Scanning Tunneling Microscope Vibration Damping System

Final Report

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DISCLAIMER

EXECUTIVE SUMMARY

Our team was tasked with creating the structure of a scanning tunneling microscope that will be used for imaging at the atomic level by an Electrical Engineering team. Because of the sensitivity of STMs, the structure would need to be dampened from vibrations in order for images to have a high resolution. The damping system would need to create an average difference of 4 decibels between the testing surface and STM to ensure that adequate damping is present in the structure. After being given restrictions for the structure such as the dimensions, necessary parts, and amount of damping occurring as mentioned previously, the team set out to identify the best way to solve the problem given. Once we were given a basic model from the EE team, we began modifying the structure to our client's needs. The size and dimensions of the structure continuously changed to be able to satisfy those needs. After the first semester had finished, the basic structure of the STM was completed. After the initial process of designing the structure was complete, we then had to focus primarily on the damping system of the STM. The team did research on damping systems and how to construct them, such as through the use of different materials like steel and rubber. Although the team had initially planned to utilize springs for the damping system, it was quickly discovered that the alternative solution of using steel plates and viton rubber would be a much more efficient and accessible solution. After identifying the process in which we would dampen the structure, manufacturing the cement base for our STM, as well as constructing an acoustic box to encase it was the next step in constructing the STM. Low carbon steel plates and viton rubber were purchased as well for the damping system. Once the design of the STM structure was finalized, the team set up the STM and began testing using accelerometers. Using these accelerometers, we were able to find millivolt values that correspond to acceleration values, identifying the difference in acceleration and therefore vibration. After conducting our tests with the STM resting on the damping system, there was an average decibel difference of 4 dB across all tests, signifying that our damping structure was working properly. The process of designing the STM was very informative, allowing our team to directly interact with our client and get real-world experience while also learning more about the design process by participating in it directly. Looking forward, the damping structure can be iterated upon and improved through more testing.

ACKNOWLEDGEMENTS

The scanning tunneling microscope mechanical team would like to acknowledge the following people for their contributions to the project.

Dr. Carlo daCunha

For sponsoring and funding the scanning tunneling microscope project. Along with meeting with the team weekly and giving the team guidance to successfully complete the project.

Dr. Constantin Ciocanel

For assisting the team with vibration calculations and interpretation of the raw data the team collected when running simulations.

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1 BACKGROUND

1.1 Introduction

The Scanning Tunneling Microscope (STM) project is a joint project between an electrical engineering team and the mechanical engineering team. The goal of this project is to create a functional scanning tunneling microscope with it having a resonant frequency of one hertz (1 Hz) or lower. With this frequency that low the microscope will be able to produce clear images of the specimen. Failure to do so will result in lower resolution images which may be usable depending on how close to the goal it is. The sponsor and client for this project is Dr. Carlo daCunha wants this microscope to have the ability to do more research on specimens at an atomic level. With this research we can understand metals more and understand their structure to make smaller electronic devices while still having more power than older generations of technology. During this semester the team has added insight to the mechanical body holding the electrical components suggesting improvements to the design of it.

1.2 Project Description

Scanning Probe Microscopes (SPMs) are powerful tools for imaging conductive and semi-conductive surfaces at an atomic scale. Scanning Tunneling Microscopes (STMs), a type of SPM, which uses a tunneling current between a metallic tip and the surface being studied. Commercial STMs can be expensive, which has caused cost-effective home-built alternatives with similar analytical powers to become popular. The start of the semester the electrical engineering team had an early design for the body since they needed a body to test their electrical components. The design was triangular with three adjustment screws with a tall base for the screws to go into. The design also had one hole in the top of it which was meant to fit the piezoelectric tube.

2 REQUIREMENTS

The following sections will document the different engineering and customer requirements given to us by our client. The understanding of these requirements as well as their implementation into our design was of the utmost importance when considering how the STM would be constructed. Meeting these requirements will allow the team to better predict the accuracy and reliability of the STM as well as cater its design to the needs of our client.

2.1 Customer Requirements (CRs)

The customer requirements that are presented in this report have been discussed with our client and aim to provide a clear objective for our team to accomplish. The requirements cover a variety of aspects of the design of the microscope, including vibration damping, compactness, secure electrical components, affordability and much more. By meeting these requirements listed below, the bench-top STM will provide high quality imaging with high precision and ease of use.

1. Compact Design - The microscope must have a compact design and be suitable for use on a benchtop or desktop. (Weighting: 5/5)

2. Dampen Vibration: The microscope should be designed to minimize the effects of external vibrations on the sample and the tip. This will allow us to achieve high resolution imaging.. (Weighting 5/5)

3. Space for Electrical Components: The microscope should be capable of holding and securing the electrical components in place. (Weighting: 5/5)

4. Adjustable Height Settings: The microscope should have adjustable height settings to accommodate various sample sizes and shapes. (Weighting: 4/5)

5. Cost Effective: The design of this STM should not exceed the budget that was set by the client at the beginning of the project. (Weighting 4/5)

6. No magnetic field present: The microscope should not generate any magnetic field that may interfere with the sample or other nearby devices. (Weighting 4/5)

7. Precision Adjustments: The microscope should be capable of making precise and accurate adjustments to the tip position and the sample stage in all three axes to ensure high-resolution imaging. (Weighting: 4/5)

[changes to CR's to better fit client's needs (updated for second semester)]

2.2 Engineering Requirements (ERs)

The engineering requirements that are presented in this report were constructed to meet the needs of our customer. We have developed this list of requirements after speaking with our client and building the customer requirements list seen above. Each of these requirements provides a quantifiable measurement and satisfies the customers needs.

1. Minimize Dimensions of Structure - Set the dimensions of the microscope to be less than 2.5 inches in length and width.
2. Isolate the structure of the microscope from the surface - A decibel difference between surface

and structure greater than 4dB.
3. Fine Threaded Screws - Use of fine threaded screws with a value greater than 50 threads per inch to allow for specific adjustment of structure.
4. Affordable Material Selection - Use of affordable materials to keep budget less than $500.
5. No Magnets used within Structure - 0 Magnets used within the structure to ensure no magnetic field is present.

[changes to ER's to better fit project design(updated for second semester)]

2.3 Functional Decomposition

This section will discuss the way each subsystem will be functioning. This includes a breakdown of how each subsystem works, and a block box model with a functional model. The first important subsystem is the dampening system. The second important subsystem is the STM body. The third subsystem is the height adjustment system. The functional decomposition will ensure that there will be a clear understanding of what the function of each subsystem is.

2.3.1 Black Box Model

Following will be the black box model constructed for the STM. This black box model allowed the team to easily identify the subsystems present and identify how each is important.

