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Software Development for Data Analysis in Vibration Testing

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SOFTWARE DEVELOPMENT FOR DATA ANALYSIS IN VIBRATION TESTING

ABSTRACT

Rocket launches are violent and involve harsh events such as vibrations and shocks. Every structural system has its own natural frequency. When the frequency of the external forces (shocks and vibrations) syncs up with the natural frequency of the whole system, it leads to resonance. This causes the forces acting on the system to be multiplied several folds. It can lead to a structural failure or even complete loss of the system in some cases.

To ensure, that every spacecraft launched in to space is able to withstand these environments, every component undergoes environmental testing on ground. To characterize and find the natural frequencies of the system, a resonance survey is performed with the vibration testing system. This is done both, before and after the system is subjected to any mechanical environmental tests. The comparison of these resonance surveys helps to identify whether or not the Device Under Test (DUT) has passed the testing criteria.

In this work the vibration testing system available at Tartu Observatory, University of Tartu has been introduced along with the method for vibration testing in use. The aim of this work was to develop a software that would perform visualization and analysis of the vibration testing data. It has been made sure that the resultant plots of the software are easily customizable with the help of a Graphical User Interface (GUI), to meet specific customer requirements. In addition, the software is capable of identifying the resonances in the data which show up as peaks. It calculates the amplitude and frequency shift in the resonances to easily show the user, whether the test object has passed the tests.

The developed software has been in use in the Laboratory of Space Technology at Tartu Observatory, UT for 8 months. The test certificates handed over to the customers after vibration testing has been performed, contain the plots that are generated by this software.

CERCS: T320, Space Technology

Keywords: Vibration testing, data analysis, software development, GUI, python

TARKVARA ARENDAMINE VIBRATSIOONIKATSETUSTE ANDMEANALÜÜSIKS

LÜHIKOKKUVÕTE

Kanderaketi üleslaskmise tagajärjel tekivad väga tugevad vibratsioonid ja pörutused. Igal süsteemil on oma loomulik sagedus. Kui väliste jõudude (vibratsioonide ja pörutuste) sagedus vastab terve süsteemi loomulikule sagedusele, tekivad resonantsid. Resonantsid suurendavad mitmekordselt jõude, mis süsteemile mõjuvad. Süsteemi struktuurid aga mõningatel juhtudel ka terved süsteemid võivad selle tagajärjel katki minna.

Tagamaks, et kosmosesse saadetakud satelliidid kanderaketist tulenevatele jõududele vastu peavad, tuleb kõiki komponente erinevates keskkondades eelnevalt katsetada. Süsteemi iseloomustamiseks ja loomulike sageduste leidmiseks viiakse läbi resonantsanalüüs. See teostatakse vibratsioonisüsteemiga nii enne kui ka pärast süsteemi mehaanilisi katsetusi. Resonantsanalüüsi tulemusi võrreldes saab tuvastada, kas katseobjekt läbis katse või mitte.

Käesolevas töös on tutvustatud Tartu Ülikooli Tartu observatooriumi vibratsiooni katsetamise süsteemi ja meetodit. Magistritöö eesmärgiks on arendada tarkvaralahendus, mis võimaldaks vibratsioonikatsetuste andmeid visualiseerida ja analüüsida. Luues kasutajaliides on tagatud, et tarkvaras tulemusi esitavad graafikud on kergesti kohandatavad vastavalt klientide nõuetele. Lisaks võimaldab tarkvara tuvastada katseandmetes resonantse, mida kuvatakse piikidena. Tarkvara suudab erinevate katsete puhul välja arvutada amplituudi ja sageduse erinevused ning võrreldes tulemusi omavahel järelda, kas katseobjekt läbis katse või mitte.

Arendatud tarkvaralahendus on olnud kasutusel Tartu Ülikooli Tartu observatooriumi kosmosetehnoloogia laboris 8 kuud. Katsetustunnistustel, mis klientidele peale vibratsiooni-katsetusi väljastatakse on esitatud käesoleva tarkvaraga loodud graafikud.

CERCS: T320, Kosmosetehnoloogia

Võtmesõnad: Vibratsioonikatsed, andmeanalüüs, tarkvaraarendus, kasutajaliides, python

TABLE OF CONTENTS

ABSTRACT.....	2
LÜHIKOKKUVÕTE.....	3
TABLE OF CONTENTS	4
LIST OF FIGURES	6
LIST OF TABLES.....	7
LIST OF ABBREVIATIONS.....	8
CH.1 INTRODUCTION.....	9
1.1 BACKGROUND.....	9
1.2 OBJECTIVES	10
1.3 OVERVIEW OF THE WORK.....	10
CH.2 VIBRATION TESTING.....	11
2.1 THE NEED FOR VIBRATION TESTING	11
2.2 THEORETICAL BACKGROUND	12
2.2.1 Free vibrations.....	12
2.2.2 Forced vibrations.....	14
2.2.3 Resonance and its importance.....	14
2.3 DESCRIPTION OF VIBRATION TEST SYSTEM AT TARTU OBSERVATORY	16
2.4 PROCEDURE FOR VIBRATION TESTING	18
CH.3 SOFTWARE DEVELOPMENT AND PROGRESS.....	21
3.1 NEED FOR SOFTWARE.....	21
3.2 TECHNICAL DESIGN REQUIREMENTS	24
3.2.1 Additional requirements.....	24
3.3 AVAILABLE SOLUTIONS.....	25
3.4 SOFTWARE DEVELOPMENT AND SOLUTION	26
3.4.1 External libraries used.....	26
3.4.2 Software design.....	27
3.4.3 The Graphical User Interface (GUI)	29
3.4.4 Amplitude and frequency shift analysis	34

3.4.5 User manual for the software	38
3.5 TEST RESULTS AND ANALYSIS	39
3.5.1 Example of testing results	39
3.5.2 Analysis of the results	43
3.5.3 Future scope	44
CH.4 CONCLUSIONS.....	45
REFERENCES	46
ACKNOWLEDGEMENTS	48
ANNEX A: USER MANUAL	I
ANNEX B: TEST LOG	VIII
ANNEX C: EXAMPLE OF A DATA INPUT FILE	XI
ANNEX D: SAMPLE TEST REPORT	XII
NON-EXCLUSIVE LICENSE TO REPRODUCE THESIS	XXV

LIST OF FIGURES

Fig. 2.1	A single DOF spring and mass system.....	12
Fig. 2.2	A damped system	13
Fig. 2.3	Example indicating the resonance points on a sine sweep graph (0.5 g)	15
Fig. 2.4	Principle setup diagram of the vibration bench.....	16
Fig. 2.5	Example of mounting the vibration sensors on a test setup	18
Fig. 2.6	Example of a sine sweep characterization for a DUT	19
Fig. 3.1	Example of resonance survey from the proprietary software.....	22
Fig. 3.2	Software design and flow chart	27
Fig. 3.3	The graphical user interface	30
Fig. 3.4	The slider bars to set threshold and minimum distance parameters.....	35
Fig. 3.5	Shown comparison of resonance peaks.....	36
Fig. 3.6	Enhanced look into maximum and minimum values	36
Fig. 3.7	Enhanced look into comparison	36
Fig. 3.8	Peak comparison plot (Fail Case).....	37
Fig. 3.9	Peak comparison plot (Pass Case).....	38
Fig. 3.10	Base test setup for a 1U cubesat.....	39
Fig. 3.11	Sine sweep characterization comparison of Case I	40
Fig. 3.12	Peak plot and comparison (Case I).....	41
Fig. 3.13	Sine sweep characterization comparison of Case II.....	42
Fig. 3.14	Peak plot and comparison (Case II)	43

LIST OF TABLES

Table 2.1 Component description of the vibration system	17
Table 3.1 List of buttons and their function in the GUI.....	31
Table 3.2 List of adjustable parameters in the GUI	32
Table 3.3 List of output elements in the GUI.....	33

LIST OF ABBREVIATIONS

1U	1 unit
BKSV	Brüel & Kjær Sound & Vibration Measurement A/S
CSV	Comma Separated Values
DUT	Device Under Test
ECSS	European Cooperation for Space Standardization
EL	Exceeds Limit
ESA	European Space Agency
FFT	Fast Fourier Transform
FOSS	Free and Open Source Software
GPS	Global Positioning System
GUI	Graphical User Interface
ISO	International Organization for Standardization
JPEG	Joint Photographic Experts Group
PCB	Printed Circuit Boards
PNG	Portable Network Graphics
PSD	Power Spectral Density
RMS	Root Mean Square
TV	Television
TO	Tartu Observatory
UT	University of Tartu

CH 1. INTRODUCTION

1.1 BACKGROUND:

Today, our society is heavily dependent on artificial satellites. Every day functions such as communications, television (TV) relay, navigation with Global Positioning System (GPS), observational astronomy, surveillance etc., are all dependent on satellites [1]. The advent of cube satellites [2] i.e. small size satellites has resulted in an increase in the amount of satellites being launched every month by several fold, and this number is going to increase further in the next few decades [3]. Cubesats are now being used to perform cutting edge research and can serve as technology demonstrators for future missions. Even with the rapid increase in the number of satellites being launched every year, the cost to launch one has remained very high, as rocket launches are the only way to put a spacecraft into orbit.

Traditionally the launch vehicles have been expendable i.e. they cannot be refurbished and relaunched. Even with multi-ton rockets, the total payload that can be delivered to space is just a small fraction (2 % to 4 %) of their overall mass [4]. There are some new companies such as SpaceX and Blue Origin that are researching and experimenting with new solutions for this problem [5], but for now the fact remains that the cost of sending one kilogram of mass, even as a piggyback payload to space is very high [6]. Thus, to justify the time and money put into development of satellites, every piece of hardware needs to be well tested before launch to ensure nominal operations once in space.

A rocket launch can be described as a controlled explosion of fuel and oxidizer. And it is an extremely harsh environment [7], payloads experience dynamic loads such as :

- High frequency shocks,
- Sinusoidal vibrations,
- Random vibrations.

Resonance within the whole system (the rocket) and the structure of the satellite can result in complete structural failure and even loss of the whole rocket [8]. Thus, it is very important to ensure that every satellite can withstand these environments and is the main reason why there are very strict guide lines set by ESA for testing. The ECSS standard (ECSS-E-ST-10-03c) for Space Engineering, 'Testing' lists all the requirements and procedures for testing of space components [9].

1.2 OBJECTIVES

In this work the setup for vibration testing system at the Tartu Observatory (TO), University of Tartu and the procedure used for testing has been described. The main aim was to develop, test and evaluate a software application to perform analysis of the data from the vibration testing system and improve the data visualization solution.

It is essential to develop a custom software because a similar solution which meets all the requirements is not readily available. The end result of this work i.e. the developed software application will be used in the Laboratory of Space Technology at TO, to produce graphical results of testing and give an analysis of the tests performed on a Device Under Test (DUT).

The developed software takes the data from the current vibration control and logging program (Crystal Instruments EDMS [10]) for each of the tests. Thus, it will be used to supplement the old software. It needs a Graphical User Interface (GUI) to display and compare the different test runs with additional analysis and comparison functions built in. The GUI needs to be easy to understand and use, to enable the user to customize the visualization parameters as required.

1.3 OVERVIEW OF THE WORK

This work comprises of four main chapters. Namely:

- Chapter 1: Introduction
Introduction to the problem and stating the objective.
- Chapter 2: Vibration testing
In this chapter, need for vibration testing along with the theoretical background is given. It helps in understanding the need for the software development. It also explains the method of vibration testing in use along with the setup used at Tartu Observatory.
- Chapter 3: Software development and progress
This chapter describes the requirements and software development progress. It explains the main functionality of the developed software and introduces the GUI. Sample test results are also presented at the end of this chapter along with the future scope of work.
- Chapter 4: Conclusions
The final chapter draws conclusions of the complete work.

CH 2. VIBRATION TESTING

2.1 THE NEED FOR VIBRATION TESTING

Launch of a spacecraft can be categorized into a set of events, each of which have several independent sources of loads for launch vehicle and testing.

The dynamic-frequency loads can be divided into two:

- The low-frequency dynamic response (sinusoidal vibrations), typically from 0 Hz to 100 Hz. For some launch vehicles the range of low-frequency dynamic response can be up to 150 Hz.
- The high-frequency random vibration environment, which typically has significant energy in the frequency range from 20 Hz to 2000 Hz, transmitted from the launch vehicle to the payload at the launch vehicle/payload interfaces.

Environmental testing is performed at varying magnitudes and durations to verify the design of space systems and to screen flight hardware for quality of workmanship. The first step in this process is the definition of the maximum expected environmental conditions during launch and in-orbit operation. Data from previous flights and ground tests are then analyzed in order to make predictions for a specific mission. These environments are then used to formulate the design and requirements and, later, test requirements for various subsystems and components. [7]

Recent progress in the area of computational mechanics allows predicting and assessing the effects of medium and high frequency vibrations. However environmental testing, such as random vibration, acoustic and shock, has proven necessary for instruments and units because, in general, as structural responses become more difficult to predict with the increase in complexity and decrease in size of systems. [11]

The combined effect of low-level sine vibrations and random vibrations can be very hazardous to the integrity of the spacecraft and cause total system failures in some of the worst cases [8]. The combined effect of vibrations and shocks can cause any of the following effects:

- Structural disintegration,
- Formation of cracks and fracture in materials,
- Screws and fasteners can come loose and harm any of the other onboard components,
- Traces or Vias in the Printed Circuit Boards (PCB) can become damaged,
- Integrated circuits may crack,
- Connectors may bend,
- Onboard mechanisms such as deployable antennas, solar panels etc. can fail.

Any of the aforementioned effects can lead to total system failure.

2.2 THEORETICAL BACKGROUND

Vibration as a term describes oscillation in a mechanical system which can be defined by the frequency and amplitude. Vibration system are comprised of means for storing potential energy, kinetic energy and means by which the energy is gradually lost i.e. a damper. In a damped system, some energy is dissipated at each cycle of vibration and must be replaced from an external source if a steady state of vibration is to be maintained. [12]

An ideal system would be the one that does not lose energy i.e. if an oscillation is introduced into the system, it will just continue to oscillate at its natural frequency for eternity without any reduction in the amplitude, but due to damping the oscillations eventually subside. The two factors which contribute to damping are:

- **External forces** : External influence from the environment such as friction, atmospheric pressure and other similar forces, small in magnitude but an influence on the system. (In the space environment these forces can usually be neglected);
- **Internal resistances**: Every material has internal resistance or stiffness which opposes the oscillations.

2.2.1 Free vibrations

A simple, single Degree of Freedom (DOF) system is shown in **Fig. 2.1**. This is an ideal system with no damper.

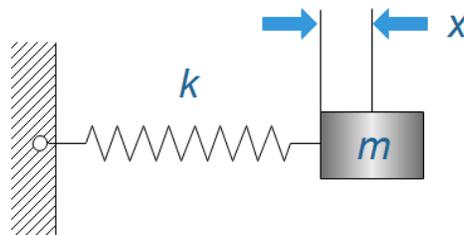


Fig. 2.1 A single DOF spring and mass system

It can be described in form of a mathematical equation as follows:

$$m\ddot{x} + kx = 0 . \quad (2.1)$$

Where ' m ' is the mass of a rigid body with displacement ' x ' and acceleration ' \ddot{x} '. The spring has a stiffness coefficient of ' k '.

Solution for the differential Eq. (2.1) is found to be:

$$x = A \sin \sqrt{\frac{k}{m}} t + B \cos \sqrt{\frac{k}{m}} t , \quad (2.2)$$

Where A, B are constants and the term $\sqrt{\frac{k}{m}}$ is the angular natural frequency defined by:

$$\omega_n = \sqrt{\frac{k}{m}} \quad \text{rad/sec.} \quad (2.3)$$

The period of this sinusoidal oscillation is:

$$\tau = \frac{2\pi}{\omega_n} . \quad (2.4)$$

The inverse of this period is the '*natural frequency*' of the system:

$$f_n = \frac{1}{\tau} = \frac{1}{2\pi} \sqrt{\frac{k}{m}} . \quad (2.5)$$

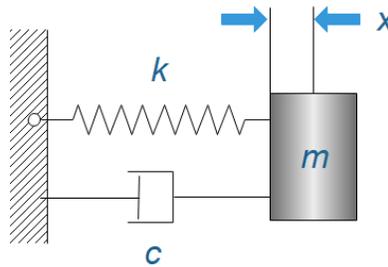


Fig. 2.2 A damped single DOF system

In the next case a viscous damper with damping coefficient of ' c ' is added to the system (**Fig. 2.2**). The resultant equation is Eq. (2.1) but with the added factor of the damper:

$$m\ddot{x} + kx + c\dot{x} = 0 . \quad (2.6)$$

The solution of this second order differential equation depends on the damping coefficient i.e. if its equal, greater than or less than the *critical damping coefficient* c_c ; which can be found as:

$$c_c = 2\sqrt{km} = 2m\omega_n . \quad (2.7)$$

Where ω_n is the natural undamped frequency of the system as in Eq. (2.5). The ratio $\zeta = c/c_n$ is the fraction of *critical damping*.

When $\zeta \geq 1$, then in both of the cases there are no oscillations. But when $\zeta < 1$, oscillations are possible in the system, and in this case, the relation of **damped natural frequency** (ω_d) to **the undamped one** (ω_n) is:

$$\omega_d = \omega_n(1 - \zeta^2)^{1/2} \quad \text{rad/sec.} \quad (2.8)$$

2.2.2 Forced vibrations

Forced vibrations are a result of a constant or periodic external force introduced into the system. It also might be the result of the movement of the foundation that supports the system itself (base excitation). This makes the system oscillate/vibrate at a particular frequency (not necessarily its natural frequency). This adds a factor $f(x)$ i.e. the external force, to the Eq. (2.6) :

$$m\ddot{x} + c\dot{x} + kx = f(x) . \quad (2.9)$$

The external applied force can be constant in nature, periodic or one that increases with time. In this case the calculation of natural frequencies becomes very complex, and the derivation is out of scope of this work, but can be found in [12].

2.2.3 Resonance and its importance

*There is a characteristic value of the driving frequency at which the amplitude of oscillation is maximum. This condition is called **resonance** and the value at which resonance occurs is called the **resonant frequency** [13].*

For a system under the effect of forced steady-state vibrations (as in section 2.2.2), the peak values for displacement, velocity and acceleration response occur at slightly different forcing frequencies.

This means, that generally every system has three resonance frequencies, and the relation of these to the damped and undamped natural frequencies are:

- Damped natural frequency (Eq. 2.8) : $\omega_n(1 - \zeta^2)^{1/2}$;
- Velocity resonance frequency: ω_n ;
- Acceleration resonance frequency: $\omega_n/(1 - 2\zeta^2)^{1/2}$;
- Displacement resonance frequency: $\omega_n(1 - 2\zeta^2)^{1/2}$.

In real physical systems, the degree of damping is usually so small that the difference among these resonance frequencies is negligible. This is the reason why in general case of vibration testing, the terms ‘natural frequency’ and ‘resonance frequency’ are used interchangeably. [12]

Thus, resonance occurs only at the natural frequency of the system. The frequency of the external excitation has to be equal or about near equal to the natural frequency. The energy in the system at these frequencies becomes much higher due to constructive interference, and this aggregation of energy causes significant increase in the amplitude of the vibration which can have extremely adverse effects on the whole system. If the interference pattern is destructive then the effect is opposite and we get anti-resonance, which is still useful for complex systems.[14]

One of the major problems with assessing spacecraft structures is that the excitation sources and the structural response occur over a very wide frequency range i.e., from very low frequency up to medium and high frequencies. Hence, identification of natural frequencies or resonant frequencies is of utmost importance. Resonance in the system can result in structural failure and disintegration. As mentioned earlier, there have been multiple instances in the history of space flight, which have resulted in complete failures due to resonance, for example, rockets/satellite launchers disintegrating midflight, satellites failing to withstand the vibrations during rocket launches etc. These types of failures can be avoided if every component and assembly is subjected to vibration testing before flight.

