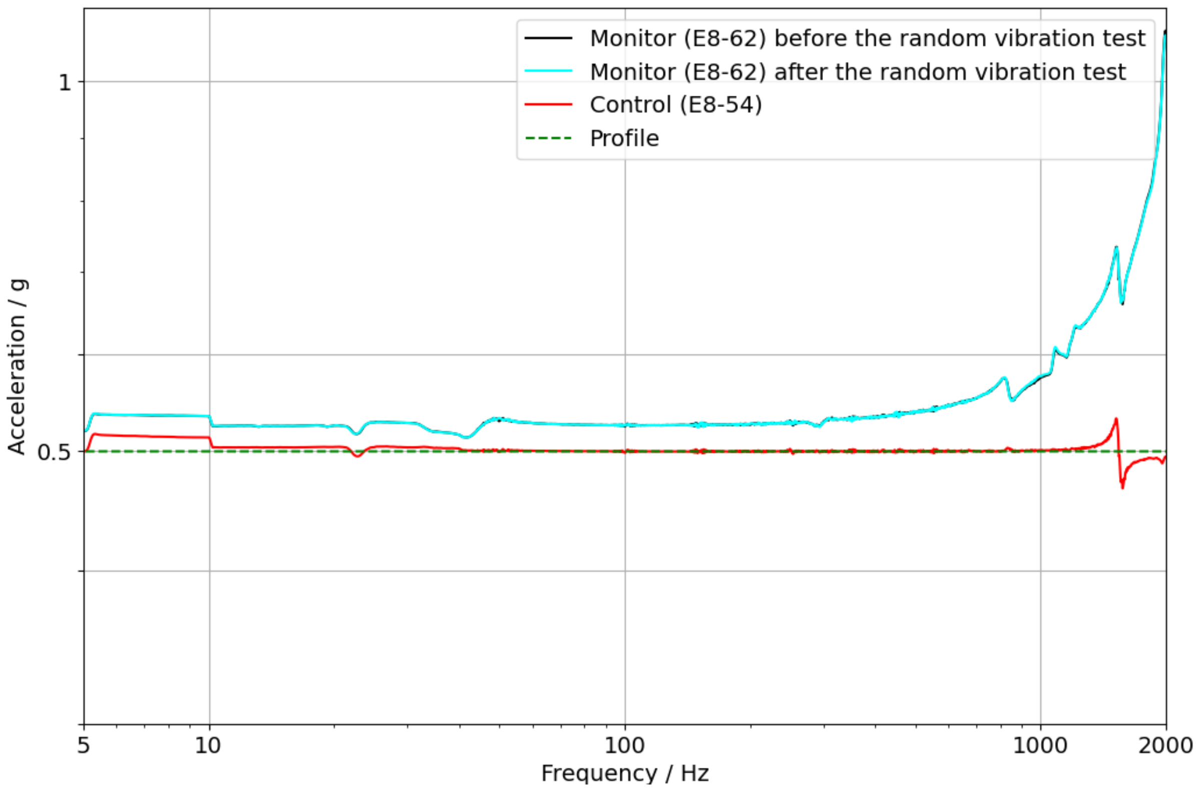

Figure 5.17. E8-62 reference sine vibration tests before and after the Z-axis random vibration test (runs 13 & 15)

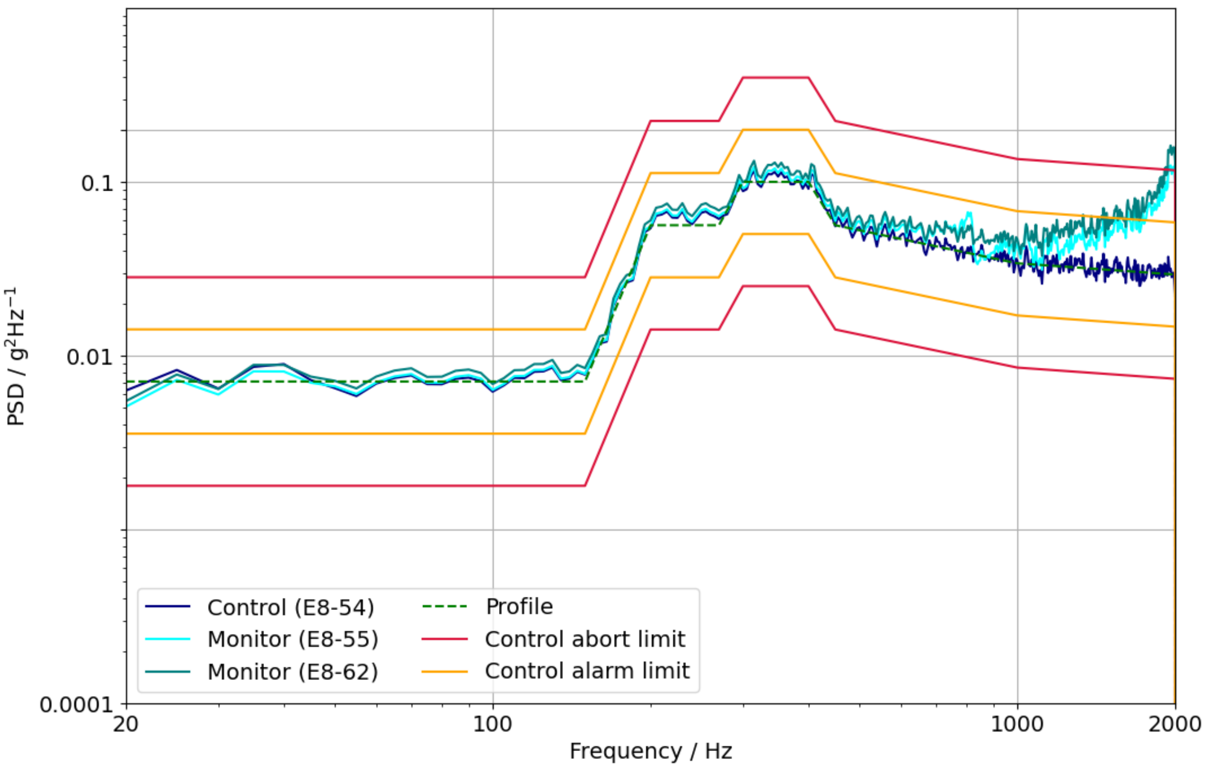

Figure 5.18. Z-axis random vibration test (run 14).

6. Measurement uncertainty

Uncertainty analysis has been carried out according to the European co-operation for Accreditation guide EA-4/02. The expanded uncertainty is given for the coverage factor of k = 2. The measurement uncertainty is ±10 % for acceleration and ±1 % for frequency.

7. Environmental conditions

The testing was performed in a laboratory with automatic air conditioning where the air temperature is kept in the range of (22± 3) °C and the relative humidity of air (55± 10) %.

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