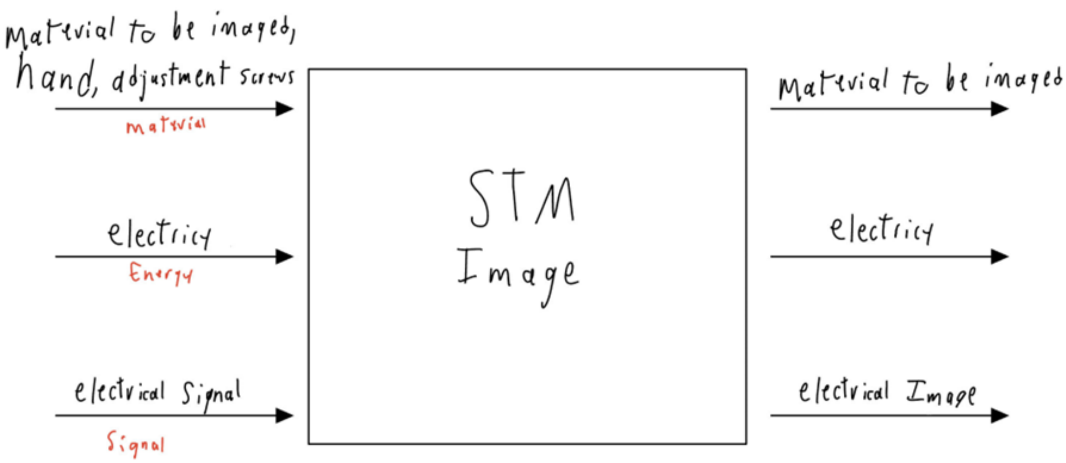

Figure 1: Black Box Functional Model

Figure 1 shows the black box functional model where the inputs and outputs are shown for the material, energy, and signal. The materials needed are the user's hands to adjust the height screws, the high adjustment screws to make sure that the STM is at the correct level, and the material that we are trying to image. For the energy going in and out of the STM there is electricity to run the piezoelectric actuator. For the signal there is an electrical signal going into the scanning wire as well as a signal coming out of the signal wire.

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The first subsystem is the dampening system. This system will stop vibrations from passing from the outside environment into the scanning tunneling microscope. This system will be made of steel plates that will hold the STM while damping any vibrations, so that any vibrations propagating from the surface will not affect the STM while it is being held still. This will be accomplished by having multiple layers of steel plates residing under the STM base. Figure 2 shows the functional model with the input and outputs.

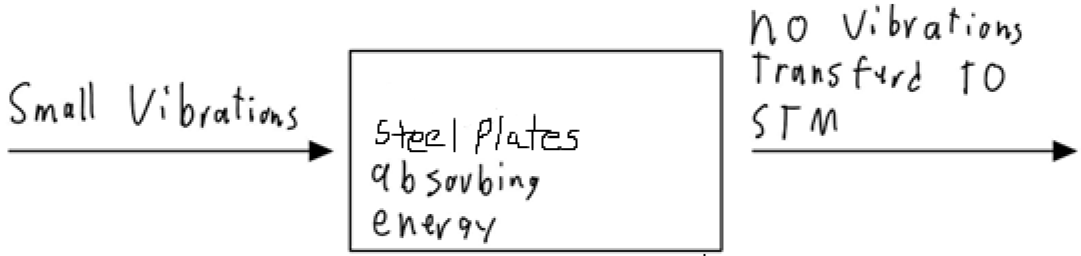

Figure 2: Damping System Functional Model

The second subsystem of the scanning tunneling microscope is the body. This system is made up of the top and bottom platforms. The function of these platforms is to both hold the microscope itself as well as allow the users to be able to have each of the pieces removable and replaceable. The bottom platform will give a place for adjustment screws to sit while holding the piece of material that we will be imaging. Figure 3 shows the functional model with the input and outputs.

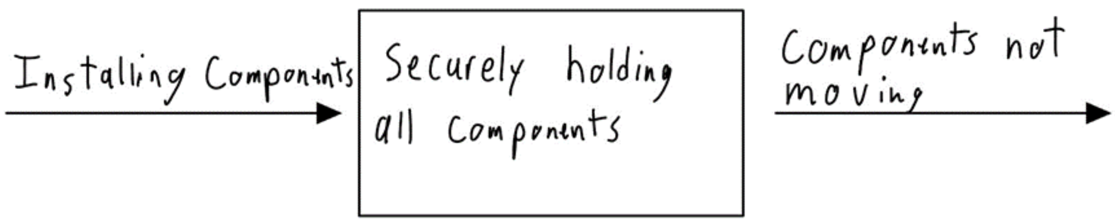

Figure 3: Body Functional Model

The third subsystem is the height adjustment system. This system will be made up of three height adjustment screws. The function of these pieces will be to allow for vertical adjustment of the height that the microscope will be sitting at. This will be accomplished by having the adjustment screws attached to the top plate and pushing against the bottom plate. By adjusting these screws up or down the distance between the top and bottom plates will be increased or decreased. Figure 8 shows the functional model with the input and outputs.

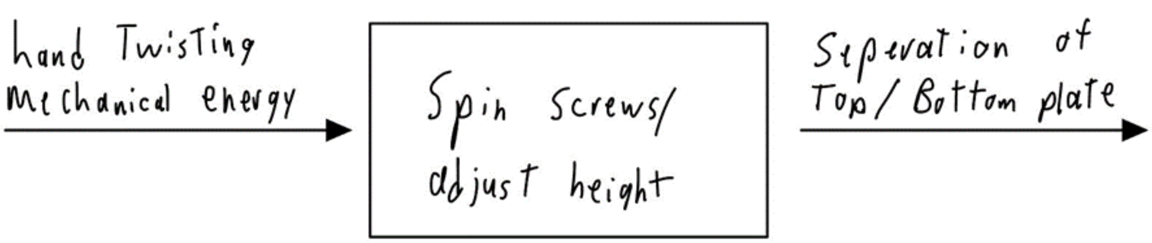

Figure 4: Height Adjustment Functional Model

When identifying the different subsystems within the STM like above, the team gained a better understanding of why choices were made in terms of designing the STM and how to make the design better as a whole.

[updated first subsystem to better match current damping system and added intros]

2.4 House of Quality (HoQ)

After developing the customer requirements and the engineering requirements, we built a house of quality. The QFD allowed us to analyze which requirements were most important based on the weight that we gave to each customer requirement. This showed us which requirement to focus on more and ensure that we allocated the appropriate amount of time to each requirement. After completing this analysis, we found that damping the vibrations and allowing a maximum of 1 hz resonance frequency is the most important part of our design. The analysis done in the QFD can be seen below in figure 5.

System QFD

Project: QFD STM ME CAPSTONE
Date: 10/22/23

Legend
A NaioSTM NaioSTM –
B SNE Alpha SNE Alpha:
C VHX-7000 Series Adopted by

1	Minimize dimensions of structure					
2	Isolate the structure from surroundings/surface	3				
4	Integrate Fine Thread thumb screw	3	0			
5	Affordable material selection	9	-3	-3		
6	No magnets used within structure	0	-3	0	3	

			Technical Requirements					Customer Opinion Survey				
		Customer Weights	Minimize dimensions of structure	Isolate the structure from surroundings/surface	Integrate Fine Thread thumb screw	Affordable material selection	No magnets used within structure	1 Poor	2	3 Acceptable	4	5 Excellent
1	Compact Design	5	9	3	3	9	0	C				AB
2	Dampen Vibrations	5	3	9	3	0	3			AB		C
3	Space for Electrical Components on Structure	5	9	3	0	0	0					ABC
4	Adjustable Height Between Scanning Tip and Sample	4	3	3	9	0	0			AB		C
5	Cost-effective	4	3	0	0	9	0	C	AB			
6	No Magnetic Field present within STM	4	0	3	0	3	9					ABC
7	Precise Adjustment of the Structure	4	3	0	9	0	0			AB		C
	Technical Requirement Units		in^2	dB	pitch (in)	$	NA					
	Technical Requirement Targets		<25in^2	>4	.25 80	500	None					
	Absolute Technical Importance		141	99	102	93	51					
	Relative Technical Importance		2	5	4	6	7					

Figure 5: House of Quality for STM

[QFD updated with new CR’s and ER’s]

2.5 Standards, Codes, and Regulations

When considering standards and codes employed in the process of creating the STM, the main example in question regards drawing standards used for the STM. Because the STM is very low-risk, not many codes apply to designing it other than drawing standards for the individual parts when constructed within an engineering drawing. These standards allow us to not only follow the formatting and design expectations of ASME, but also allow for effective communication of our design to other engineers.