Resonances during vibration testing show up as sudden peaks during a resonance survey performed at a constant acceleration. A detailed explanation of the procedure is given in section 2.4.

An example of a sine sweep conducted at TO is shown in **Fig 2.3**. The constant acceleration in this case was set to 0.5 g.

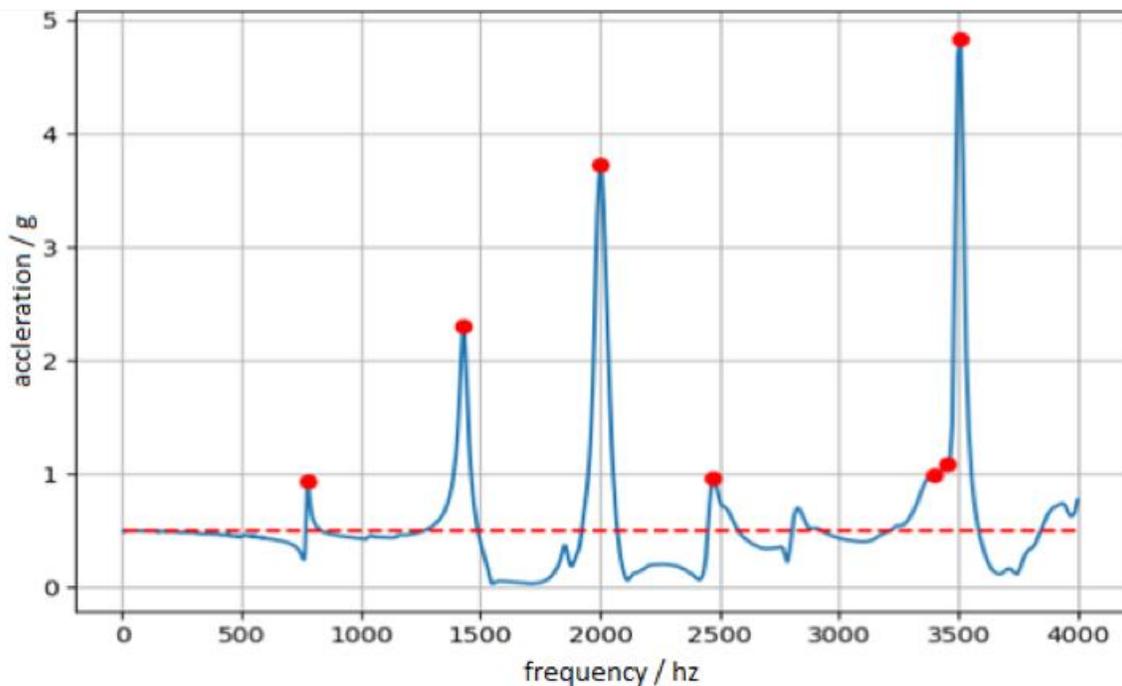


Fig 2.3 Example, indicating the resonance points on a resonance survey graph at acceleration 0.5 g.

It can be seen that during the run, the structure experienced acceleration as high as ~ 5 g i.e. 10 times of the applied force.

Note: The units of acceleration used for vibration testing can either be ‘g’ or the SI unit, ‘ m/s^2 ’ depending on the customer requirement and the standard used for testing. Most of the customers at TO, follow the ECSS documentation [7] for mechanical loads set by ESA, in which ‘g’ (equal to ~ 9.81 m/s^2) is the standard unit in use for acceleration.

2.3 DESCRIPTION OF THE VIBRATION TEST SYSTEM AT TARTU OBSERVATORY, UNIVERSITY OF TARTU

The vibration system at Tartu Observatory (TO), University of Tartu has been functional since the year 2014. It was acquired to gain the ability to perform inhouse vibration testing for a 1U cubesat [2].

The main exciter bench, amplifier and power supply are manufacture by ‘LDS’ and are used in conjunction with measurement and control unit provided by ‘Brüel & Kjør Sound & Vibration Measurement A/S’ (BKSV). The primary setup is a closed loop system and is shown in the **Fig 2.5** [15] and described in **Table 2.1**.

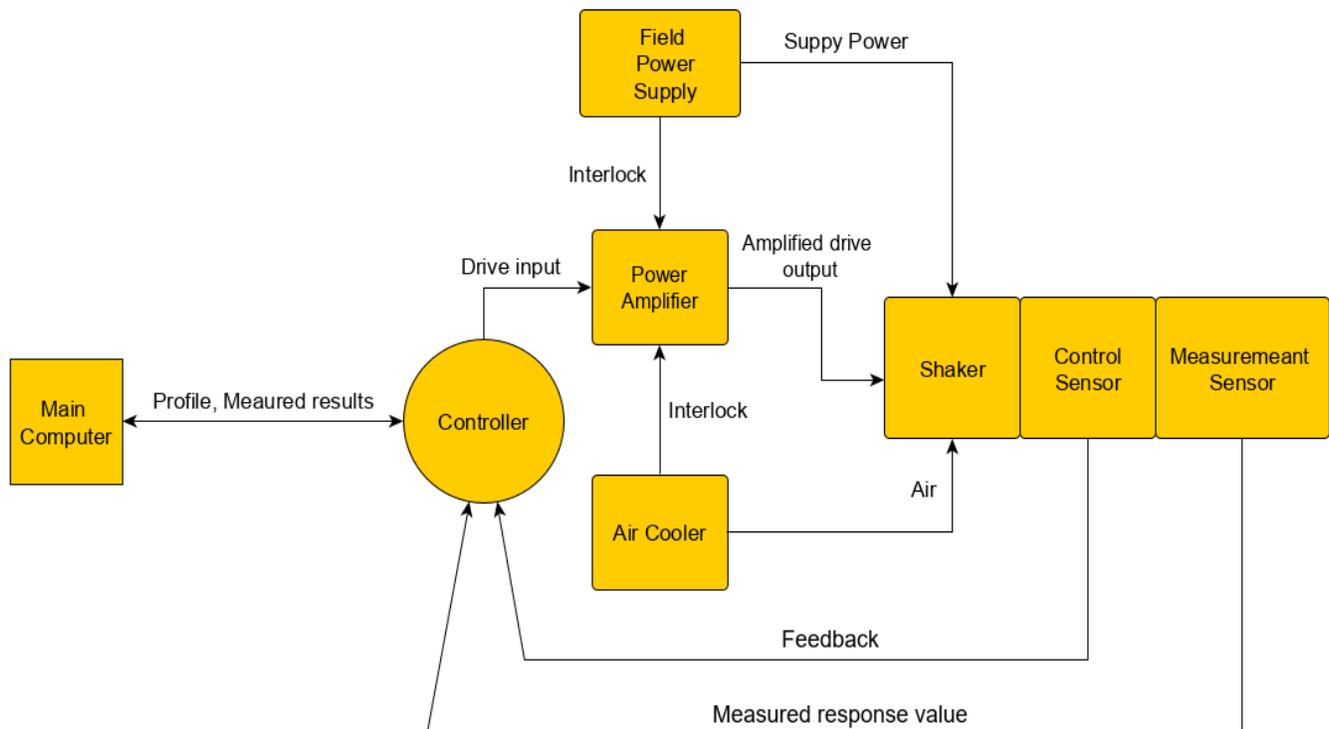


Fig. 2.4 Principle setup diagram of the vibration bench.

Table 2.1 Description of components of the vibration testing system at TO.

No.	Component	Description
1	Shaker	The main test bench is a electrodynamic air-cooled shaker rated for 2.2 kN peak force for Devices Under Tests (Hereafter referred to as DUTs). Maximum mass can be upto 50 kg with peak acceleration of 980 ms^{-2} [16].
2	Controller	The main control and measurement system is manufactured by BKSU, 'Type 7541'. It has 4 channels for inputs and a single drive output. The controller is a standalone system with internal memory and can work without a PC in certain configurations [10].
3	Power Amplifier	The PA 1000L amplifier is the one that takes the drive input from the controller and sends it to the shaker. It is an adjustable 1kW amplifier with inbuilt safety systems [17].
4	Cooling system	A suction-type air pump is responsible for keeping the whole shaker assembly cool during operation and provides an airflow of $0.094 \text{ m}^3/\text{s}$ [16]
5	Power supply	The main field power supply to the shaker is FPS-10L-70 V capable of providing upto 16 A of constant current during operations [18]
6	Sensors	There are two different suppliers of the accelerometers currently in use: 1) BKSU, 'Type 4521-001' with functional range up to 7000 m/s^2 in amplitude within 0.1 Hz to 8 kHz frequency range [19] 2) PCB Piezotronics, 'Type 356A44', Triaxial accelerometer with functional range up to 981 m/s^2 within 0.7 Hz to 7 kHz in frequency range[20]
7	Control software	Bundled proprietary software 'Crystal Instruments EDM' <i>version 4.2.0.3</i> , which interfaces with the controller and is responsible for both drive output and measurement input. Separate licenses are required to unlock various modules [10]

2.4 PROCEDURE FOR VIBRATION TESTING AT TO

The Laboratory of Space Technology at Tartu Observatory is a part of the Testing Center of University of Tartu and has been tending to customers since early 2015. The laboratory has been accredited to the **ISO 17025:2005** standard [21]. All the procedures and requirements for environmental testing are set in accordance to the same standard. Customers that perform tests at the laboratory are majorly enterprises which develop space technology or sensitive electronics for general applications and are in need to test their products to ensure proper working in harsh environments that they will be subjected to.

This section lists the general procedure in use for environmental testing for a test object. This sample case is of a test conducted on an empty fixture for a 1U (10x10x10 cm) small satellite [2], the test object is termed as Device Under Test (DUT) during the proceedings of testing.

To control the vibration bench and gauge the response of the DUT, at least one control accelerometer sensor and one monitor accelerometer sensor are needed. An example of a test setup is shown in **Fig 2.5**. There is a provision to include another monitor sensor in the setup, if needed.

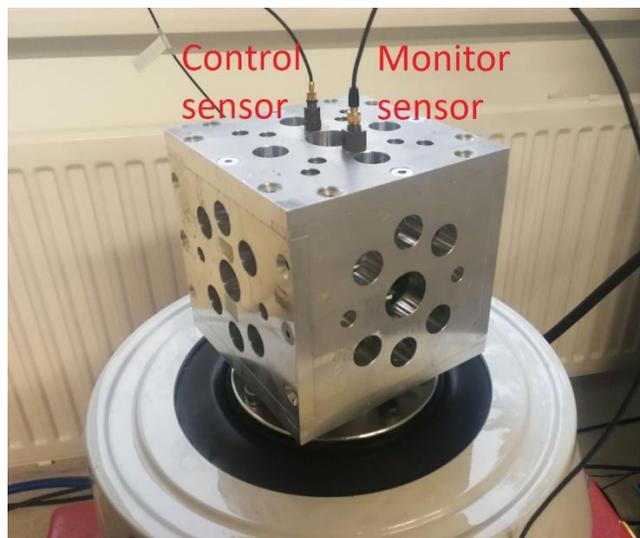


Fig 2.5 Example of mounting the accelerometers on a test setup.

To find the resonant frequencies of a system, a procedure called as resonance sweep is performed. It involves subjecting the test system to a frequency sweep at a fixed sweep rate and a constant acceleration.

Before beginning with the tests on the DUT, the characterization of the empty fixture is done first. Fixture is a mechanical structure to attach the DUT to the vibration bench. This serves to verify that the fixture itself does not have any low-lying natural frequencies which could potentially interfere with the actual tests of the DUT.

General procedure for mechanical testing of a DUT is as follows:

Step 1: First a resonance sweep also known as swept sine is performed. For this sample test the axis was X. The step gives us a base line characterization of the system. The resonance frequencies are identified, and the data is saved from the test. The data from monitor sensor is labelled as '*monitor before*' or '*monitor 1*'. A sample resonance sweep at 0.5 g from 5 Hz to 2000 Hz is shown in **Fig 2.6** :

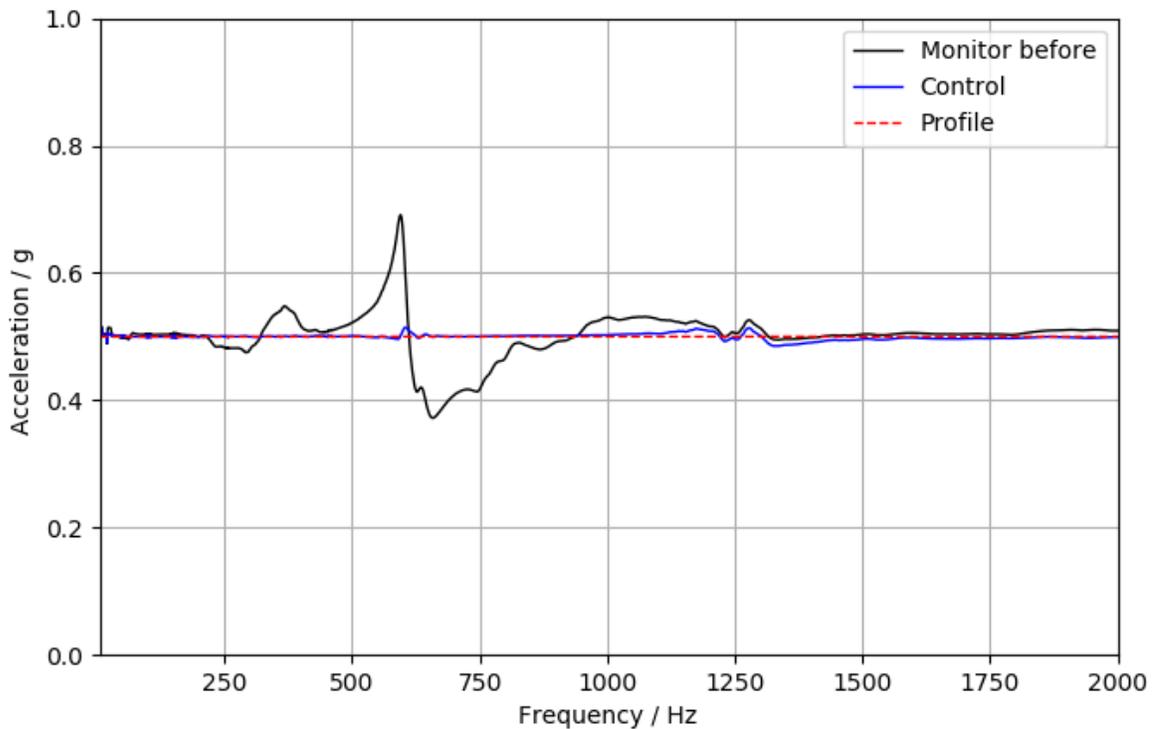


Fig 2.6 Example of a sine sweep characterization for a DUT.

Step 2: In the next step the DUT undergoes one of the following testing profiles :

- **Sinusoidal vibrations:** Generally, from (5...120) Hz at a set sweep rate of 2 octaves per minute [9]. The peak acceleration varies according to different requirements. For the 'Vega' satellite launcher, the peak acceleration is ~ 22 g [22]. The selection of profiles, that the DUT is tested against is the responsibility of the customer.
- **Random vibrations:** Profiles are set based on the rocket launcher and client specifications. A Power Spectral Density (PSD) curve has to be defined, nominally in the range of (5...2000) Hz. Most commonly, Root Mean Square (RMS) acceleration for the test is ~ 9 g.

- **Mechanical shock:** A hammer drop shock test with peak acceleration reaching up to 20,000 g is available at Tartu Observatory [23]. Parameters are set to individual customer specifications.

Step 3: After the mechanical tests, the DUT is subjected to another resonance sweep. The data from the monitor sensor is labelled as '*monitor after*' or '*monitor 2*' this time.

Step 4: Post processing of the data is done after the testing. The resonance sweep data from Step 1 and 2 are plotted and analyzed.

Step 5: All the prior steps are repeated for each axis (x, y and z). It is to be noted that only one of the tests is performed between each set of resonance sweeps i.e. each different test (sine vibrations/ random vibrations/ shocks) in each axis should have its own set of resonance sweeps.

A detailed test log of sine vibration, random vibrations and shock testing conducted for a customer at the Tartu Observatory has been provided in Annex B for reference.

CH 3. SOFTWARE DEVELOPMENT AND PROGRESS

3.1 NEED FOR SOFTWARE

After the vibration testing has been performed according to the procedure described earlier in section 2.4, the results are the frequency-amplitude graphs from the swept sine characterization of the DUT. The comparison of resonance surveys performed before and after each environmental test (sine/random/shock) show if there has been any change in the structure which shows up as shifting of the resonance frequencies. With the identification and calculation of the shift, the result of the testing i.e. whether the DUT has passed the test successfully or not, can be found.

The proprietary software with the BKSV vibration control and data logger system, the 'Crystal Instruments EDM' version 4.2.0.3 [10], is used to visualize the data. This software has an inbuilt resonance search function, but it requires a separate license and cannot be accessed at present. A sample of a graph produced by the proprietary software is shown in **Fig 3.1**.

The proprietary vibration control software has the option to compare two graphs simultaneously as well (**Fig 3.1**), but the implementation is not ideal and lacks configuration options. Some of the other major problems with the proprietary software are:

- **Visualization and customization**
The implementation of data visualization in the present software is not ideal. Plots are difficult to read and understand. The legend is not configurable, and the font size is fixed. For resonance comparison, multiple plots are made on top of each other and can be very difficult to understand for the customers. It lacks customization options to meet customer specifications.
- **Proprietary data file format**
The live data is stored in a proprietary file format which can't be accessed. This hinders the user's ability to access the data from outside the application. The only option is to export the data individually within the required format from inside the software interface.

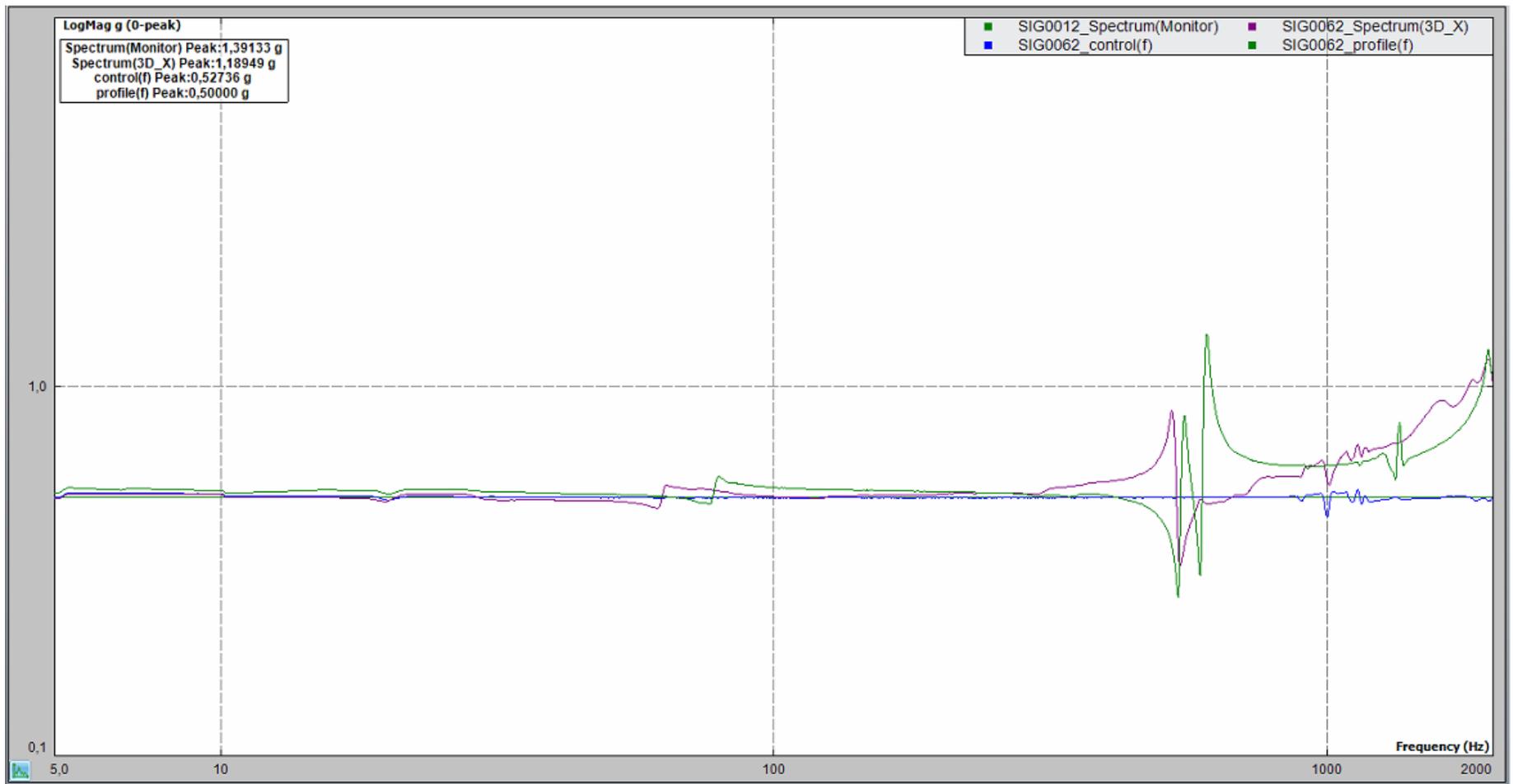


Fig 3.1 A sample graph of resonance survey from the proprietary software.