Table 1: Applicable Codes and Standards

Standard Number or Code	Title of Standard	How it applies to Project
ASME Y14.5M-2004	ASME Drawing Standards	Allows our engineering drawings to follow expected standards of ASME

3 DESIGN SPACE RESEARCH

3.1 Literature Review

Each student conducted a literature review in order to gain a better understanding of the STM and the different components of designing around vibration. The sources found varied between websites, books, and scholarly articles, outlining different features of damping and STMs. There was a large focus on damping within these sources, as the team wanted to better understand how to dampen the structure of the STM. Research such as materials that aid the damping of vibrations as well as accommodating for it when designing the structure was the primary focus of our research and gave the team a better understanding of the concept of vibration and how to avoid it within a structure. Understanding how others build homemade STMs was also a great benefit, inspecting how others solved the problems vibrations can bring. The use of these sources allowed us to better implement a damping system into the structure of the STM because of the understanding gained from the research.

[Updated to only be a summary of the literature review]

3.2 Benchmarking

Below will be the benchmarking conducted by the team. These benchmarks were made to ensure the components and systems within the STM operate smoothly and efficiently.

1.1.1 System Level Benchmarking

1.1.1.1 Existing Design #1: STM Head

The first system-level design to be analyzed is the STM head made in a homemade STM. Looking at different examples of how the scanning tip will be made could allow the team to employ some of the following techniques with their design. The tips must be sharp enough to pinpoint individual atoms to allow for proper imaging. The method used in the example consisted of the wire being used for the tips and pliers. The wire was pulled taught while cut with pliers, stretching the edges of the wire and keeping them extremely thin.

Figure 6: STM Head

1.1.1.2 Existing Design #2: Sample Platform

The next system-level design example includes the sample platform to hold the specimen being tested with the STM. To allow for ease of access, the platform should be open enough to insert and remove testing samples that will be placed within the STM. The platform should also aid in vibration mitigation and not add to any adverse effects not wanted within the design. The platform gives enough space to keep the specimen stable for imaging purposes while keeping accessibility available to the user.

Figure 7: Platform for Sample

1.1.1.3 Existing Design #3: Adjustment Screws

The third system-level design example would be the stability of the STM as a whole. In the design found by the team for this specific example, the STM used screws on each side of the platform for adjustability of the STM head. This range of motion is crucial for the platform and allows the microscope to attain proper data through contact with the scanning head. The screws are also placed evenly to allow for adjustment on a specific side of the scanning head, allowing the tip of the STM to be manually adjusted by the user.

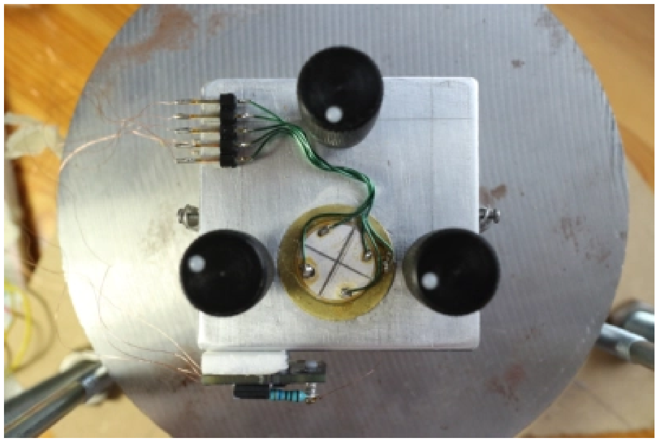

Figure 8: Adjustment Screws on STM Platform

1.1.2 Subsystem Level Benchmarking

Subsystem-level benchmarking was also a part of the design of the STM. There are a few components that go into the accuracy and efficiency of the STM that are imperative to accurate data acquisition. One of the first requirements of our team is to have the tip sharpness fine enough to achieve high resolution imaging. This can be achieved by measuring the tip radius to identify how sharp it is, identifying whether the scanning tip is capable of producing the image results the team expects. The durability of the scanning tip is important as well, allowing the user to utilize the scanning tip multiple times and still attain worthwhile results.

Noise levels are also a crucial factor when considering the results of the STM. Managing the amount of noise present in the design can quickly increase the quality of data retrieved from the STM. Accommodating for the level of noise not only in the environment around the STM but within the STM itself can lead to more clear results quickly. The team would need to first measure any significant sources of noise within the components of the design and then design accordingly to mitigate said vibration. The bottom-most platform is another part of the design where vibration can be mitigated the most. Placing the design on top of a dense material such as concrete can decrease the amount of noise within the design, as well as the amount of noise able to be received by the instruments of the STM.

[added summary to section]

CONCEPT GENERATION

4.1 Full System Concepts

The full system design concept generations combine many subsystem concept generations together to provide an idea of what the fully assembled system will look like. It also allows us to see how each subsystem will work together to accomplish the final goal.