- **Resonance search**
As mentioned earlier, resonance search is included in the software, but the functionality is locked under the current license.
- **Graphical User Interface**
The present GUI implementation is old and non-intuitive. It requires a lot of steps to access simple functions for customizing the colors and labels of the plots. It reduces the efficiency of the user.
- **Older version**
The ‘Crystal Instruments EDM’ version 4.2.0.3 is old (2013) and cannot be updated to the newer version which has additional new functions and bug fixes. Acquiring the new version’s license is a complicated process and not very cost effective.
- **Technical support**
At present there is no technical support from the company (Crystal Instruments) for the older version. Any bugs and issues remain unsolved.

Additionally, when comparing two sets of resonance sweeps, as the original software falls short of options to show the peaks and differences in the data. Thus, the requirement for the new software would also be to compare and analyze the data. Resonances show up as peaks in the data during resonance surveys and the amplitude & frequency comparison at which they occur is of utmost importance.

The ECSS standard for Testing of Space systems [9], mentions that only 20 % amplitude shift and 5 % in frequency shift between sine sweeps is acceptable, so the developed solution would need to find, compare and display the shifts and present them in a format that is easily understandable.

A GUI would make the process of comparing and editing graphs faster. A nominal testing report requires at least 7 to 8 comparison graphs. The number is doubled if there are two monitor sensors in use or a three-dimensional accelerometer is connected. A GUI would make it possible to select each particular run data separately and customize the visualization according to customer’s specifications.

The new software solution will augment the functionality of the current proprietary software in use.

3.2 TECHNICAL DESIGN REQUIREMENTS

In addition to the requirements mentioned just above, other requirements were found during authors work with the vibration testing setup and preparing test reports. Feedback from personnel of the Space Technology Laboratories at TO was also considered.

The technical requirements for the developed software were set as follows:

- Ability to read the input data in '*.xlsx' format;
- Ability to support input of multiple data channels (monitors, control, safe limits, profile);
- Ability to change the units of acceleration from 'g' to 'm/s²' (modify the input data);
- Ability to change the scale of the graphs (linear/log);
- Ability to have editable titles, legends, line colors etc.;
- Ability to find and plot the peaks in the data;
- The peaks need to be adjustable due to amount of variation seen in data acquired;
- Ability to show the maximum and minimum acceleration seen in the data and at which particular frequency;
- Ability to compare apparent resonances and identify amplitude and frequency shift (if any);
- Ability to save the generated graphs in whichever format required (*.png' or *.jpeg').

3.2.1 ADDITIONAL REQUIREMENTS

- *User Guide*

The software will be used by test engineers working at the Laboratory of Space Technology at the University of Tartu, Tartu Observatory. Hence, it needs to be easy to understand and use. A user guide needs to be available which explains the basics of how to use the software.

- *Flexibility*

With different customers from very diverse fields which are not interconnected in any way at times, there are numerous different requirements for formatting of the results and visualization of data in the reports. Hence, the software needs to be flexible enough to accommodate these needs.

3.3 AVAILABLE SOLUTIONS

The provider of the software (BKS) currently in use at TO, has recently changed their product offerings [24] and all older products have been dropped with no technical support available anymore. The search for available solution was limited to Free and Open Source Software (FOSS) as generally seen the signal processing industry the license fees for software are exponentially high and are mostly subscription based.

There are some open source solutions which deal with acquisition and visualization of single stream of data. The two major ones that are free to use are:

- ***Tom Irvine's vibration data***
One of the largest open sources of software and tutorials for shock and vibration analysis is maintained by Tom Irvine. MATLAB [25], and Python [26], versions of his signal analysis GUI are available, but it is more focused towards raw data acquisition and processing. [27]
- ***Slam Stick Lab***
Slam Stick Lab is another data acquisition software which is free to use, but currently it only works with the proprietary Slam Stick (data acquisition modules) recording files, but there are plans to open it up to import other format files in the future. [28]

Both of these FOSS are maintained by individual users but did not meet the software requirements set in section 3.2. As described earlier, customization for different customers was of paramount importance along with the resonance search and comparison function. Hence the need for a custom software solution.

An option to design a software from scratch which would take direct input from the accelerometer time data streams with a separate data acquisition module was considered. Delving deep into the subject matter, it was found that the numerous filters will need to be experimented with in addition to the requirement of a large amount of testing the system. The data acquisition system present at TO already has this inbuilt, and it has been optimized by the source company through years of testing. Thus, the new software would be redundant, take a huge amount of time to get basic functionality working and the end result might not be as good as the one that already exists. So, this area of work was shelved for now and the improvement of the present system and visualization was preferred.

3.4 SOFTWARE DEVELOPMENT AND SOLUTION

The software was developed using Python programming language [26] because of the following reasons:

- Ease of design and integration,
- Cross platform support,
- Availability of extensive documentation,
- Great support and big community behind scientific and mathematical operations,
- Faster developmental cycle,
- Free to use license.

Pyside [29] module was utilized to create the graphical user interface. Pyside has its own graphical representation tool, but it was found to be bugged and hence Matplotlib integration with Pyside was used.

3.4.1 External libraries used

- **Pyside**
Pyside is a python binding/library of the cross-platform GUI toolkit Qt, which is currently developed by the Qt company [30]. It can be used as an alternative to Python's standard Tkinter library package and has a unique and varied set of customization options. It is very flexible and powerful. [29]
- **Matplotlib**
Matplotlib is a python library for generating 2D plots. It has a MATLAB [25] like interface but combines even better functionality and cross platform usage. [31]
- **Peakutils**
Peakutils is a python package which provides peak detection in a 1D array of data. It includes options for estimating baseline, gaussian fitting etc. to further increase the resolution of peak detection. [32]
- **Openpyxl**
Openpyxl is a python library to parse and write Excel 2010+ xlsx/xlsm/xltx files. It provides the user with the ability to read/write natively from Python itself. [33]
- **NumPy**
NumPy is a fundamental package for scientific computing with Python [34]. It provides the users with a powerful N-dimensional array object, calculus and other sophisticated functions.

3.4.2 SOFTWARE DESIGN

The software design and flow is shown in **Fig 3.2** and described further below.

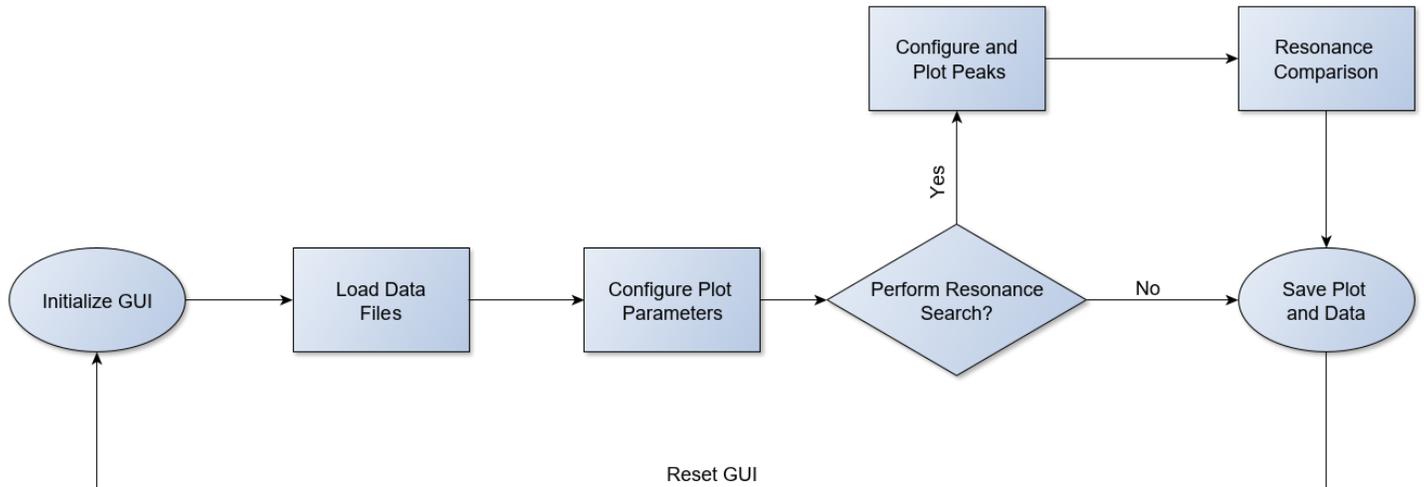


Fig 3.2 Software flow chart.

- **Initialize**

There are three initializing functions to get the basic GUI up and running. The first is *_init_()* which sets up the main window with the name and icon. Loads the flags and colors. Then *init_ui()* configures the window with the layout which includes:

- a) The main canvas to visualize the graphs;
- b) Buttons to load data, customize the plot, plot peaks and run analysis;
- c) Text boxes to display results and further change parameters of the plot;
- d) Tick boxes to change the scale of the plot;
- e) Sliders for the peak finding function;
- f) Scroll menu to change the color of the plots.

- **Load data**

To load the run data from the performed runs (sine sweeps) that are being compared there are three functions to input Monitor 1, Monitor 2 and control data respectively. In addition, the control sensor data is also loaded into the program and saved in an array. The Load buttons call the corresponding loading function, for ex. For Monitor 1 it connects to *loadmonitor1()* function, which then connects to the *OpenFile()* function for the user to select the data file in '*.xlsx' format. The

openpyxl library is then used to parse the data into an array and the last step is to plot it on the canvas and visualize the data.

- **Plot configuration**

The functions which handle the basic plot configuration are:

a) *xrangechange()*

Sets the range of the x axis according to the input.

b) *yrangechange()*

Sets the range of the y axis according to the input.

c) *profile_plot()*

As the primary function of the software is to visualize and compare sine sweeps, which are generally performed at constant acceleration. This function changes the profile plot according to the input (acceleration) by the user.

d) *ylogscale()*

Switches the Y axis scale of the graph from linear to log and refreshes the units in the comparison data output.

e) *data_unit_change()*

Checks if the input data is not already in m/s^2 and then changes the units from g to m/s^2 , multiplying the y axis values by gravitational acceleration 'g'. Also refreshes the units in the comparison data output.

f) *legend_change()*

Changes the labels of the plot legend according to the input.

g) *mn1_change() / mn2_change() / cnt_change() / prof_change()*

All of them individually change the color of the respective plots according to the user input.

h) *plot_title()*

Alters the title of the plot, can be left blank as well.

- **Peak find and plot**

The *peakcheck()* function is the one that is called when the button 'plot peaks' is pressed. It connects to *peak_plot()* function and allows it to be only called once after the initialization, it disables the button.

The *peakchange()* function is called, when either of threshold or minimum distance (sliders) for calculating peaks is changed by the user. It also checks for any unit

changes in the data, finds the new peaks accordingly, then it refreshes the plot and plots the new peaks.

- **Resonance analysis**

The *printpeaks()* parses through all the input data to find maximum and minimum values in both frequency and amplitude. It also compares the peaks (resonances) that have been found and calculates the amplitude and frequency shift in peaks.

The values are then compared to the allowed shift in amplitude and frequency (according to the ECSS standards [9]), indicating where the shift is within limits or not. Additionally, it opens up another plot window, which shows the comparison between each resonance points of the two sine sweeps.

- **Reset and Save plot**

The *clearall()* function purges all the data from arrays and re-initializes the whole GUI. The *saveplot()* function grabs the canvas from the main window and opens up a dialog box for the user to save the image. The software has been configured to offer the user a choice between two different formats for saving the final graph, ‘*.jpg’ and ‘*.png’, either of which can be selected in the save file dialogue according as needed.

3.4.3 The Graphical User Interface

Fig 3.3 showcases the GUI window which greets the user upon running the program for the first time.

The first task of the user is to load three data files that are, monitor data from two runs to be compared and then the control sensor data. The profile is loaded automatically as a constant acceleration profile of 0.5 g, this value can later be altered. The threshold and min. distance slider have preset value of 0.5 and 25 respectively.

The buttons and other output and input elements in the GUI have been described in form of tables for the ease of understanding. **Table 3.1** lists all the buttons and their function in the GUI. **Table 3.2** lists the additional editable parameters such as input text boxes, sliders, scrolls and checkboxes. **Table 3.3** lists the output elements in the GUI.

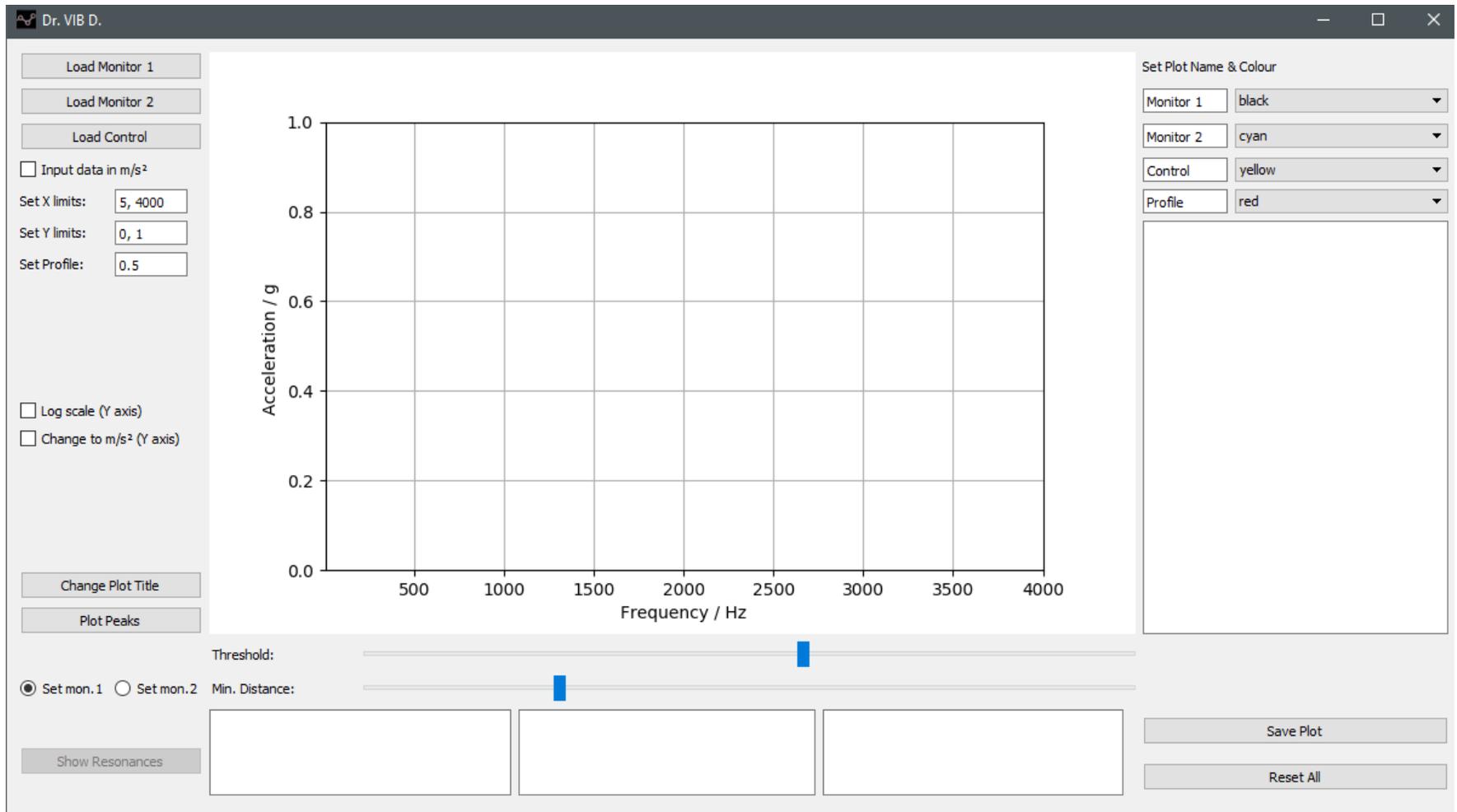


Fig 3.3 The Graphical User Interface.

Table 3.1 List of buttons and their functionality in the GUI.

No.	Button Tag	Preset Function	Enabled at Initialization	Comments
1	Load monitor 1	Opens up a file selection dialogue box in '*.xlsx' format to load monitor 1 data	Yes	Up to discretion of the user to choose correct files
2	Load monitor 2	Opens up a file selection dialogue box in '*.xlsx' format to load monitor 2 data	Yes	Up to discretion of the user to choose correct files
3	Load control	Opens up a file selection dialogue box in '*.xlsx' format to load control data	Yes	Up to discretion of the user to choose correct files
4	Change Plot Title	Opens up a dialogue box to edit the title of the plot	Yes	---
5	Plot Peaks	Calculates the peaks in the data and plots in onto the main canvas	Yes	Can only be clicked once, is disabled afterwards
6	Show resonances	Lists all the found peaks; also lists the amplitude & frequency shift	No	Gets enabled after Plot Peaks has been called
7	Reset All	Resets the GUI and purges all the caches and configurations	Yes	---

Table 3.2 List of adjustable parameters in the GUI.

No.	Adjustable Parameter	Input Type	Preset Function	Enabled at Start	Comments
1	Input data in m/s^2	Checkbox	Identifies that the input data is in ' m/s^2 ', Changes the units in output display boxes	Yes	Available before loading any data files, disabled later
2	Set X limits	Text edit box	Sets the lower and upper limits for the X axis	Yes	---
3	Set Y limits	Text edit box	Sets the lower and upper limits for the Y axis	Yes	---
4	Set Profile	Text edit box	Sets the amplitude level for the profile	Yes	---
5	Log scale (Y axis)	Checkbox	Switches the scale of Y axis to log	Yes	The lower limit for Y Scale has to be set to be non-zero
6	Change to m/s^2 (Y axis)	Checkbox	Changes the units of the input data to ' m/s^2 ' by multiplying all the acceleration data by 'g'	Yes	---
7	Set mon.1/ Set mon.2	Radio buttons	Mutually exclusive buttons to set Threshold and Min. distance levels for either Monitor 1 or Monitor 2	No	Get enabled after Plot Peaks has been called
8	Threshold	Slider	Sets the minimum threshold above which to find peaks	No	Enabled after the Peak Plot button has been clicked
9	Min. Distance	Slider	Sets the minimum distance between two consecutive peaks	No	Enabled after the Peak Plot button has been clicked
10	Set Plot Name & Color	Combo of Text edit and scroll boxes	Alters the label and color of each plot individually	Yes	---

Table 3.3 List of output elements in the GUI.

No.	Output Element	Output Type	Preset Function	Enabled at Start	Comments
1	Monitor 1 display	Non editable text box	Displays the max and min acceleration(at which freq.) for Monitor 1 data	No	Enabled after all data files have been loaded
2	Monitor 2 display	Non editable text box	Displays the max and min acceleration(at which freq.) for Monitor 2 data	No	Enabled after all data files have been loaded
3	Comparison measurement display	Non editable text box	Comparison between max and min acceleration (at which freq.) for Monitor 1 & 2	No	Enabled after all data files have been loaded
4	Resonance point comparison display	Non editable text box	1) Lists all the identified resonance freq.(and their amplitudes) 2) Lists the amplitude and frequency shift 3) Warning labels	No	Enabled after Peak Plot has been clicked
5	Main Plot	Non interactive plot	The main canvas for the plot display	Yes	This is the window which is saved as a picture
6	Resonance Plot	Not editable text box and Interactive plot	1) Lists the identified resonances 2) Opens up resonance plot window	No	Enabled after Peak Plot has been clicked

3.4.4 Amplitude and frequency shift analysis

Due to the complexity and cost involved in space missions, high precision has to be maintained in every step of the development cycle. It is the component level testing which is used to verify that the final design meets all constraints and therefore the importance of analyzing the amplitude and frequency shifts in data is paramount after vibration/shock testing.

As mentioned earlier, according to the ECSS standards for testing of space craft components the margin for amplitude shift is 20 % and 5 % in frequency shift [9]. Exceeding these margins can have very adverse effects, manufacturing processes might need to be reviewed in case of a manufacturing or assembly flaw. The worst-case scenario could be, that a design overhaul is needed which would result in increased costs and timeline of the mission.

One of the requirements for the software was to integrate a method to find the peaks/extremities in the data. This has been implemented by the use of peakutils module available under the open MIT license [32]. The package provides the user with utilities and functions for the detection of peaks on one dimensional (1D) array of data. The module requires two input parameters to be set by the user:

- Threshold;
- Minimum distance.

Threshold parameter: It is the value in relation to the maximum point in the data above which the peaks are found. This helps to weed out the unwanted peaks that might occur due to the high sampling rate in the data and list the ones that are of importance.

Minimum distance parameter: It sets the minimum distance between two peaks and also helps to weed out the unwanted peaks due to inconsistencies in the data.

The software implements the selection of both of these parameters by the use of sliders (**Fig 3.4**) as it was found that the resonance sweeps for different structures are so varied that it is impossible to have one set value for all. In this implementation the user has full control over the selection of peaks and is expected to perform the best selection visually.

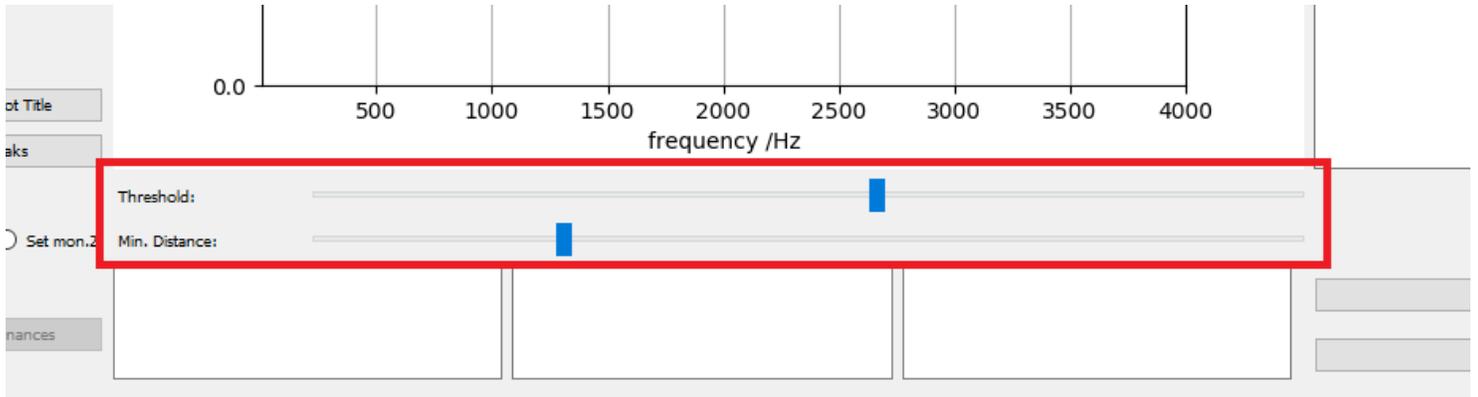


Fig 3.4 The slider bars to set threshold and min. distance parameters.

Next part is the calculation and comparison of amplitude and frequency shift. The functions which handle this section are *printpeaks()* and *printinwindow()*. The peaks in the data which are interpreted as the resonances are found by the *peak_plot()* function as mentioned earlier. The *printinwindow()* function parses through the arrays in which the y-axis data for all the plots is stored and finds the index of the maximum and minimum values. It then prints the data in the first two windows below the plot along with the x axis data as well (seen in **Fig 3.5 & 3.6**).

The third log window is for the comparison measurements between the max and min values, which shows the actual variance and variance in terms of percentages as well. This gives a primary idea if the shift is within margin or not. Further analysis for other peaks (resonances) is then calculated in the *printpeaks()* function to find the final result whether the DUT has passed the test or not. **Fig 3.5** and **Fig 3.7** show how the information is shown to the user.

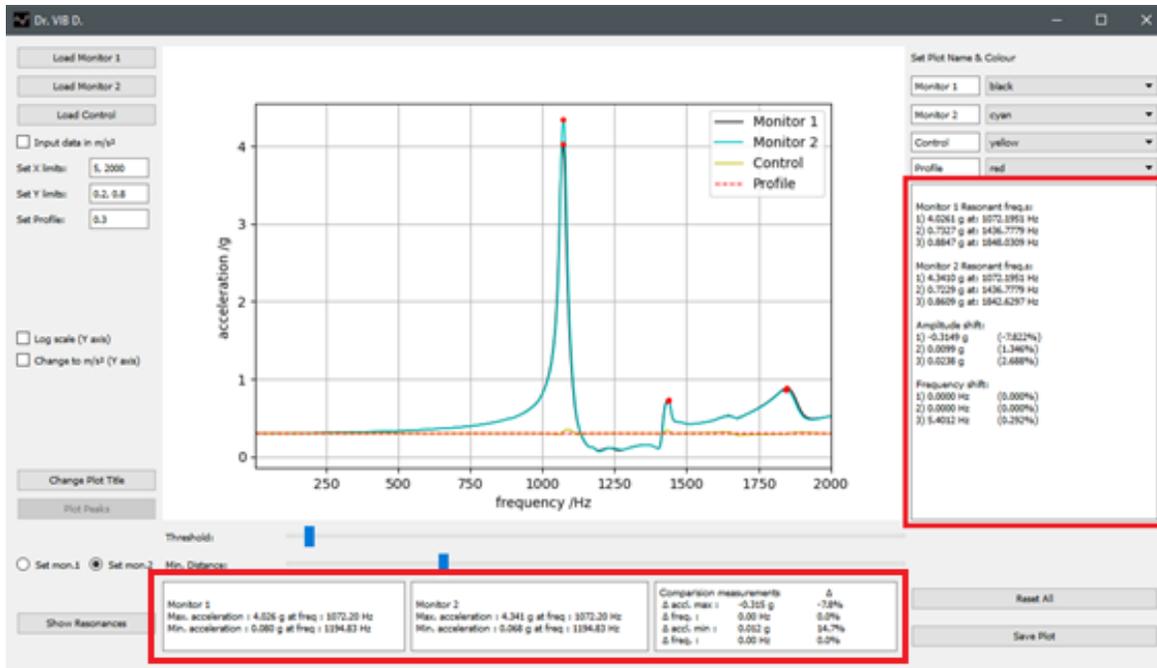


Fig 3.5 Shown comparison of resonance peaks.

<p>Monitor 1</p> <p>Max. acceleration : 7.360 g at freq : 2792.70 Hz</p> <p>Min. acceleration : 0.260 g at freq : 517.88 Hz</p>	<p>Monitor 2</p> <p>Max. acceleration : 1.880 g at freq : 3986.65 Hz</p> <p>Min. acceleration : 0.054 g at freq : 2738.51 Hz</p>	<p>Comparison measurements</p> <p>Δ accl. max : 5.479 g 74.5%</p> <p>Δ freq. : -1193.95 Hz -42.8%</p> <p>Δ accl. min : 0.206 g 79.2%</p> <p>Δ freq. : -2220.63 Hz -428.8%</p>
---	--	---

Fig 3.6 Enhanced look into maximum and minimum data.

<p>Monitor 1 Resonant freq.s:</p> <p>1) 2.0383 g at: 542.1100 Hz</p> <p>2) 7.3596 g at: 2792.6979 Hz</p> <p>3) 6.0405 g at: 3288.0164 Hz</p> <p>Monitor 2 Resonant freq.s:</p> <p>1) 0.970 g at: 551.0340 Hz</p> <p>2) 1.270 g at: 3626.4358 Hz</p> <p>3) 1.880 g at: 3986.6471 Hz</p> <p>Amplitude shift:</p> <p>1) 1.068 g (52.406%) EL!</p> <p>2) 6.090 g (82.749%) EL!</p> <p>3) 4.160 g (68.874%) EL!</p> <p>Frequency shift:</p> <p>1) -8.924 Hz (-1.646%)</p> <p>2) -833.738 Hz (-29.854%) EL!</p> <p>3) -698.631 Hz (-21.248%) EL!</p>
--

Fig 3.7 Enhanced look into comparison

All the peaks for the both the runs are shown first, with amplitude and corresponding frequency at which they occur. The amplitude shift and the frequency shift are listed separately for each peak point as can be seen in **Fig 3.7**, and the deviation is also given in percentages. If one of the parameters exceeds the allowed margins, then a warning sign is shown next to that value as ‘EL!’ (Exceeds Limits) i.e. it exceeds limits as is also seen in **Fig 3.7**. The limits are set according to the ECSS as stated in section 3.1 [9].

To make the comparison more intuitive and easily understandable, another function was implemented (within *printpeaks()*) which plots the peaks in a new window. It makes it easier to visualize the shift in both amplitude and frequency.

When the ‘Show Resonances’ button is clicked, along with showing the amplitude and frequency shift, it opens up another plot window (**Fig 3.8**). In this window, the peaks for both the runs (before and after testing) are plotted separately. The peaks from the first run have a margin box around them, 5% for frequency i.e. in the x-axis and 20% for amplitude i.e. in the y-axis. If the corresponding peaks from the second run are inside this margin box, then the limits are met, and the DUT is said to have passed the testing. **Fig 3.9** shows how it looks on the plot, whereas **Fig 3.8** is the case when the DUT has failed the testing.

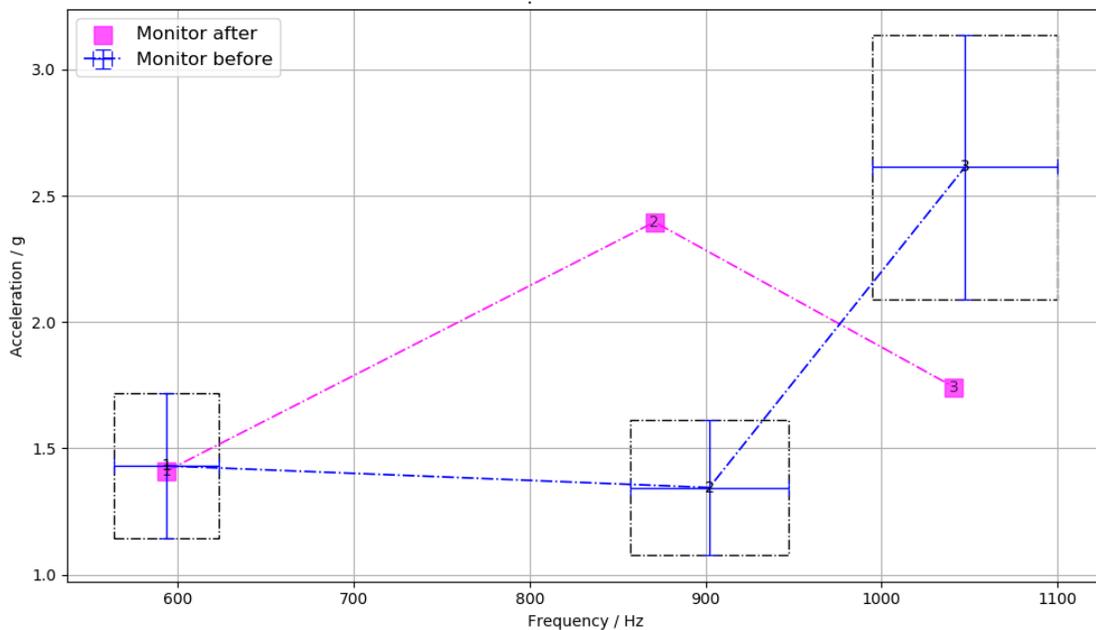


Fig 3.8 Peak comparison plot (Fail Case).

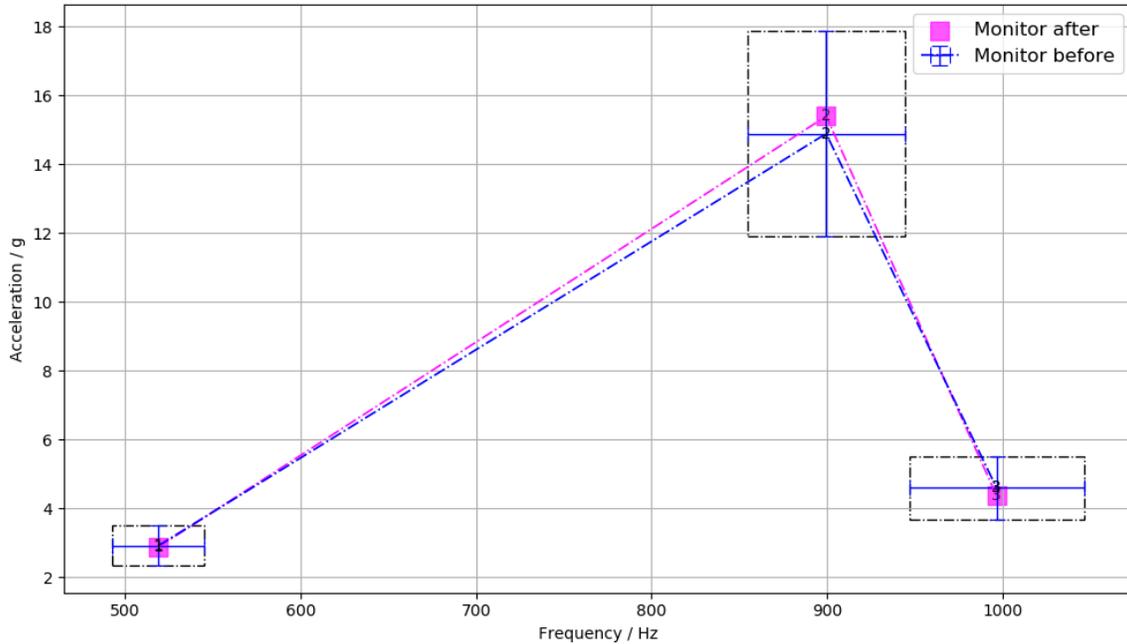


Fig 3.9 Peak comparison plot (Pass case).

3.4.5 User manual for the software

The software is built to serve as a visualization and analysis tool on top of the proprietary software that is in use with the BKS Control and Measurement System [10]. The data files have to be extracted from that in the '*.xlsx' format. 'Monitor before' is the data from the accelerometer, before the DUT has undergone environmental testing (sine vibrations, random vibrations or shock). 'Monitor after' is again the data from the same sensor, in the same location after the tests have been performed. A sample file that is loaded, is provided in Annex C. This software is meant to be used by the engineers at Tartu Observatory, thus a user manual for the same has been created which can be seen in Appendix A.

The user guide gives detailed step by step instructions to configure a plot, and how to perform the resonance analysis in the data which is also included in the software. Effort has been made to simplify the procedure.

3.5 TEST RESULTS AND ANALYSIS

The primary aim of the software to make visualization of the resonance surveys and customize the plots as per individual customer specifications has been achieved. Furthermore, comparison and analysis of resonance has also been implemented.

The software has been written and tested on the Windows 10, 64-bit operating system. It has been installed on the vibration testing system computer at Tartu Observatory to make it easily accessible to other engineers working there.

3.5.1 Example of testing results

The case given here is the results following the testing of a 1U cubesat conducted at Tartu Observatory. The base as shown in **Fig 3.10**, consists of a fixture which holds the satellite inside and is attached to the vibration bench with four screws. The two particular cases, from which the data has been taken from are described below:

- **Case I:** The cubesat was subjected to a shock test. Resonance surveys were performed both before and after the test. In this particular case, some components had become detached inside the satellite.
- **Case II:** The design was improved upon and the cubesat was again subjected to the same shock testing procedure and resonance surveys.



Fig 3.10 Base test setup for a 1U cubesat.

The exported data from both of these cases is then loaded up and visualized in the developed software Dr. Vib D. version 1.1. **Fig 3.11** shows the comparison for Case 1. The accelerometer data is labeled as '*Monitor before*' for the resonance survey before testing and monitor after for the survey done after the testing. Profile for the sine sweep is a constant acceleration of 0.5 g in all cases.

Case I: When the DUT failed the test

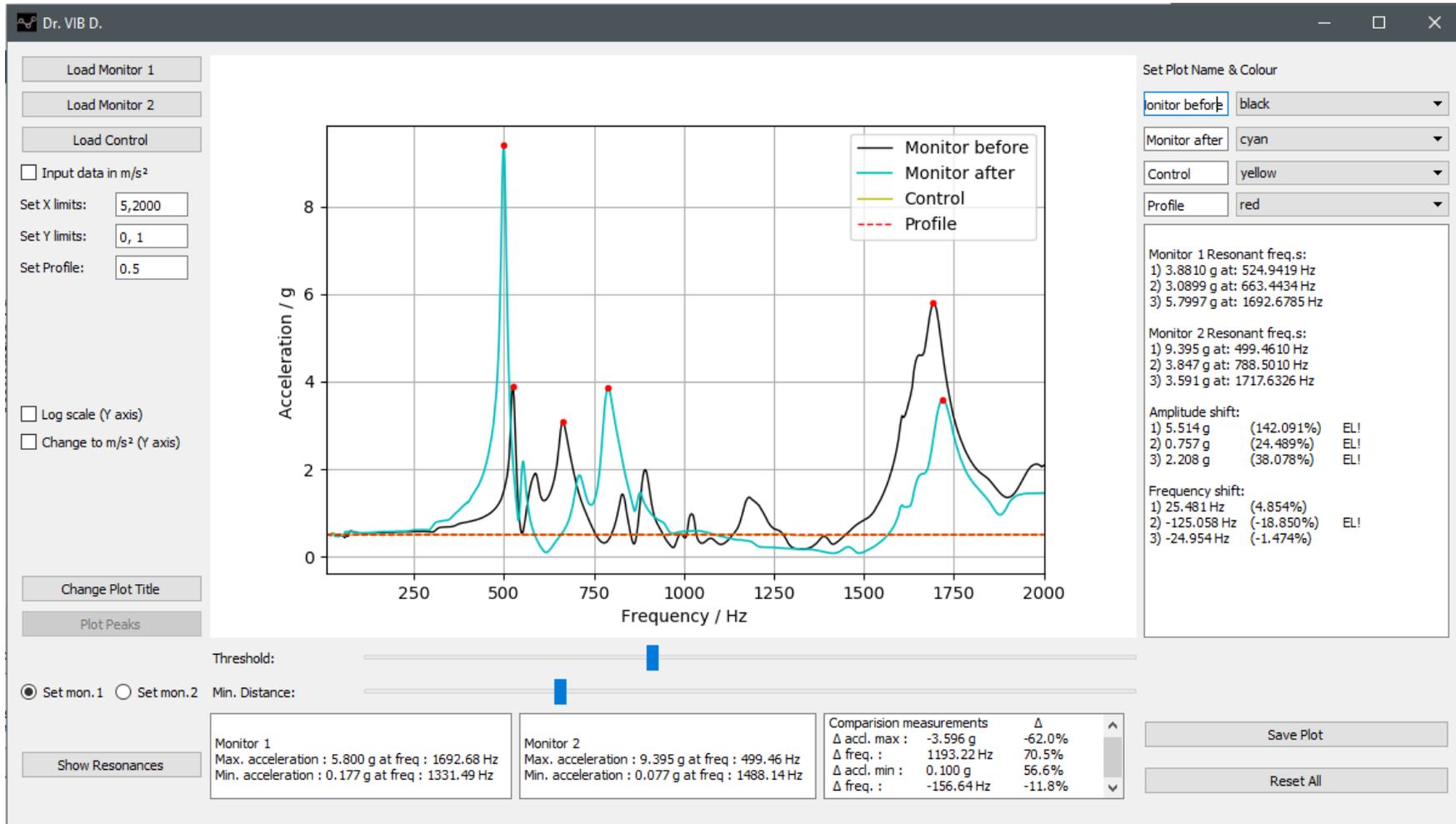


Fig 3.11 Sine sweep characterization comparison for Case I.