4.1.1 Full System Design #1: Triangle Body with Cement base and Spring Suspension

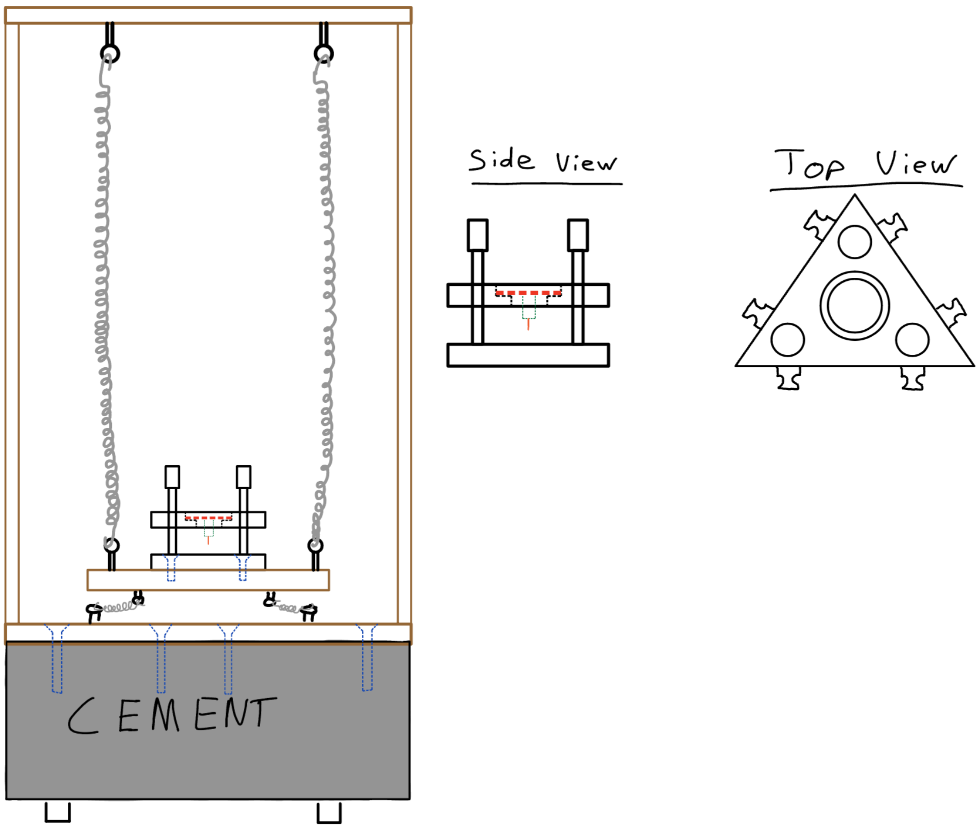

Figure 9: Overall Design Concept 1

The triangle body with cement base and spring suspension shown in figure 9 is a design that incorporates all of the goals of our project. The cement works as a large mass to absorb initial vibrations coming through the feet. It also works to hold the device steady while working on the STM, this is an added safety feature. The Springs work as a secondary vibration isolator. The body holds all of the electrical components and allows the user to adjust the tip in multiple different axis using the three adjustment screws. This ensures that the tip can be aligned perpendicular to the sample at the correct height above it. The triangular design ensures that the springs are evenly applying pressure to each of the screws.

Pros	Cons
• Heavy • Isolates Vibrations • Allows for fine vertical adjustment • Multi Axis leveling of the Tip • Uniform Spring force on each side • Few Moving Parts	• Difficult to Machine • Possible error in the spring calculations

4.1.2 Full System Design #2: Electronic Height Control on Cement Block

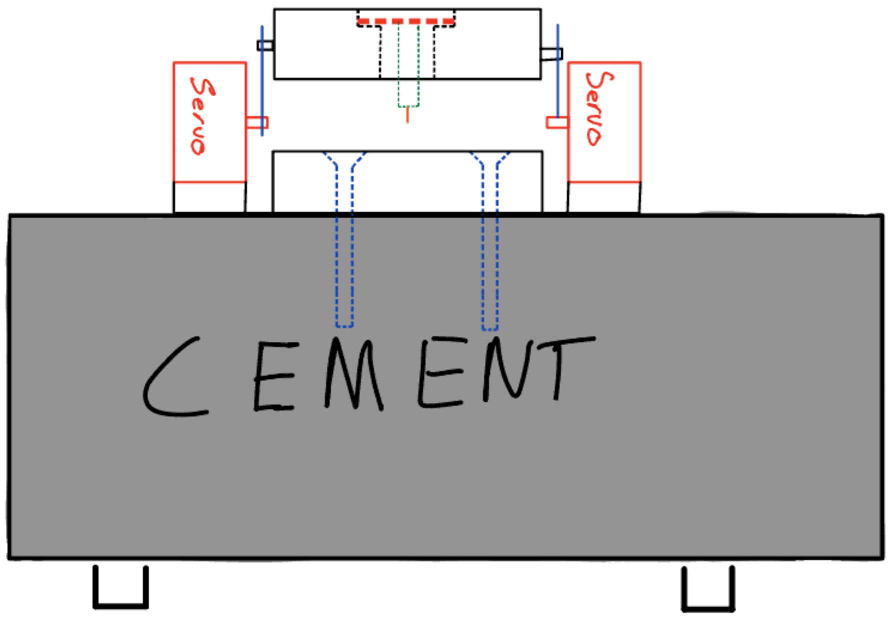

Figure 10: Overall Design Concept 2

The Electronic Height Control on Cement Block design shown in Figure 10 is another design that we considered in our concept generation. This is a simple design for vibration isolation; however it might not achieve the desired isolation. The height adjustment is electronic which would provide a reliable way to repeat setups if you are scanning the same sample many times. However it would be difficult to achieve the level of accuracy and precision in the height of the scanning tip.

Pros	Cons
• Heavy • Basic Vibration Isolation • Multi Axis leveling of the Tip • Easy repetition setup	• Not very precise Height adjustment • Initial setup is more difficult • large vibrations will not be damped

4.1.3 Full System Design #3: Spring Suspension Nut and Bolt Body

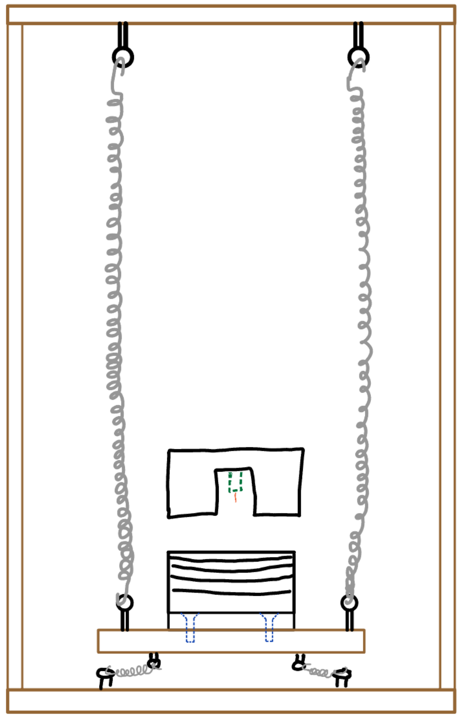

Figure 11: Overall Design Concept 3

The final full system design that we considered was the Spring suspension with nut and bolt body shown in figure 11. This design utilizes spring to dampen the vibrations coming into the system. The body is designed like a nut and bolt, the top will rotate onto the bottom and thread into place. This would allow for fine height adjustment, but it would not be able to adjust the angle of the scanning tip.

Pros	Cons
• Isolates Vibrations • Allows for fine vertical adjustment • Few Moving Parts	• Difficult to Machine • No multi axis Tip adjustment • No weight on the bottom • Hard to position the sample • Difficult to route the wires

4.2 Subsystem Concepts

Each system displayed below will work together to accomplish the goals set by our customer. Each section focuses on a specific part of our design in order to find the best design for each function.

4.2.1 Subsystem #1: Structure

This is the part that will hold the body and isolate any incoming vibrations. This is a crucial piece to the design as it is what everything is mounted to.