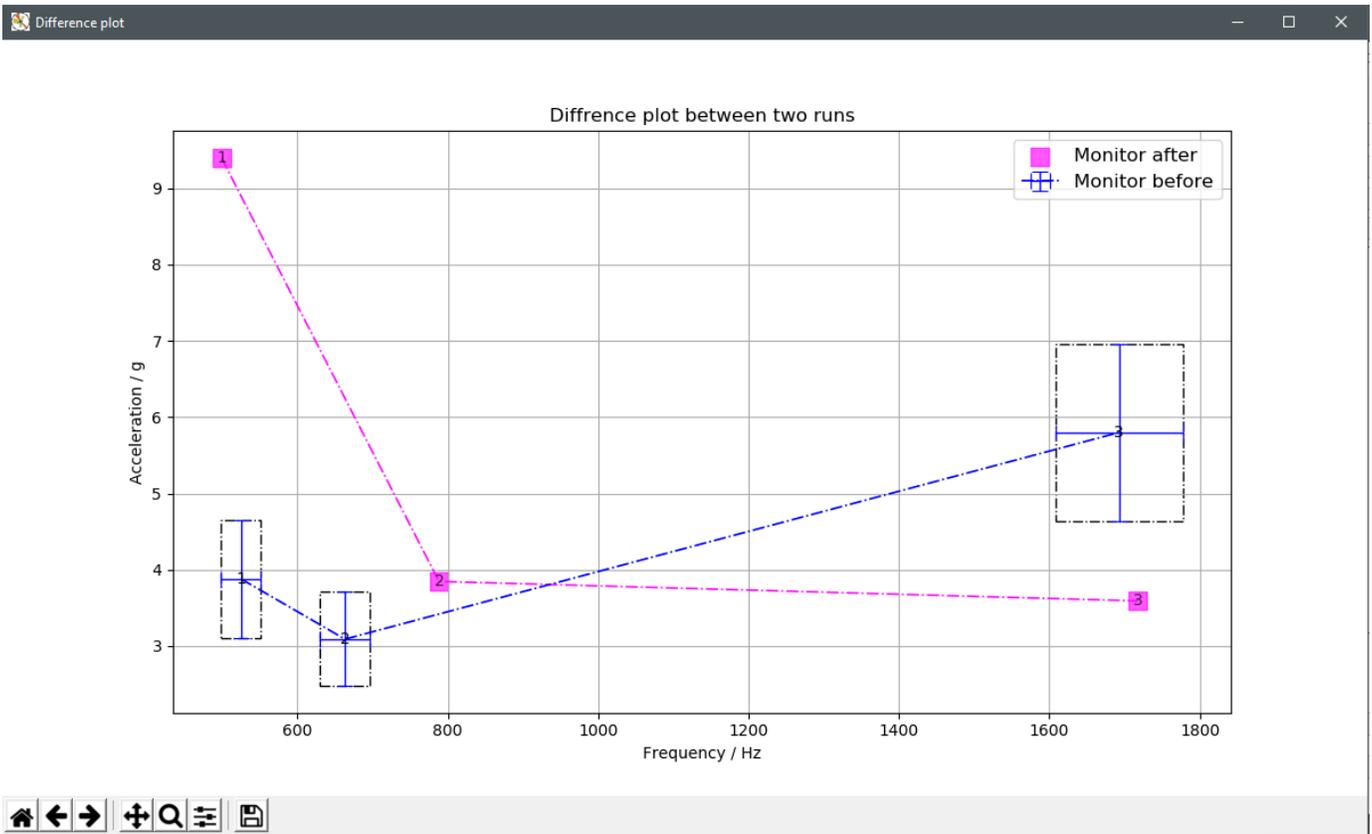


Fig 3.12 Peak plot and comparison (Case I).

Case II:

Same procedure is followed for the comparison of Case II. **Fig 3.13** and **Fig 3.14** show the resonance survey comparison and the resonant plot and analysis respectively. In this case the DUT has passed the test.

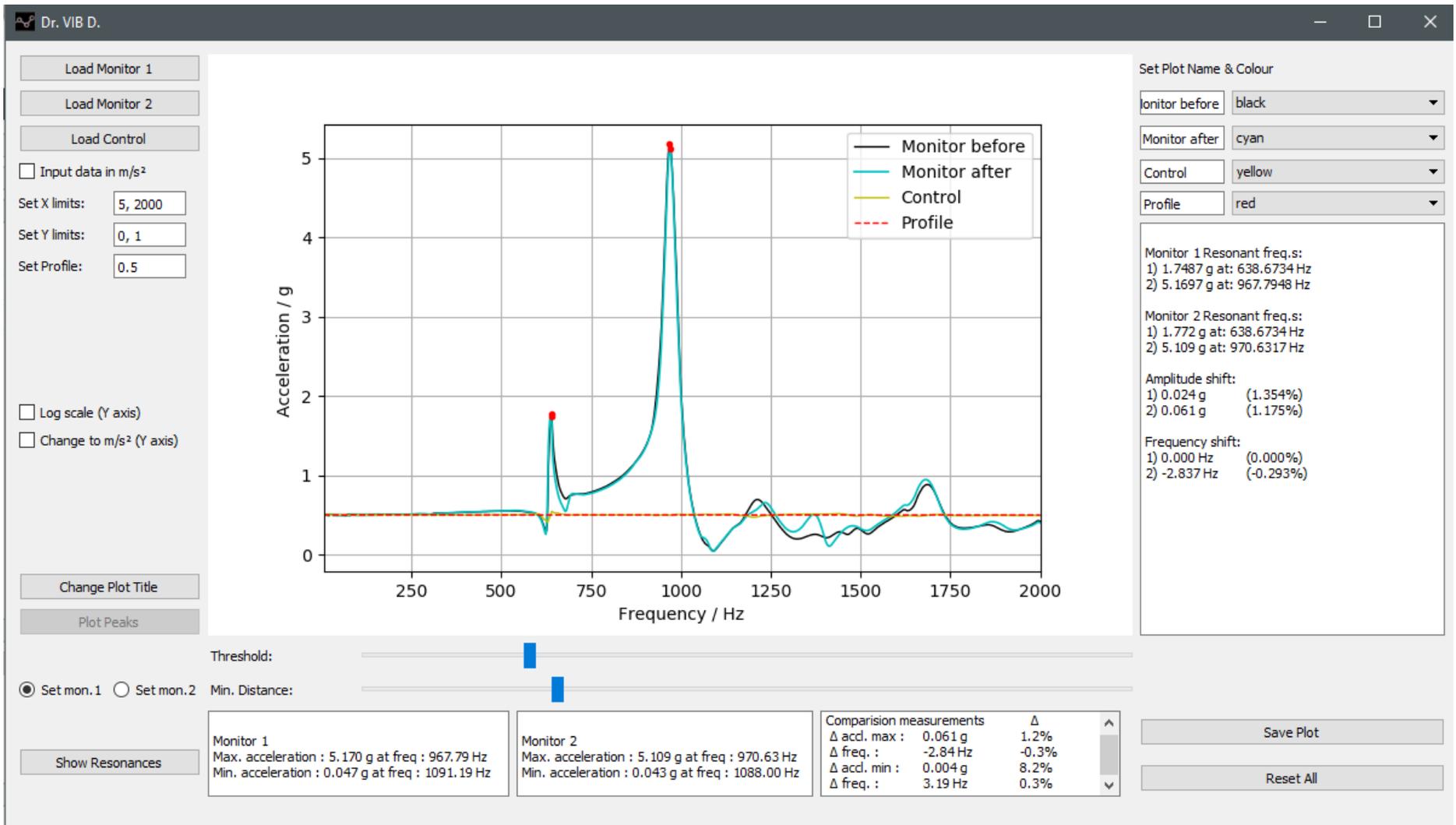


Fig 3.13 Sine sweep characterization comparison for Case II.

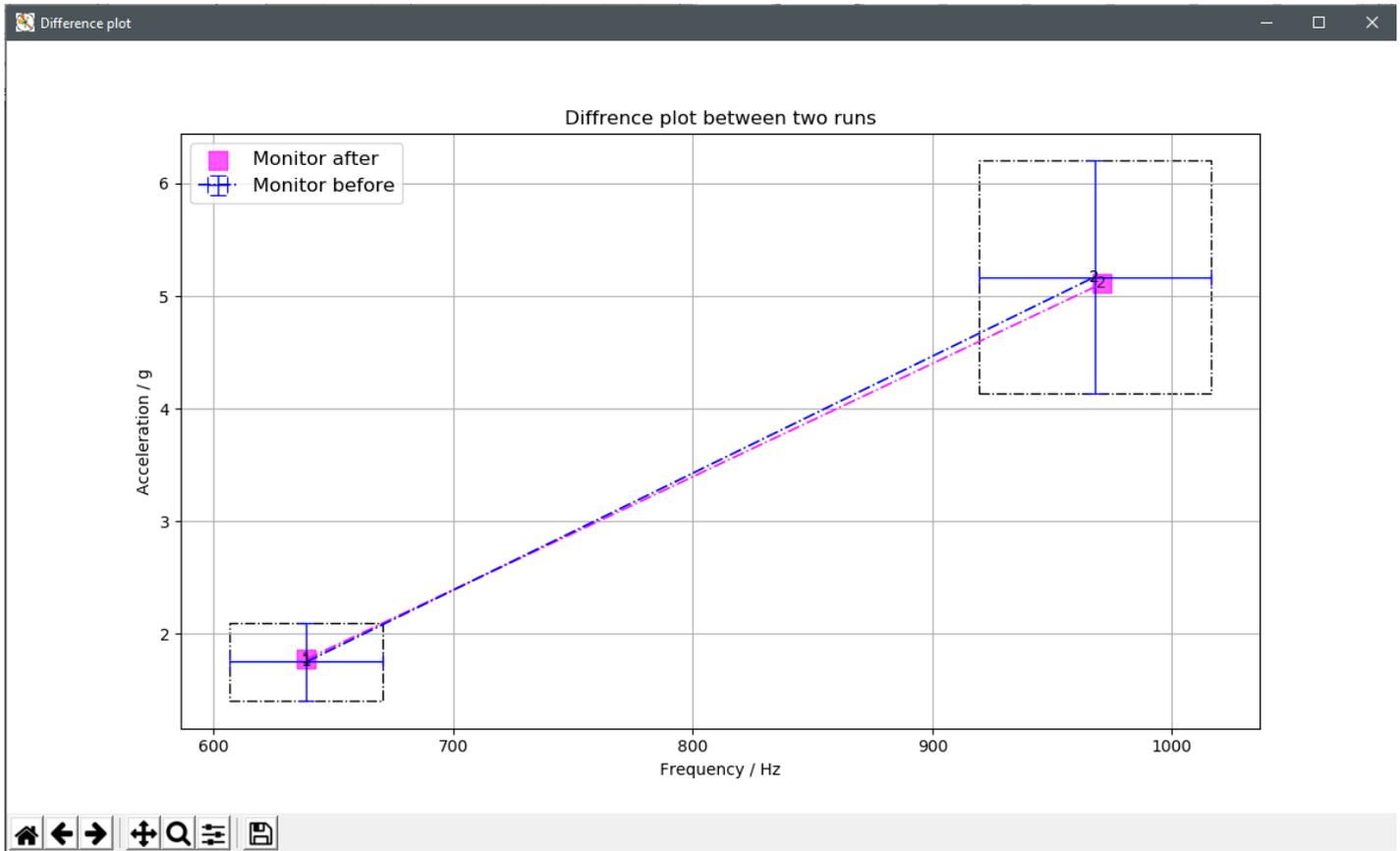


Fig 3.14 Peak plot and comparison (Case II).

3.5.2 Analysis of sample test results

In **Case I** some of the components came loose in after the shock tests and the reference sine sweeps indicate the same i.e., the resonance frequencies are not the same. The amplitude and frequency shifts are calculated by the program and listed as 'EL!' (Exceeds limits). This can be seen in **Fig 3.11**. Further, these peaks are plotted with margin boxes to visualize the shift better, this is seen in **Fig 3.12**.

In **Case II** where the satellite has undergone redesign, the problem has been fixed and can be seen in **Fig 3.13** and **Fig 3.14**, that the amplitude and resonance shifts are within limits.

This verifies that the software is successfully able to visualize the data and the peaks and perform comparison as well.

3.5.3 Future scope

Future work on this software will be continued as the author continues his work in the Laboratory of Space Technology at TO. Some of the main features that will be added to the software are:

- Addition of metadata to the saved plots, so the user to open the plots again in the same software and have access to the previous configuration.
- Currently there exists a fork of the software which enables the user to plot the data directly from sine and random vibration tests. This differences from the main branch are that it provides options for more data inputs for ‘alarm’ and ‘limits’ in the profile, in addition to plotting the control and monitor sensor data. It will soon be merged with the present solution to increase its functionality.
- There is a possibility of making the system acquire live data from the sensors and hence removing the use of vibration controller for measurement of data. This would remove the issue of licensing different elements of the software (which are locked at present) and all elements could be implemented inhouse.

CH 4. CONCLUSIONS

The method for vibration testing along with the vibration testing system at Tartu Observatory for performing the same has been described in this thesis. The author's work with the system led to development of a software solution capable of visualizing the data generated by the system and which makes it easily customizable to meet specific requirements from different customers and specific cases. Furthermore, the option for comparison and analysis of resonant frequencies to characterize structural subsystems has also been implemented.

The developed software has an intuitive user interface and has been in use for about 8 months, during which the output graphs have been integrated into the accredited testing reports compiled for the clients by Tartu Observatory. An example test certificate has been provided in Annex D. The application has improved the efficiency and speed of generating test reports and certificates. The software has been improved steadily with input from the author and his supervisors while working with the vibration testing system. Additional customization options have been added over time and specifically the comparison and analysis module has improved computation and visualization of the frequency and amplitude shift in resonant frequencies.

The design requirements for the software set in section 3.2 have been fulfilled. Tests and analysis of the software performance was done as well. Development and improvement of the software will continue in future; however, this remains already beyond the scope of this master's thesis.

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Lastly, I would like to express my gratitude to Tartu Observatory, University of Tartu for providing me with the opportunity to work and learn there.

A handwritten signature in black ink, appearing to be 'Cyndi' followed by a stylized flourish.

ANNEX A

USER MANUAL FOR DR. VIB D VERSION 1.1

In this section a short user guide for the developed software has been written. The guide also assumes that the user has the software already installed and running on their system. The installation guide for the software can be found in the extended version as well. The following guide gives step by step instructions for a new user.

The software is built to serve as a visualization and analysis tool on top of the proprietary software that is in use with the BKSV system control and measurement system. The data files have to be extracted from that in the *.xlsx format. Monitor 1 is the swept sine data from the accelerometer, before the DUT has undergone environmental testing (sine vibrations, random vibrations or shock). Monitor 2 is again the swept sine data from the same sensor, in the same location after the tests have been performed. A sample file that is loaded, is provided in Annex C. The step by step guide is given below:

Step 1: Initializing the program

Fig A.1 shows the first window that opens up upon running the software. The interface has been described in the section 3.4.3.

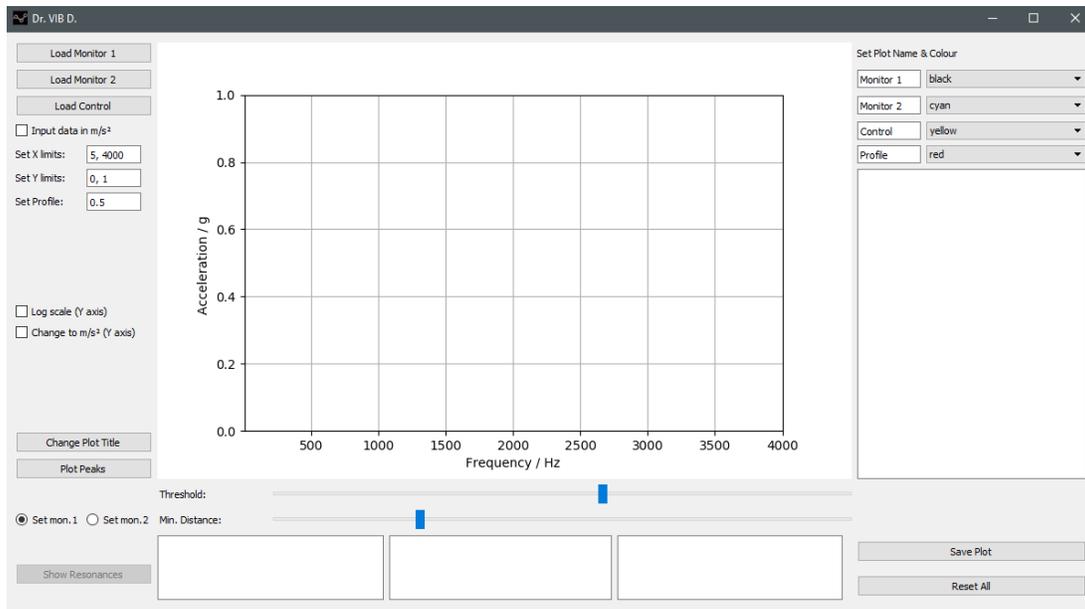


Fig A.1 Initial window shown upon running the software.

Step 2: Loading data

First step is to Load all the data files, namely Monitor 1, Monitor 2 and control. On pressing any one of these buttons, an open file dialogue opens up as shown in **Fig A.2** The data files are accepted only in the '*.xlsx' format. All three data files have to be loaded for further progress.

There is also an option to change the display units to m/s^2 if the input data is already in those units.

As soon as all the data files have been loaded, the program identifies the maximum and minimum values (both frequency and acceleration) for Monitor 1 and 2. It further calculates the differences between these values, all of which is displayed in the output text boxes also shown in **Fig A.3**.