4.2.1.1 Design #1: Cement Block Design

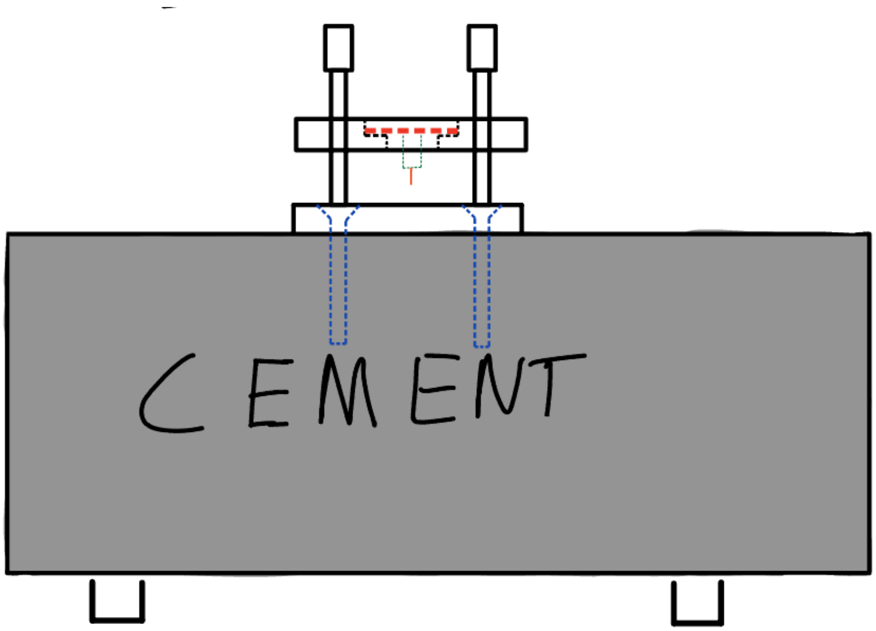

Figure 12: Cement Block Design

Pros	Cons
• Heavy • Isolates Basic Vibrations • No Moving Parts • Easy to Construct	• Lack of isolation from large vibrations

4.2.1.2 Design #2: Spring Suspension Design

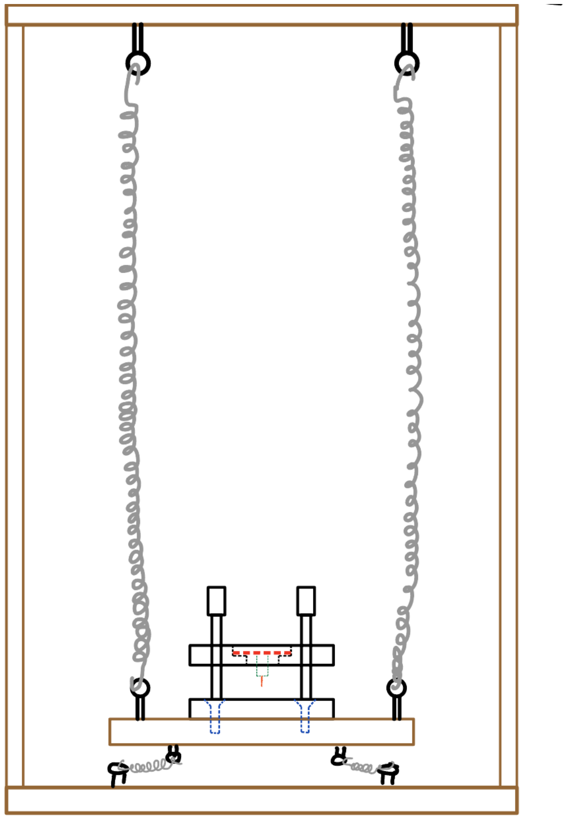

Figure 13: Spring Suspension Design

Pros	Cons
• Isolates Large Vibrations • Few Moving Parts	• No weight on the bottom • Difficult to calculate the spring tension to optimize vibration damping

4.2.1.3 Design #3: Combined Cement-Spring Suspension Design

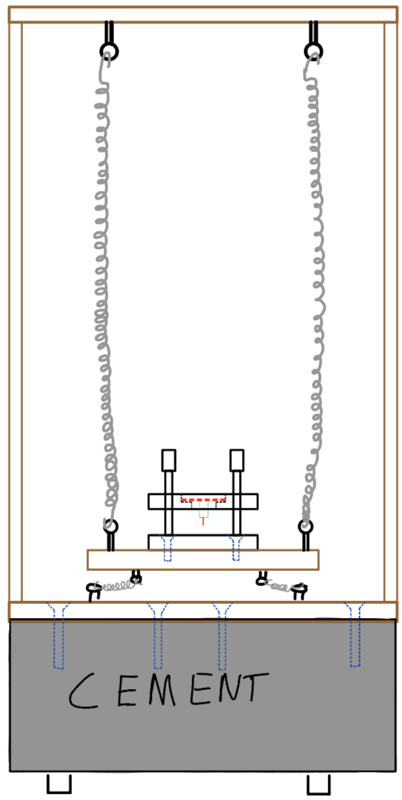

Figure 14: Combined Cement-Spring Suspension Design

Pros	Cons
• Heavy • Isolates Vibrations • Few Moving Parts	• Possible error in the spring calculations

4.2.2 Subsystem #2: Body Design

This design is what will hold all of the electrical components in place and where the sample will be placed to be scanned.

4.2.2.1 Design #1: Triangle Design

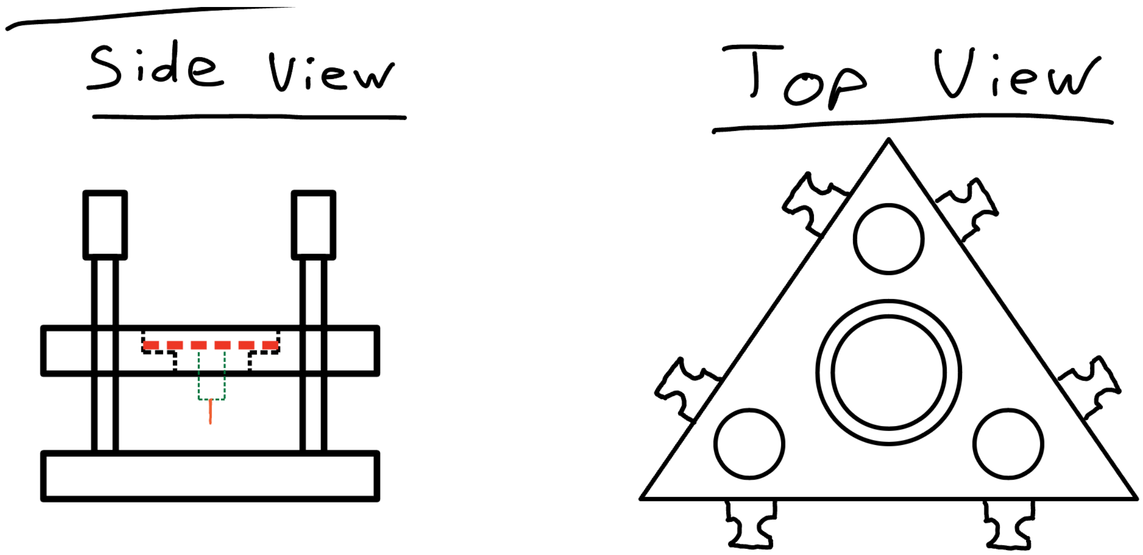

Figure 15: Triangle Design

Pros	Cons
• Allows for fine vertical adjustment • Multi Axis leveling of the Tip • Uniform Spring force on each side • Few Moving Parts	• Difficult to Machine

4.2.2.2 Design #2: Square Design

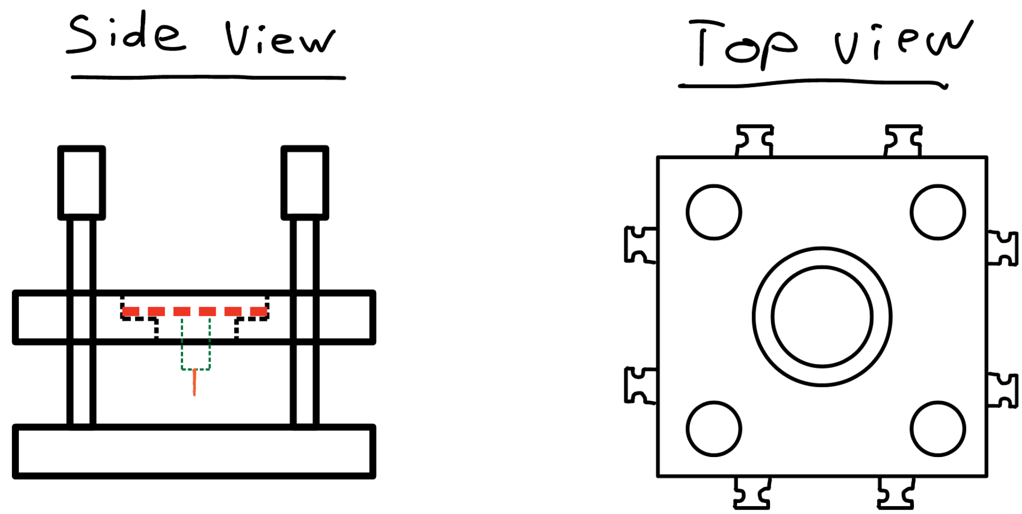

Figure 16: Square Design

Pros	Cons
• Allows for fine vertical adjustment • Multi Axis leveling of the Tip • Uniform Spring force on each side • Few Moving Parts • Easy to Machine	• Too many ways for the tip to lean

4.2.2.3 Design #3: Circular Design

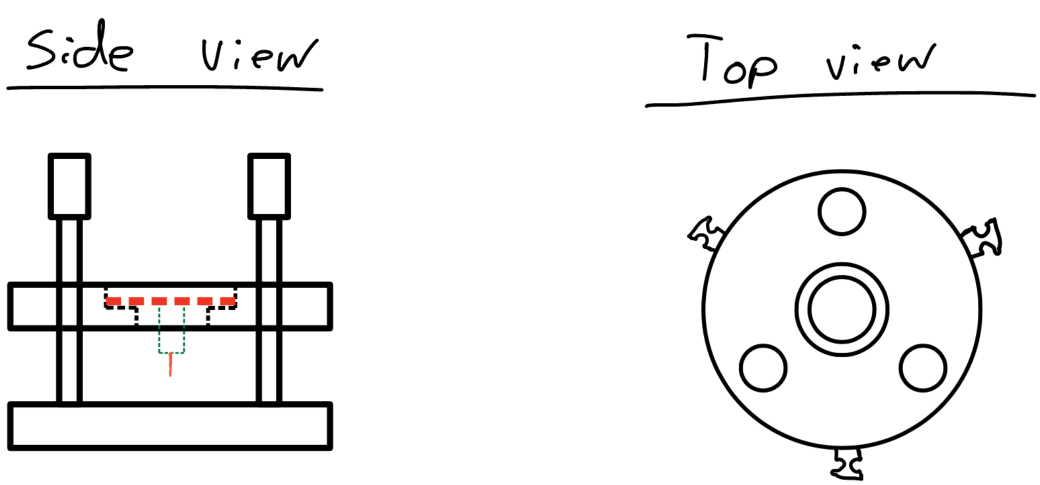

Figure 17: Circular Design

Pros	Cons
● Allows for fine vertical adjustment ● Multi Axis leveling of the Tip ● Few Moving Parts	● Difficult to Machine ● Non uniform spring force on each adjustment screw

4.2.3 Subsystem #3 Height Adjustment

This section will discuss the different methods that we considered to adjust the height of the scanning tip from the sample.

2.2.3.1 Design #1: Fine Thread Adjustment Screws

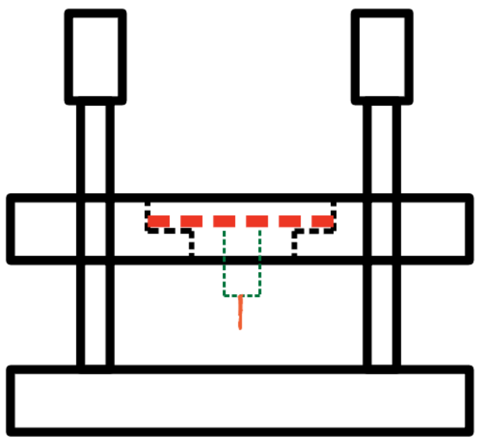

Figure 18: Fine Thread Adjustment Screws

Pros	Cons
● Allows for fine vertical adjustment ● Multi Axis leveling of the Tip ● Few Moving Parts	● Hard to reset to a previous setup

4.2.3.2 Design #2: Electronic Height Adjustment Control

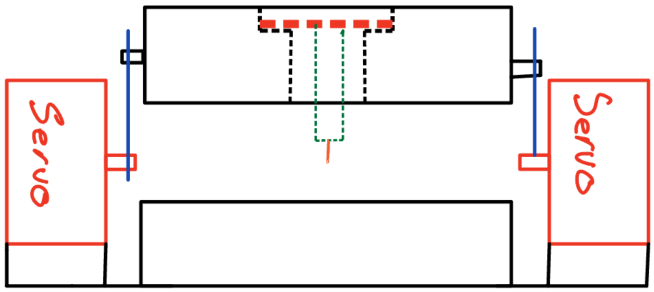

Figure 19:Electronic Height Adjustment Control

Pros	Cons
• Multi Axis leveling of the Tip • Easy to repeat a previous setup	• Does not allow fine vertical adjustment • More Moving Parts • Possible miscalibration of each servo

4.2.3.3 Design #3: Full Body Thread (Nut and Bolt Design)

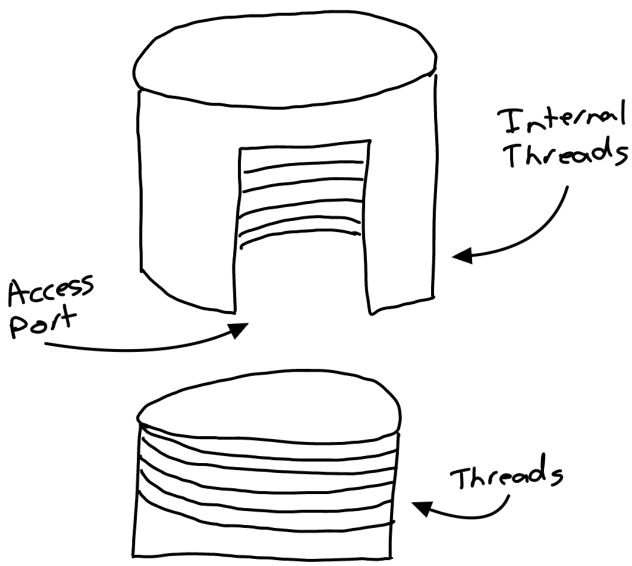

Figure 20: Full Body Thread (Nut and Bolt Design)

Pros	Cons
• Allows for fine vertical adjustment • Few Moving Parts • Top is securely attached to the bottom	• Lack of Multi Axis leveling of the Tip • Difficult to access the sample

DESIGN SELECTED – First Semester

5.1 Design Description

In our report the previous semester, we displayed many different concepts that we had generated and analyzed. We had settled on the idea of making the body triangular and utilizing fine adjustment screws to adjust the height of the scanning tip seen in Figure 6. For the vibration damping part of our project we settled on the design that would utilize springs in order to isolate the vibrations. The structure holding the springs would be placed on a cement block in order to add mass to the system, this can be seen in Figure 22.