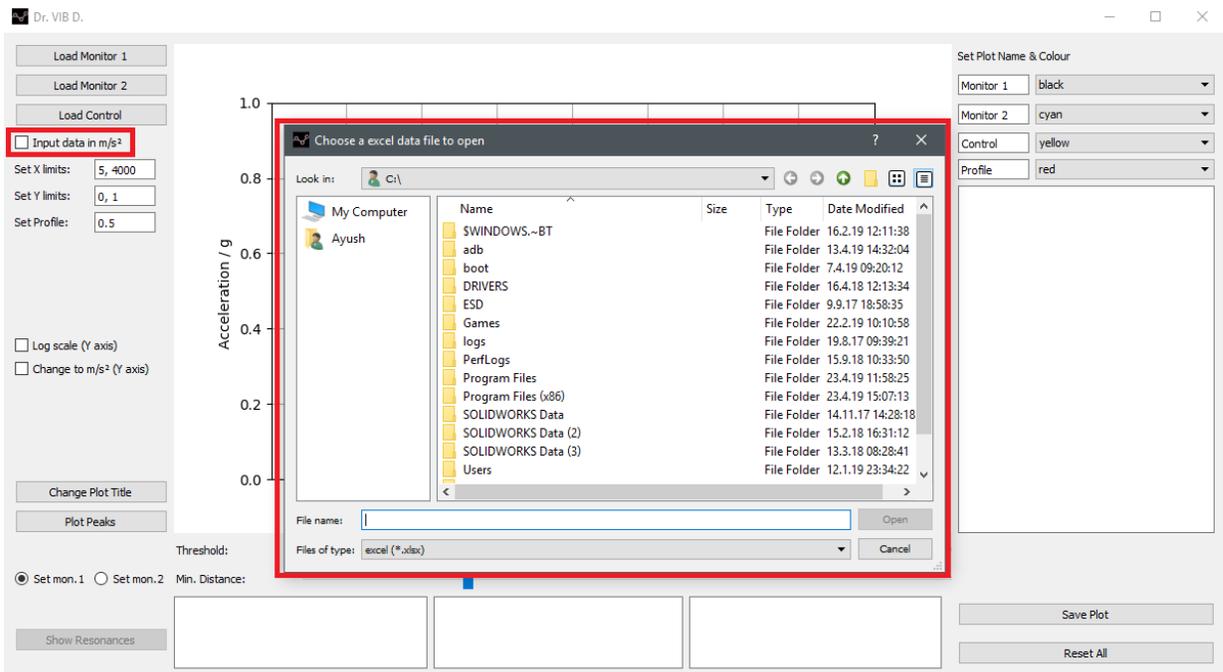


Fig A.2 The open file dialogue box and 'input units' options.

Monitor 1 Max. acceleration : 0.691 g at freq : 595.35 Hz Min. acceleration : 0.372 g at freq : 657.64 Hz	Monitor 2 Max. acceleration : 0.632 g at freq : 598.84 Hz Min. acceleration : 0.396 g at freq : 629.39 Hz	Comparison measurements Δ acc. max : 0.059 g 8.5% Δ freq. : -3.50 Hz -0.6% Δ accl. min : -0.024 g -6.5% Δ freq. : 28.25 Hz 4.3%
--	--	--

Fig A.3 The output box displaying Monitor 1&2 data along with the comparison.

Step 3: Configuring the limits and profile

The program sets the limits for both X and Y axis's automatically, but in particular cases where there is a large variation in data, or specific client requirements the limits can be set manually in the editable text boxes as shown in **Fig A.4**.

The preconfigured level for profile is set to 0.5 g. It can also be changed according to requirements.

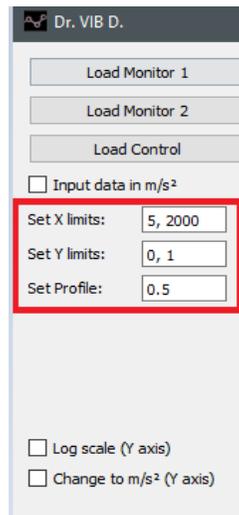
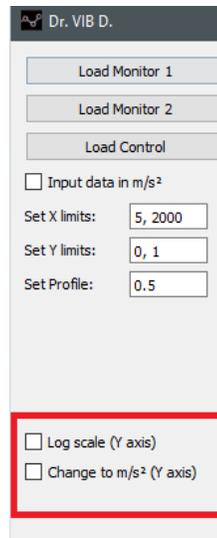


Fig A.4 Configuring the X&Y axis limits and the profile plot.

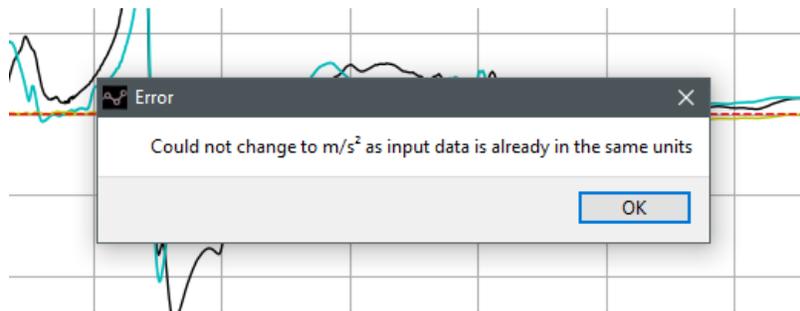
Step 4: Configuring the scale and units of the data

The scale of the Y axis is configured and can be changed to log scale, originally its set to linear. The units of the input data can be changed to m/s². This multiplies all the amplitude data (acceleration) by a factor of 'g'. Both these options are again set to client requirements (**Fig A.5 (a)**).

The option to change units of data to m/s² is disabled if the 'input data in m/s²' option has been checked at the initial loading of data. It shows an error message as shown in **Fig A.5 (b)**.



a)



b)

Fig A.5 a) Change Y axis scale to log and data units to m/s^2
b) Error message for changing units of data to m/s^2 .

Step 5: Set the title of the plot

The title of the plot can be set by calling the Change Plot Title Function, which opens up a text box for the user to enter the new title. Base configuration is “ ” i.e. no set title.

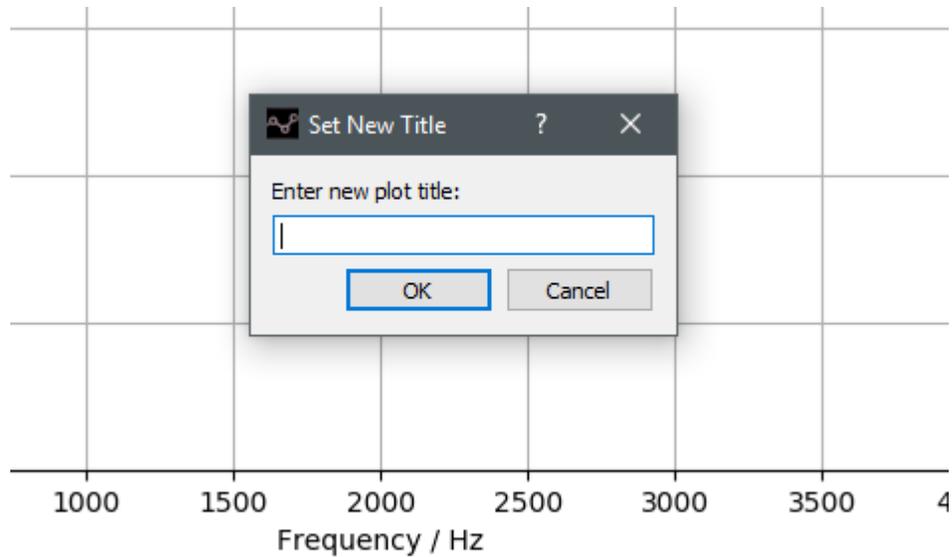


Fig A.6 Edit plot title prompt.

Step 6: Configuring the plot labels and colors

On the extreme right of the window, there are option to configure the label and color of each of the four plots which again are modified as per client requirements.

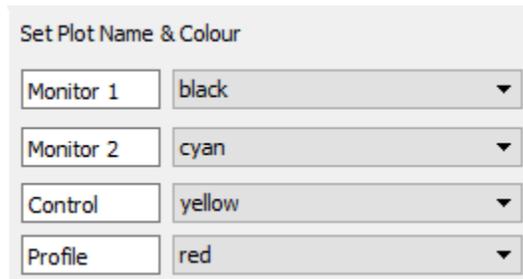


Fig A.7 Configure plot label and color.

Step 7: Peak find and plot

The basic function of visualization and modification of parameters has been achieved at the end of Step 7. This step onwards is the description of utilizing the resonance frequency analysis built into the software. The Plot Peaks button is clicked on to display the peaks in the data from Monitor 1 & 2.

The adjustment and selection of the peaks is controlled by the two sliders as pointed out in **Fig A.8**. The selection is at the discretion of the user. The first slider controls the threshold

of the values corresponding to the maximum amplitude/acceleration. The Min. distance slider then controls the allowed distance between two consecutive peaks.

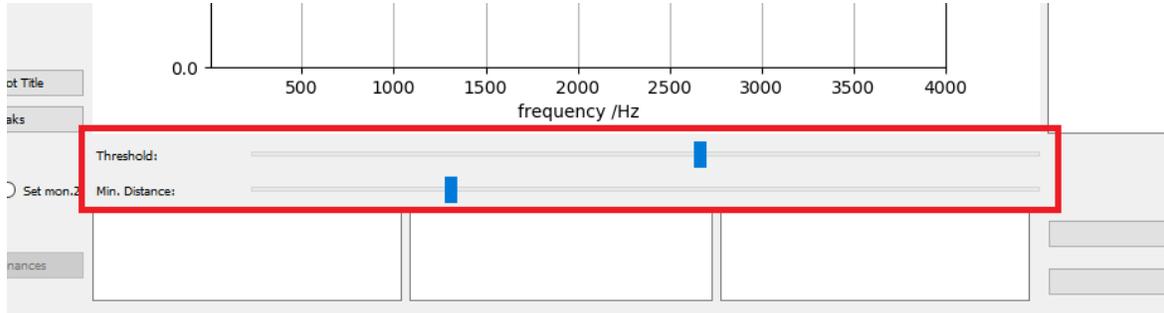


Fig A.8 Shown comparison of peaks/

Step 8: Resonance analysis

After careful selection and adjustment of the identified peaks, the Show Resonances button can be clicked on to list the resonant frequencies and their amplitudes. In addition, the amplitude shift and frequency shift are calculated and displayed in the text box as shown in **Fig A.9**. This also opens up another window (**Fig A.10**) which plots all the identified peaks and draws the margin boxes for easier visualization and comparison.

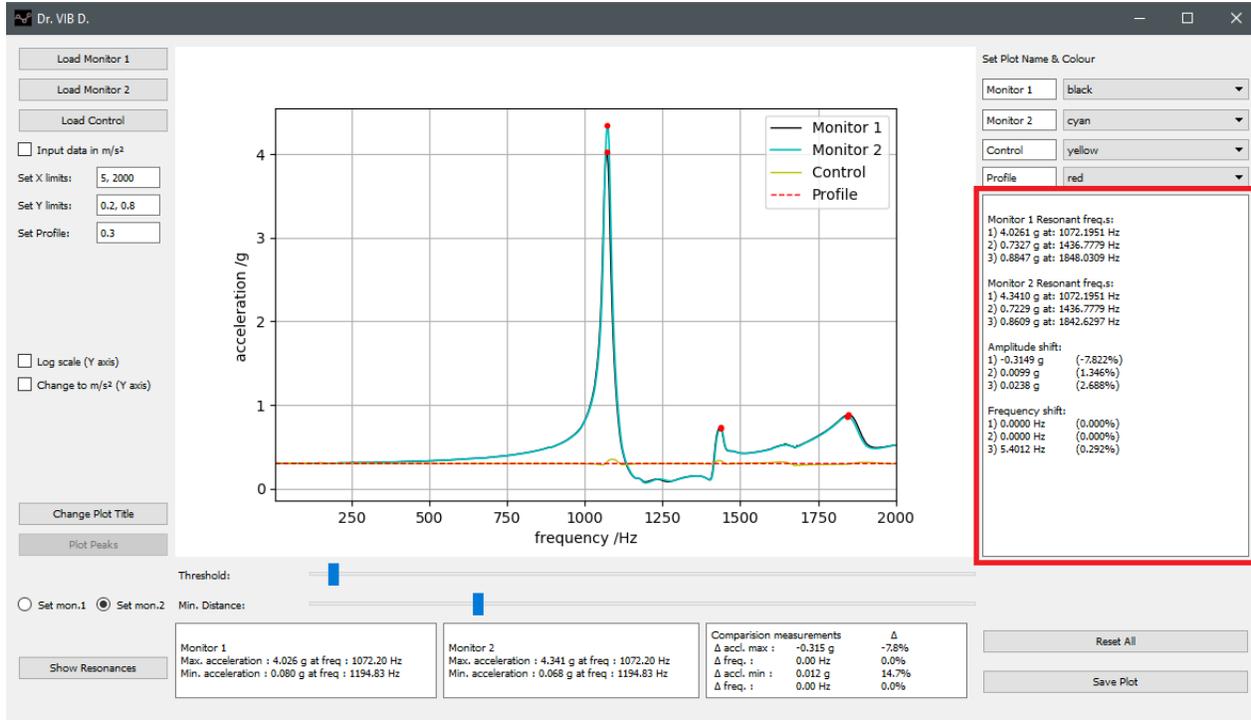


Fig A.9 Comparison of resonance peaks.

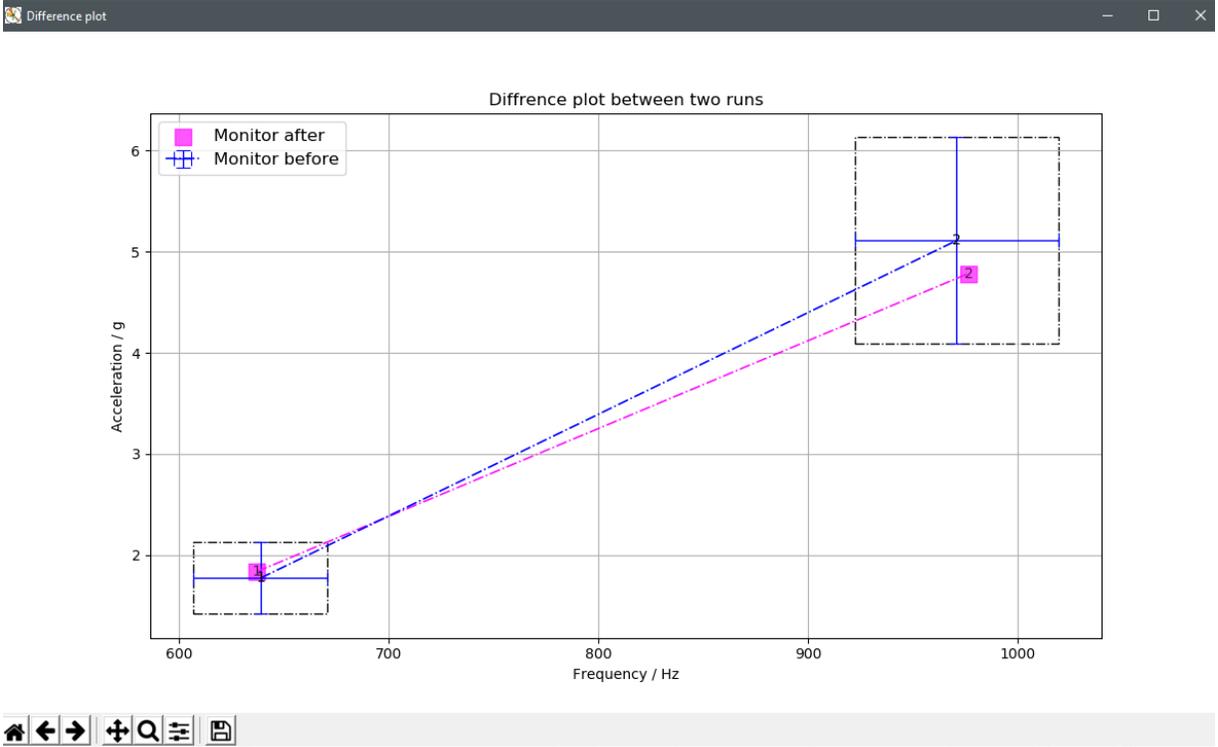


Fig A.10 Amplitude and frequency shift analysis plot.

Step 9: Saving the plot

The save plot button can be used to open a save file dialogue box, which allows the user to save the main plot in either '*.png' or '*.jpeg' format. In addition, it also generates a *.txt file which logs all the calculated data. The interface can be completely reset with the use of Reset All button, and its ready to be used for a new configuration again.

ANNEX B

TEST LOG

Some fields have been blacked out to maintain confidentiality.

Start time : 10:54

Test operators: Ayush Jain and Mari Allik

Folder: XXXXXXXXXX

note: starting profile at 2g from 10Hz instead from 5Hz

Run 16	ref. sine 0,5g	X axis	
Run 17	low sine profile (up)	x axis	aborted
Run 18	low sine profile (up)	x axis	
Run 19	low sine profile (down)	x axis	aborted
Run 20	low sine profile (down)	x axis	
Run 21	ref. sine 0,5g	x axis	

axis change to Y

note: during switching axis, screw from the bottom of the satellite loose and lying on the shaker, screwed back in

Run 22	ref. sine 0,5g	y axis	
Run 23	low sine profile (up)	y axis	
Run 24	low sine profile (down)	y axis	
Run 25	ref. sine 0,5g	y axis	

axis change to Z

Run 26	ref. sine 0,5g	z axis	
--------	----------------	--------	--

Run 27	low sine profile (up)	z axis	
Run 28	low sine profile (down)	z axis	
Run 29	ref. sine 0,5g	z axis	#ref. for random in z

Random vibrations

Folder: ██████████

z axis

Run 5	random. vega profile	z axis	aborted
Run 6	random. vega profile	z axis	

Folder: ██████████

Run 30	ref. sine 0,5g	z axis	#after random
--------	----------------	--------	---------------

axis change to y:

Run 31	ref. sine 0,5g	y axis	#before random
--------	----------------	--------	----------------

Folder: ██████████

Run 7	random. vega profile	y axis	aborted
Run 8	random. vega profile	y axis	aborted
Run 9	random. vega profile	y axis	

Folder: ██████████

Run 32	ref. sine 0,5g	y axis	#after random
--------	----------------	--------	---------------

axis change to x:

Run 33	ref. sine 0,5g	x axis	#before random
--------	----------------	--------	----------------

Folder: ██████████

Run 10 random. vega profile x axis

Folder: XXXXXXXXXX

Run 34 ref. sine 0,5g x axis #before shock, after random

Run 35 ref. sine 0,5g x axis #after shock

Run 36 ref. sine 0,5g y axis #before shock

Run 37 ref. sine 0,5g y axis #after shock

Run 38 ref. sine 0,5g z axis #before shock

Run 39 ref. sine 0,5g z axis #before shock

End time: 15:30

ANNEX C

SAMPLE DATA FILE SNIP

Usually the number of samples are 2048 for frequency and acceleration. This sample rate is fixed in the software and cannot be altered.

	A	B
1	Signal Name	SIG0001_Spectrum(3D_X
2	Software Used	Crystal Instruments EDM s
3	Instrument Used	Spider
4	Test Notes	Untitled Test Note
5	Data Acquisition Time	6/6/2018 10:31:08 AM
6	Signal Export Time	9/4/2018 3:49:30 PM
7	Sampling Rate	20.48 kHz
8	Block Size	2048
9	X Axis Data Start	99
10	X Axis Data Resolution	1.000005
11	Acquisition/Calculation Method	Undefined
12	Amplitude Scaling	0-Peak
13	Average Mode	Exponential
14	Averaging Time Constant	0
15	Number of Averages	0
16	Signal Type	Frequency
17	Display Format of Y Axis	Mag
18	Default Spectrum Type	EUpeak
19	Unit of X	Frequency (Hz)
20	Unit of Y	Mag g (0-peak)
21	Spectrum Format	Power Spectrum
22	Window Type	Hanning
23	Window Correction Mode	Amplitude
24	Energy Factor	0.09375
25	Amplitude Factor	0.125
26	X:Frequency (Hz)	Y:Mag g (0-peak)
27		99 3.007588326
28		99.00048387 3.007596253
29		99.00096774 3.007604181
30		99.00145162 3.007611949
31		99.0019355 3.007619876
32		99.00241938 3.007627804
33		99.00290326 3.007635731
34		99.00338714 3.007643658
35		99.00387103 3.007651585
36		99.00435492 3.007659512
37		99.00483881 3.00766728
38		99.00532271 3.007675207
39		99.0058066 3.007683134

ANNEX D

SAMPLE TEST REPORT

Description of the test object has been blacked out to maintain confidentiality.

	
<h1>Katsetustunnistus</h1> <h2>Testing certificate</h2>	
Katsetunnistuse nr ja kuupäev: Testing Certificate No and Date:	[Redacted]
Tellimuse nr ja kuupäev: Order No and Date:	[Redacted]
Tellijä: Customer:	[Redacted]
Katseobjekt: Test object:	1-unit CubeSat
Number: Serial number:	[Redacted]
Katseobjekti(de) saabumine laborisse: Test object arrival:	[Redacted]
Katse(te) teostamise ajavahemik: Date of Tests:	[Redacted]
Kasutatud meetod ja akrediteeritus: Method used and accreditation:	M801:23.05.2018 Vibration testing (not in the scope of accreditation)
Allkirjad: Signatures:	
<i>/allkirjastatud digitaalselt/ Riho Vendt Kosmosetehnoloogia labori juhataja Head of laboratory of Space Technology</i>	<i>/allkirjastatud digitaalselt/ Mari Allik Koostaja(d) Compiled by</i>
Dokument koosneb katsetunnistusest ja –tulemuste kokkuvõttest 13 lehel ning on välja antud ühes (1) allkirjastatud eksemplaris.	The document consists of a Testing Certificate with a Summary of Results on 13 pages in one (1) signed copy
Mari Allik, mari.allik@ut.ee, TÜ katsekoja kosmosetehnoloogia labor, Observatooriumi 1, 61602, Tõravere, Nõo vald, +372 737 4501 Testing Centre of University of Tartu, Space Technology Laboratory, Observatooriumi 1, 61602, Tõravere, Nõo vald, +372 737 4501	

Katsetunnistuse nr:
Testing Certificate No:

Kuupäev
Date

Lehekülg
Page
2 (13)

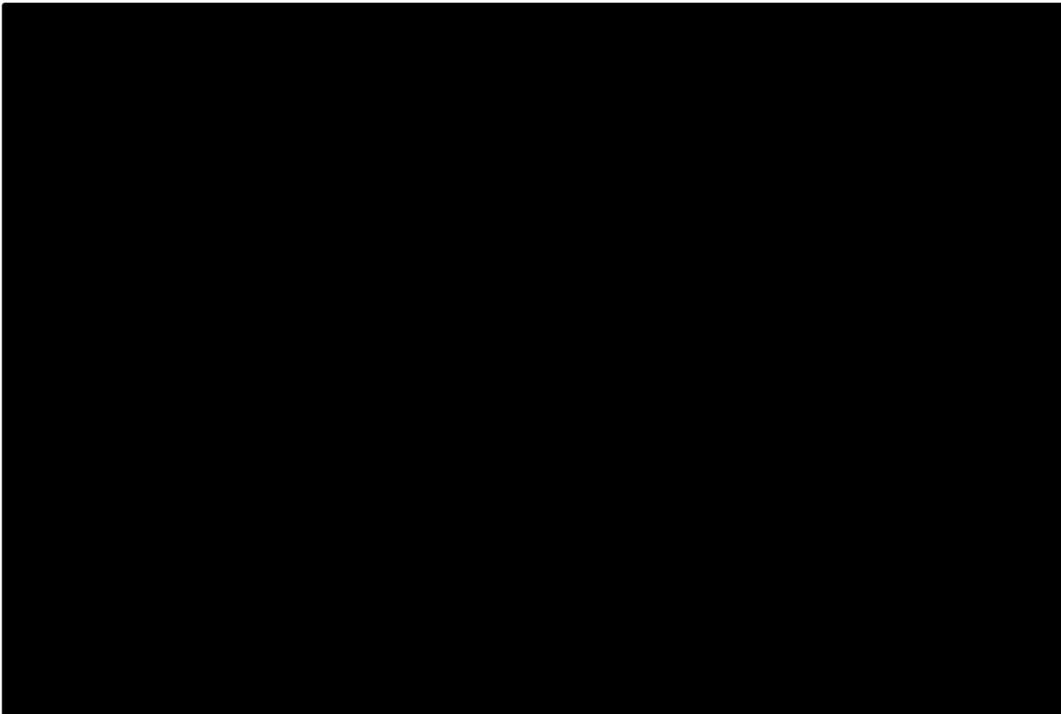
1. Testing equipment

1. Vibration controller Brüel & Kjær Type 7541 S/N 1302400,
2. Power amplifier LDS PA1000L S/N N1525 6678890,
3. Field power supply LDS FPs 10L-CE S/N N1449,
4. LDS V-650 Air Cooled Vibrator S/N 308257/1,
5. Brüel & Kjær accelerometer (control) DeltaTron 4526-001 S/N 30402,
6. PCB Piezotronics triaxial accelerometer (monitor) 356A44 S/N 206372,
7. Precision scale Kern PCB 6000-1 +/- 0.1 grams, S/N WD140114021.

2. Traceability

The measurement results are traceable to the units of SI through the standards of national metrology institutes Metroser, NIST and PTB.

3. Description of test object

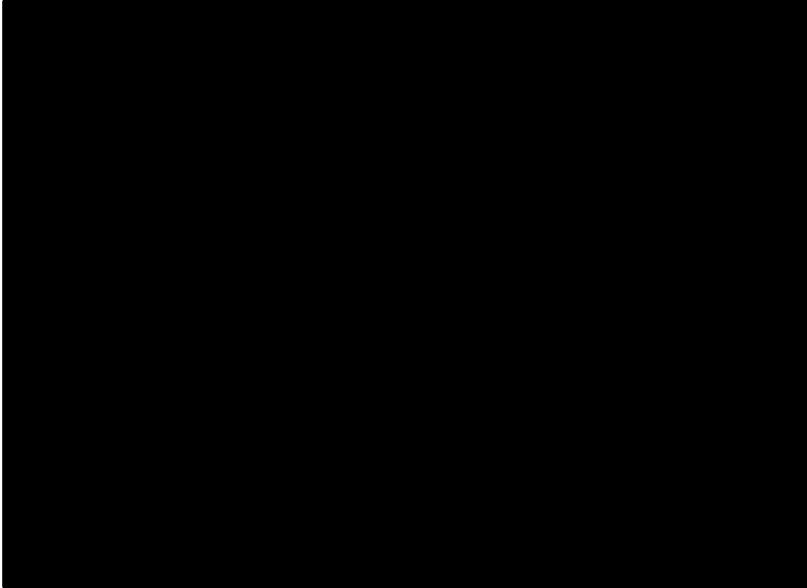


The mounting fixture (spacer plate) is mounted to the vibration bench with 7 M8 bolts and 1 M10 bolt. The M8 bolts are tightened to 25 Nm torque and the M10 bolt is tightened to 38 Nm torque. The fixture with the DUT is attached to the spacer plate with 4 M8 bolts tightened to 25 Nm torque. The controller feedback and monitor accelerometers are placed in the centre on top of the mounting fixture as seen in Figure 3.2.

Katsetunnistuse nr:
Testing Certificate No:

Kuupäev
Date

Lehekülg
Page
3 (13)



4. Test method

Vibration testing is performed according to the test procedure M801:23.05.2018 Vibration testing.

4.1 Control method and strategy

The vibration tests are performed by single point control. The signal from the control accelerometer at the reference point (see Figure 3.2) is used in order to maintain the specified vibration levels. Close loop control strategy is used during the vibration test. The cross-axis motion is monitored in 3 axis with the triaxial accelerometer during the tests and it offers no hazard to the DUT.

4.2 Test severities

The vibration profiles and test severities are presented in Tables 4.1-4.3. The number of spectral lines is 1024 for the reference sine vibration test and 450 for the random vibration tests. The frequency resolution is 3.9 Hz for the reference sine vibration tests and 8,9 Hz for the random vibration tests.

Table 4.1. Reference sine sweep profile

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

Table 4.2 Sine vibration profile

Frequency /Hz	Acceleration /g	High Abort /dB	Low Abort /dB
5	1	6	-6
10	2		
70	2		
110	1		
125	0.2		

Run No.	Frequency range /Hz	Test description	Sweep direction	Test duration/s	Comments
16	20...2000	Random vibration VEGA profile	-	120	DUT z-axis
17	5...2000	Reference sine, 0.5 g	Up	259	DUT z-axis reference after random vibration
18	5...2000	Reference sine, 0.5 g	Up	259	DUT y-axis reference before random vibration
19	20...2000	Random vibration VEGA profile	-	64	DUT y-axis (aborted)
20	20...2000	Random vibration VEGA profile	-	42	DUT y-axis (aborted)
21	20...2000	Random vibration VEGA profile	-	120	DUT y-axis
22	5...2000	Reference sine, 0.5 g	Up	259	DUT y-axis reference after random vibration
23	5...2000	Reference sine, 0.5 g	Up	259	DUT x-axis reference before random vibration
24	20...2000	Random vibration VEGA profile	-	120	DUT x-axis
25	5...2000	Reference sine, 0.5 g	Up	259	DUT x-axis reference after random vibration

Ref. sine sweep comparison after sine vibrations (X axis)

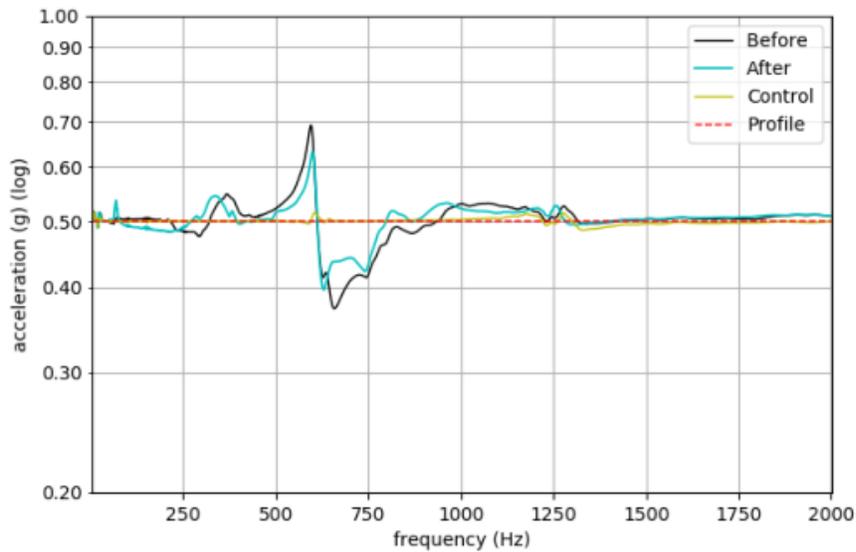


Figure 5.1. Reference sine before and after the sine vibration x-axis tests (Run 1&6)



Low sine vibrations (X axis) (up)

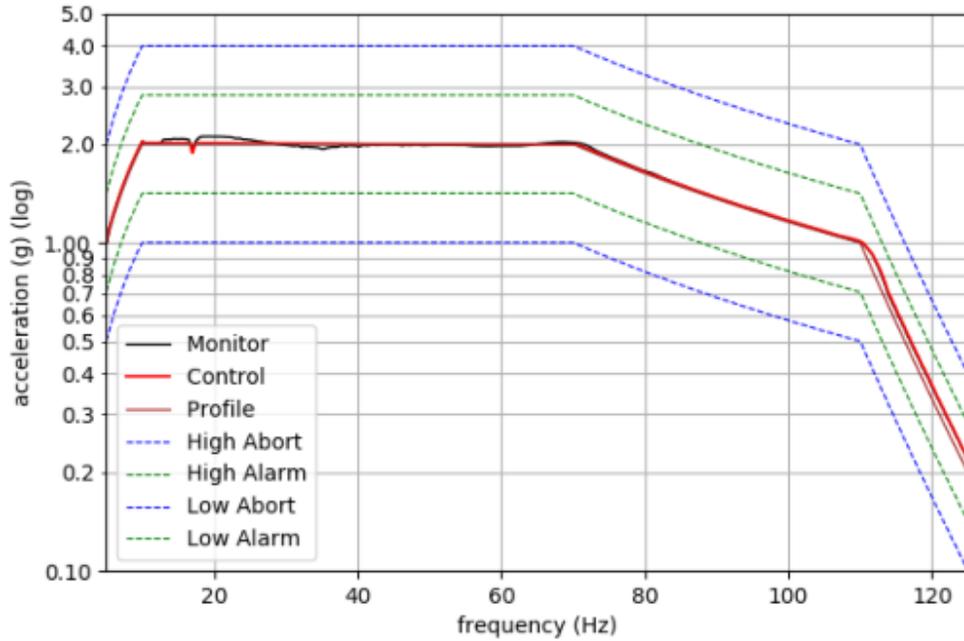


Figure 5.2. Sine vibration test for x-axis (up, Run 3)

Low sine vibrations (X axis) (down)

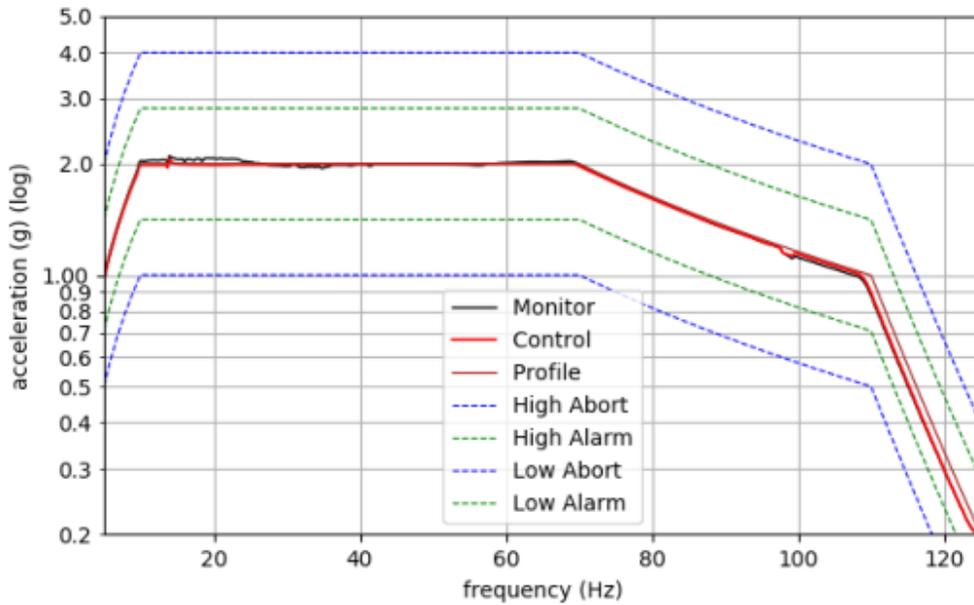


Figure 5.3. Sine vibration test for x-axis (down, Run 5)

Ref. sine sweep comparison after sine vibrations (Y axis)

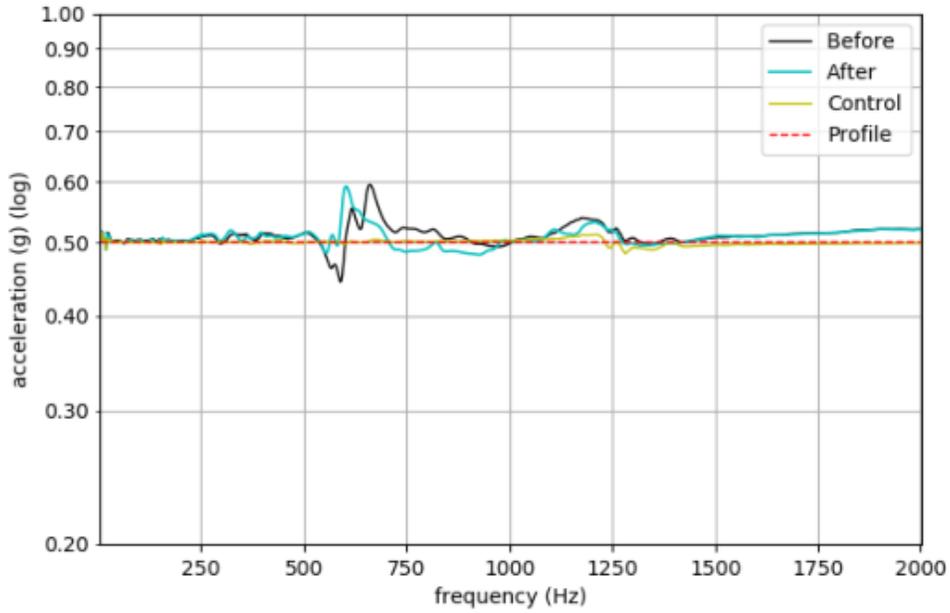


Figure 5.4. Reference sine before and after the sine vibration y-axis tests (Run 7&10)

Low sine vibrations (Y axis) (up)

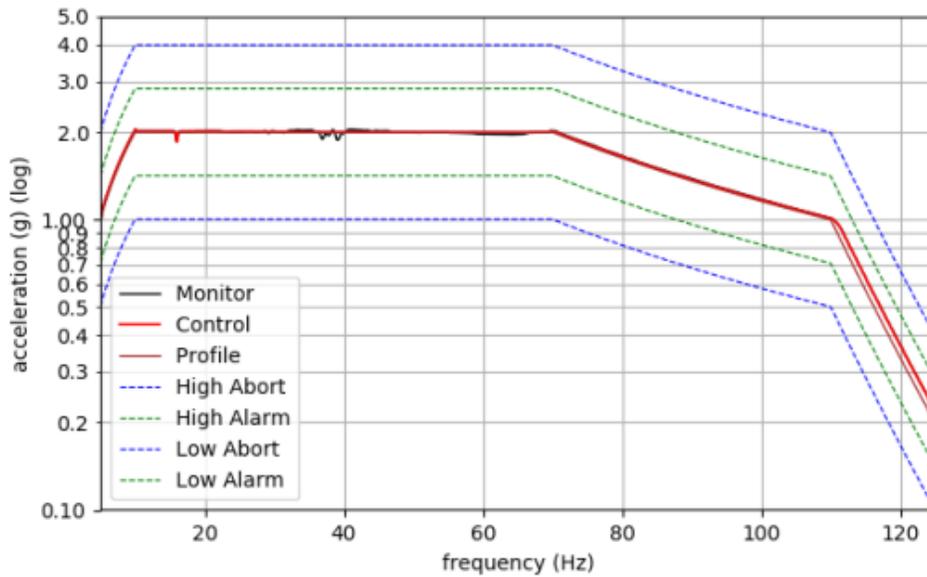


Figure 5.5. Sine vibration test for y-axis (up, Run 8)

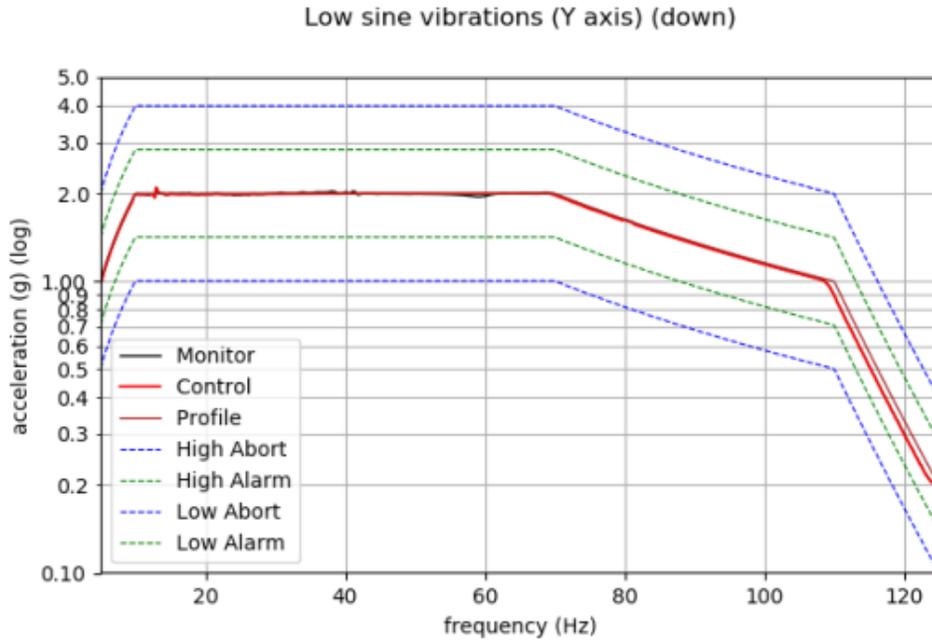


Figure 5.6. Sine vibration test for y-axis (down, Run 9)