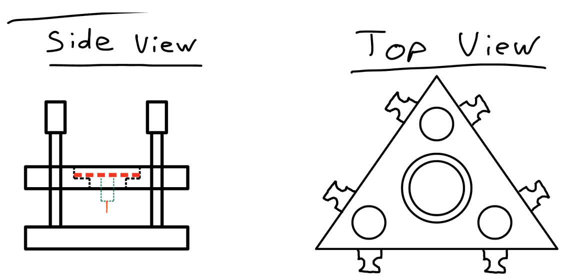

Figure 21: Preliminary Body Design

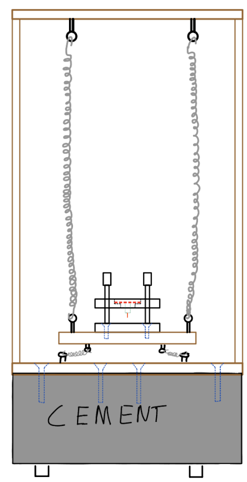

Figure 22: Preliminary Vibration Dampening Design

Once we had our design idea we were able to expand on this idea and add in every feature that the client needs. As stated in our previous report we are working with the Electrical Engineering team in order to complete this project, they need to have a solid body that they can attach their electrical systems to as quickly as possible. Due to this, our team focused on the body design and ensured that the body would meet the requirements that they had set. In order to do this we needed a temporary solution to the vibration damping problem. Our team decided to utilize another design concept that we had generated for the damping part of our design. This concept is shown in Figure 8**.** This solution was not only fast and easy, but it also meets the design requirements of having a resonant frequency of less than 1 Hz. The calculations are shown in Appendix C, but we calculated the block to have a resonant frequency of 0.017 Hz.

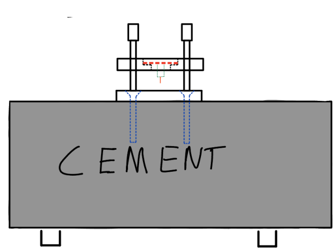

Figure 23: Cement Block Damping Design

As our team progressed through this project and communicated with the Electrical Engineering Team our design developed and adapted to the new issues that showed up. Figure 24 shows the design for the body during the first semester. These designs are also shown in more detail in Appendix B. The top triangle part is shown by the number 1. This piece has been adapted from our original design concept. We added a channel that comes down the side from the center cut out. This channel allows for the wires coming off of the piezoelectric disc to route nicely to the PCB. Numbers 2 and 4 point to the elastic pins that we demonstrated in the concept generation. We did have to modify the pins to make them larger in order to make them strong enough to hold the elastic bands. The number 3 bubble points out the base triangle. This part has been severely modified. We added the “pillars and platform” on the bottom so that the base could be securely embedded in the concrete block. Number 6 points out the fine thread adjustment screws, these have not been modified. Number 7 points out a retaining clip that was not originally in the design concept. We designed the retaining clip to hold the piezoelectric disk in place by providing a clamping force between it and the top triangle.

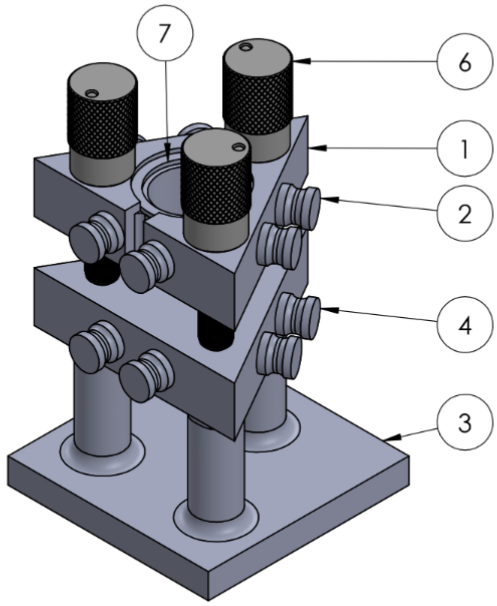

Figure 24: Assembly of First-Semester Body Design

On top of all of the design changes that we have made to the structure. The client also decided that he wanted the final design to be 3D printed rather than made out of aluminum or stainless steel. This allows the design to be easily modified and updated if there are any issues seen in the future. It is also advantageous to have the body be made out of plastic as it is non-conductive to electrical currents. One downside to this design change is that plastic is much less dense than stainless steel. This will have an effect on the resonant frequency of the body. We plan to combat this by utilizing a resin printer. Resin prints are far more dense than regular FDM prints, and they also produce much more accurate designs.

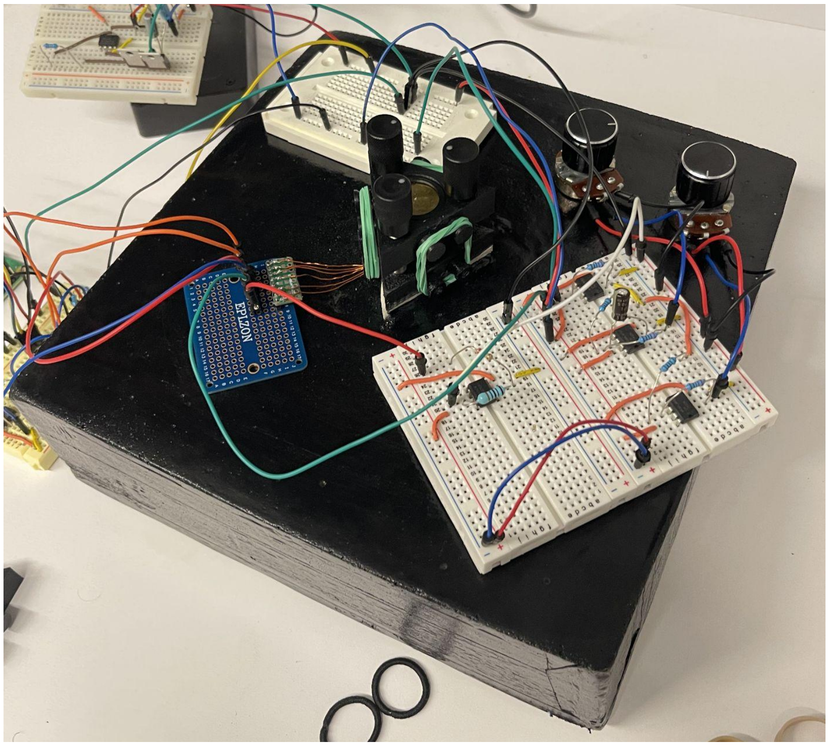

Figure 25: First Semester Design Implemented with EE Team Design

Figure 25 shows how our design has been implemented and functions with the Electrical Engineering Team's design. The piezo disk is securely held down with the retaining clip, the wires are able to route behind the elastic bands to seamlessly connect with their electrical system. Most importantly the structure is held in place in the cement block to help with the vibration damping and ensure that the scanning tip does not vibrate uncontrollably.