Ref. sine sweep comparison after sine vibrations (Z axis)

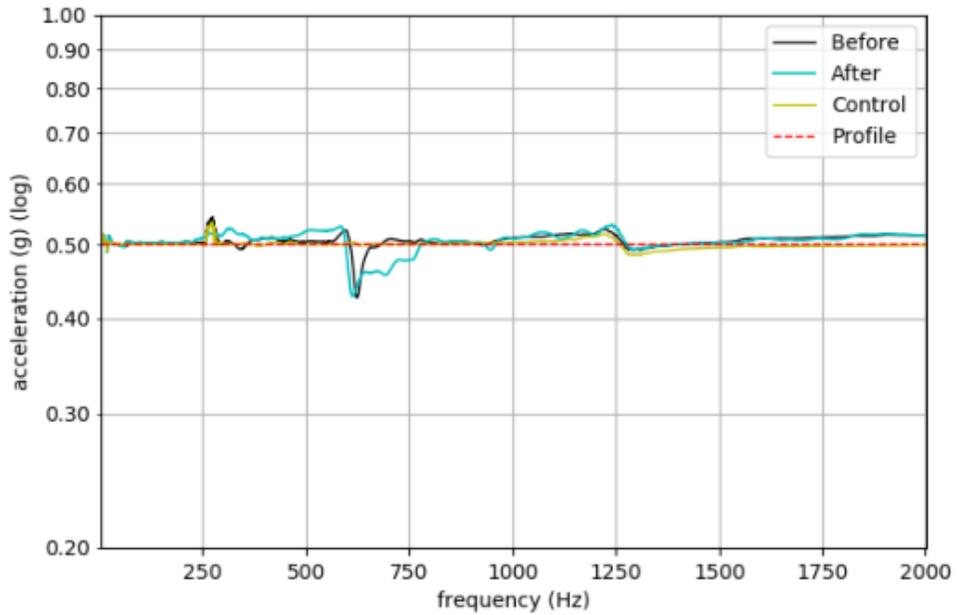


Figure 5.7. Reference sine before and after the sine vibration z-axis tests (Run 11&14)

Low sine vibrations (Z axis) (up)

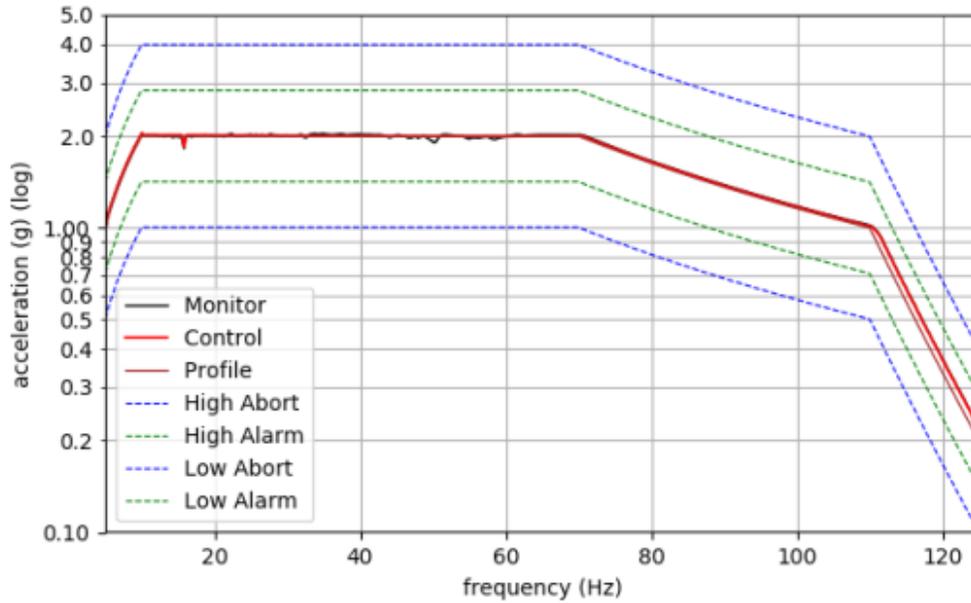


Figure 5.8. Sine vibration test for z-axis (up, Run 12)

Low sine vibrations (Z axis) (down)

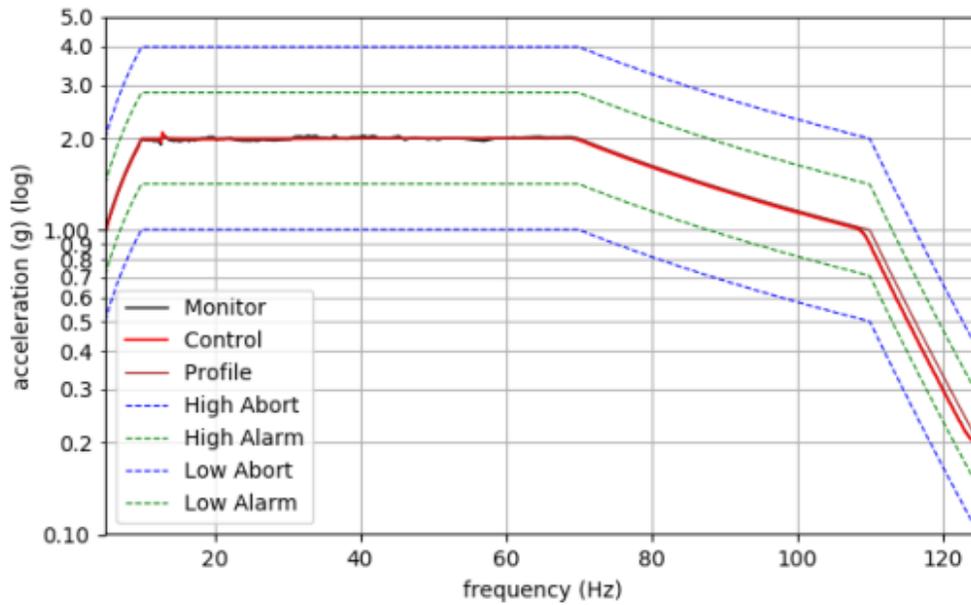


Figure 5.9. Sine vibration test for z-axis (down, Run 13)

Ref. sine sweep comparison after random vibrations (Z axis)

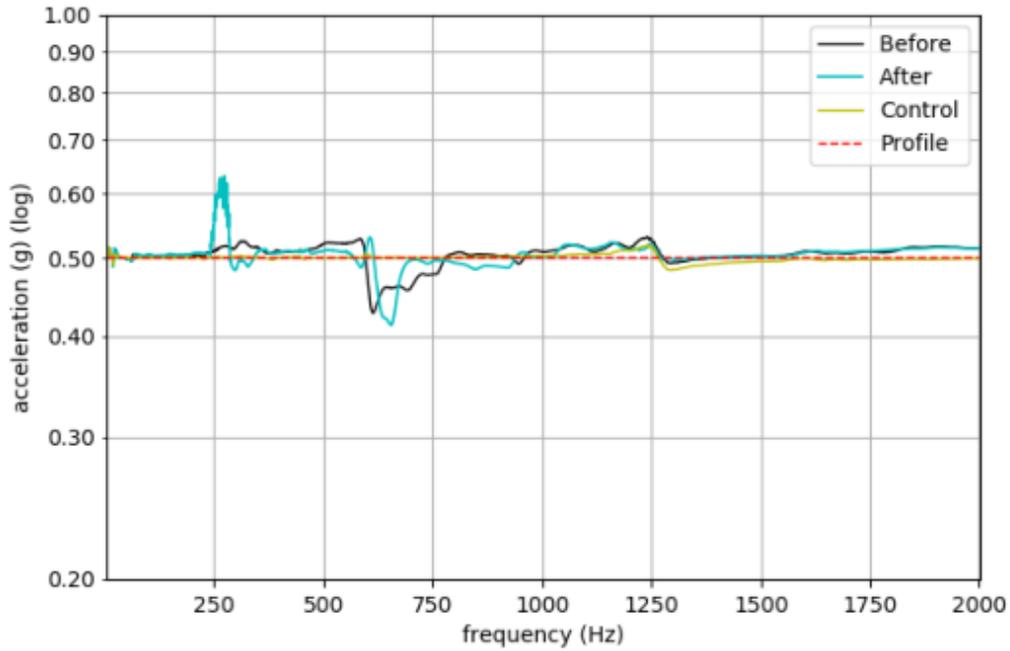


Figure 5.10. Reference sine before and after the random vibration z-axis test (Run 14 & 17)

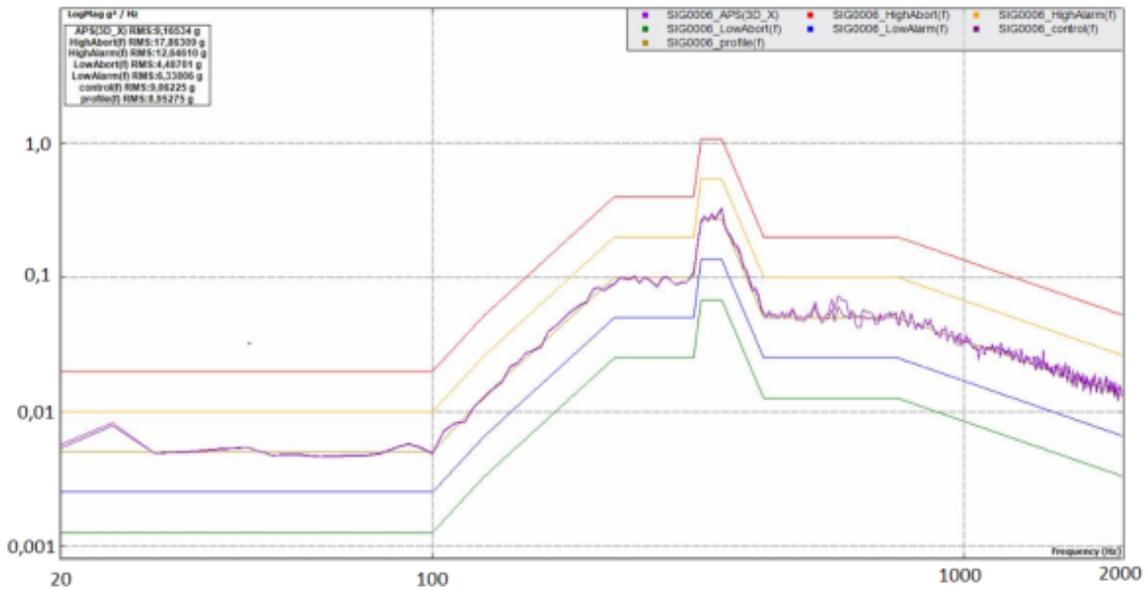


Figure 5.11. Random vibration z-axis test (Run 16)

Ref. sine sweep comparison after random vibrations (Y axis)

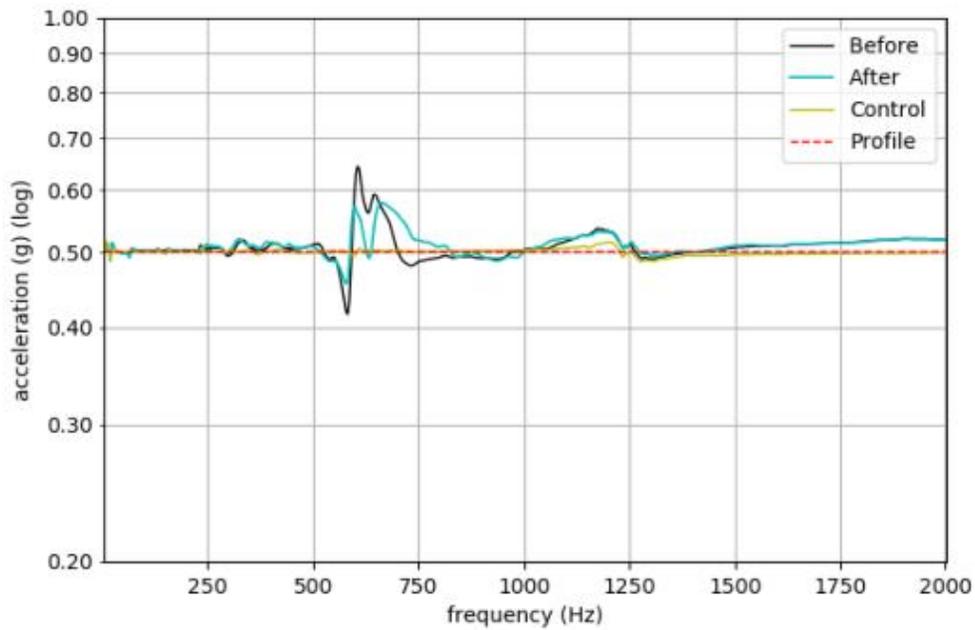


Figure 5.12. Reference sine before and after the random vibration y-axis test (Run 18 & 22)

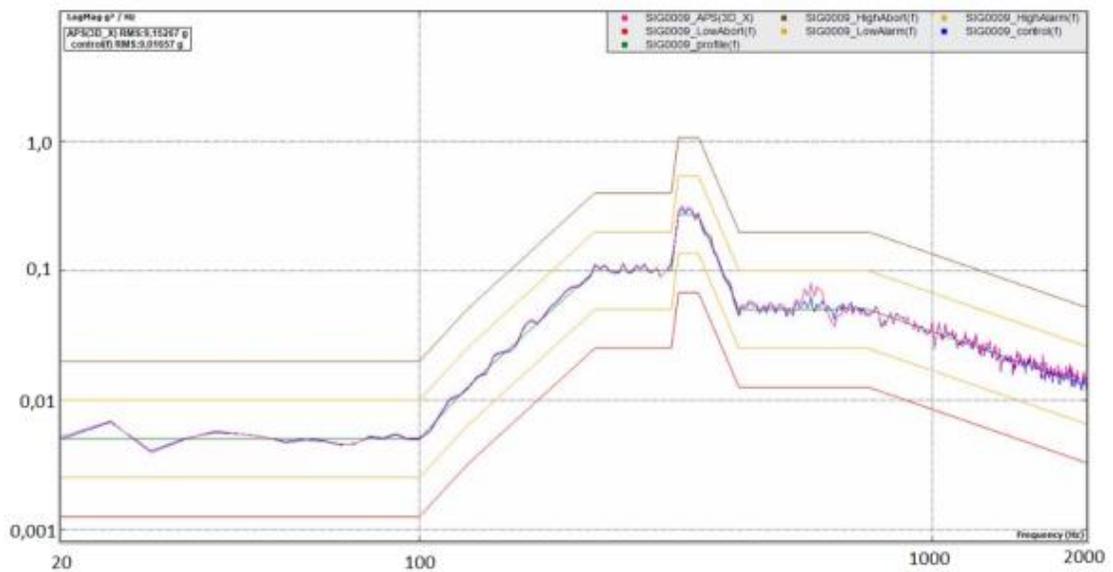


Figure 5.13. Random vibration y-axis test (Run 21)

Ref. sine sweep comparison after random vibrations (X axis)

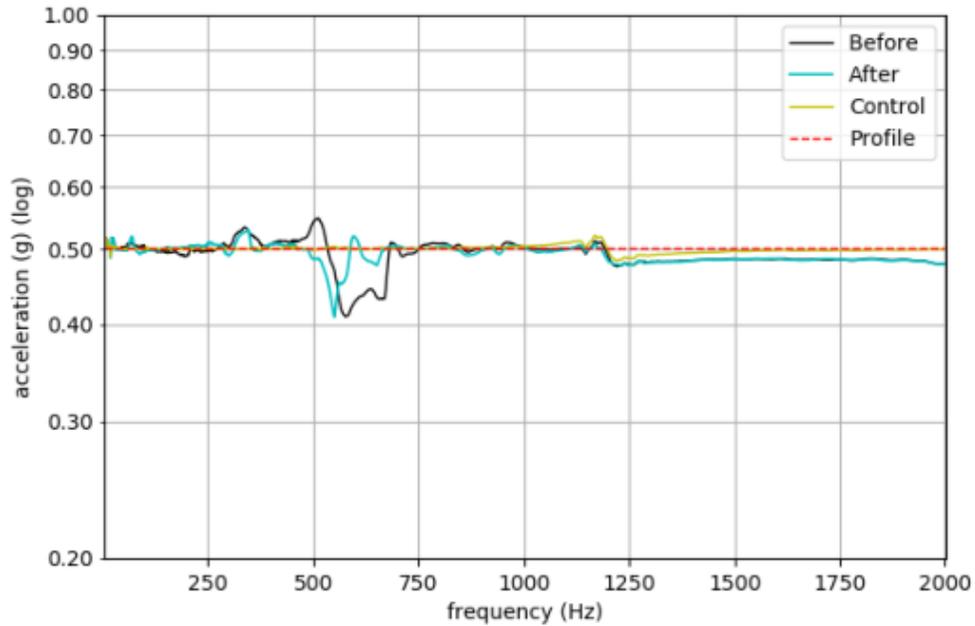


Figure 5.14. Reference sine before and after the random vibration x-axis test (Run 23 & 25)

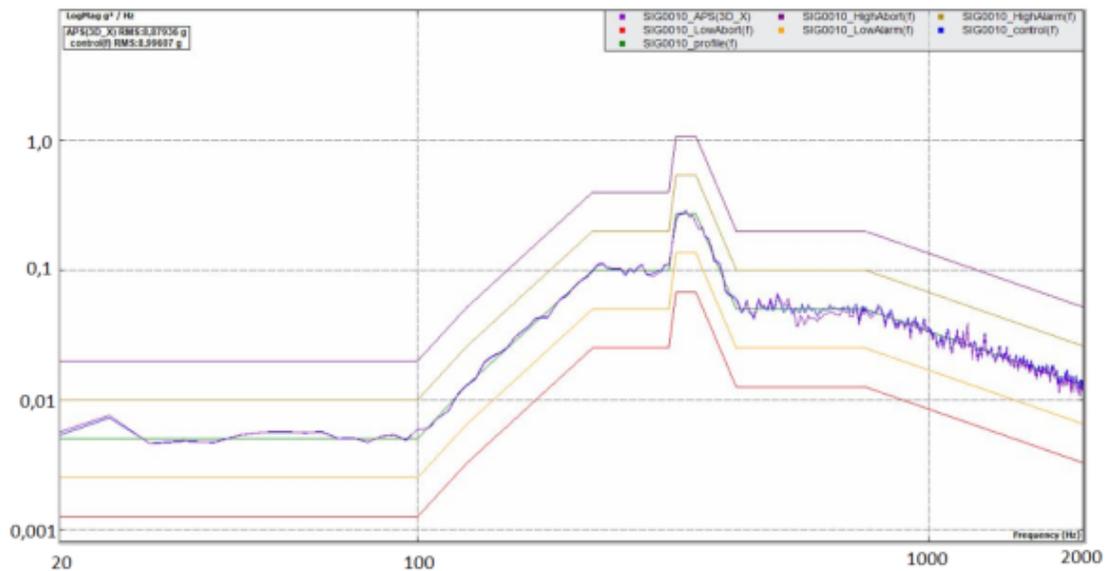


Figure 5.15. Random vibration x-axis test (Run 24)

5.1 Observations during the tests

After Run 6 a screw came loose from the DUT. See Figure 5.1.1.

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Page
13 (13)



Figure 5.1.1. DUT after screw came loose (marked with red).

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 for acceleration is $\pm 10\%$ and frequency ± 1 Hz.

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 ± 5) °C and the relative humidity of air $(55 \pm 10)\%$.

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