5.2 Implementation Plan

Due to the special nature of our team working with the Electrical Engineering team we have already started the implementation of our body design. This can be seen in Figure 25. Our team needed to have the design of the body finished by the end of this semester. We have completed our final prototype and have implemented this prototype into the EE team's electrical system. So far any issues that have arisen have been quickly solved. Many of these issues were mentioned above, such as the need for a channel to be placed in the top of the triangle in order to route the wires from the piezo disk.

The cost of our original design concept is much higher than our current design for the body. This is due to the fact that our client has decided to keep the 3D printed design as the final design material. Our original design concept had planned for the use of stainless steel or aluminum. These materials brought our cost up, by eliminating them we now only have the cost of filament which is much cheaper.

Now that we have implemented the body design and proved that it meets the needs of our customer, we are working on the simulations of our vibration damping design. Before we are able to begin building and prototyping a vibration damping device, we need to simulate our design using Solidworks and ANSYS to prove that the design will function to the criteria of our client. Appendix E outlines the schedule that we plan to follow in the fall semester in order to ensure that our design is built, tested and functioning by the end of the semester.

Project Management – Second Semester

1.2 Gantt Chart

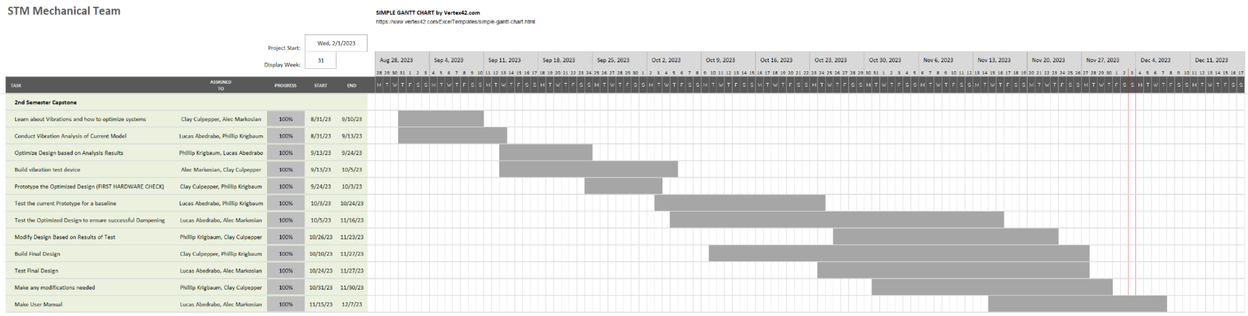

Figure 26: Gantt Chart

This Gantt Chart shows the progression of each task throughout the semester. It has helped keep our team on track by ensuring that each step got completed leaving enough time for the next step to be completed. This chart did not change much from the start of the semester till now as when it was created it was based on the known due dates. Our team could have improved this Gantt chart by moving the build data earlier as when ordering parts they took multiple weeks to arrive. This lead to our team having less time to finish the building and start testing.

1.3 Purchasing Plan

STM ME TEAM BOM

Part	Quantity Needed	Purchase Quantity	Current Quantity	Percent on Hand	Price	Total Unit Price	Need to be ordered (Y/N)	Link	Notes
Accelerometer	4	4	4	100.00%		$0.00	N		EE Team is ordering
Arduino	1	1	1	100.00%		$0.00	N		EE Team is ordering
Concrete	1	1	1	100.00%	$5.41	$5.41	N	https://www.homedepo	20 pound bag
Thumb Screws	6	3	6	100.00%	$9.02	$27.06	N	Ultra-Fine-Thread Plas	
Brass Inserts	6	3	6	100.00%	$9.00	$27.00	N	0.438" Long Brass Inse	
Internal Retaining Ring	1	1	1	100.00%	$9.82	$9.82	N	https://www.mcmaster.	
Shoulder Bolt	12	12	12	100.00%	$1.41	$16.92	N	Alloy Steel Shoulder S	
PLA	2	0	2	100.00%	$13.99	$0.00	N	https://www.amazon.co	1 kg spool
Low Carbon Steel Disks	4	4	4	100.00%	$12.04	$48.16	N	https://www.mcmaster.	
Viton O-rings	4	2	4	100.00%	$5.36	$10.72	N	https://www.mcmaster.	
Damping rubber feet	3	3	3	100.00%	$8.55	$25.65	N	https://www.mcmaster.	
Bolts for Mounting Rubber Feet	6	1	6	100.00%	$8.26	$8.26	N	https://www.mcmaster.	5/16-18 button head (Pack of 25)
Bolts for Mounting Bottom Triangle	3	1	3	100.00%	$10.69	$10.69	N	https://www.mcmaster.	1/4-20 Flat head (82 degree head) (Pack of 50)
Coupling Nut	6	6	6	100.00%	$2.27	$13.62	N	Everbilt 5/16 in. -18 tpi	Coupling Nut for fastening in concrete for feet
Acoustic Foam	5	0	5	100.00%		$0.00	N		EE Team Already had
4x8x0.75 MDF Panel	1	1	1	100.00%	$52.98	$52.98	N	3/4 in. x 4 ft. x 8 ft. MD	For Sound Deadening Box
2x2x8 Furring Strip	2	2	2	100.00%	$3.52	$7.04	N	2 in. x 2 in. x 8 ft. Furri	For Sound Deadening Box
Aluminum Foil	1	1	1	100.00%	$4.26	$4.26	N	Amazon.com: Reynold	For Sound Deadening Box
Spray Paint	1	1	1	100.00%	$6.48	$6.48	N	Rust-Oleum Painter's T	
Joint Compound	1	1	1	100.00%	$9.98	$9.98	N	DAP DryDex 32 oz. Pr	To Smooth the Concrete Base
5 inch Round Metal Duct Pipe	1	1	1	100.00%	$6.98	$6.98	N	Master Flow 5 in. x 2 ft	For Faraday Cage

	5 inch Round Duct Cap	1	1	1	100.00%	$7.54	$7.54	N	Master Flow 5 in. Roun	For Faraday Cage
	1.5 inch screws	1	1	1	100.00%	$6.87	$6.87	N	Everbilt #8 x 1-1/2 in. C	Pack of 50, for the sound deadening box
	Rubber Bands	3	3	3	100.00%		$0.00	N		
	Total without Further Dampening						$305.44			
	Remaining Purchases Total				100.00%		$0.00	100.00%		

Figure 27: Bill of Materials

The purchasing process for this project was broken up into a few main categories, vibration damping structure, concrete base, acoustic box, and testing system. The vibration damping structure consisted of thumb screws, brass inserts, rubber bands, internal retaining rings, shoulder bolts, bolts for mounting bottom triangle low carbon steel disks, and o-rings. All of the parts for the vibration damping structure are purchased from McMaster-Carr. The concrete base was constructed from damping rubber feet, bolts for mounting rubber feet, joint compound, coupling nuts, spray paint and concrete. For the concrete base the larger parts were purchased locally from Home Depot while the smaller pieces were purchased from McMaster-Carr. The acoustic box was made up of, acoustic foam, 4x8x0.75 MDF panel, 2x2x8 furring strip, aluminum foil, metal duct pipe, metal duct cap, and 1.5" screws. All of these parts were sourced locally at the Home Depot. Lastly the testing system consists of an accelerometer and an arduino, both of these were sourced from the EE team.

This bill of materials was being added as our client kept requesting more features and parts to our design. At the beginning of the semester our bill of materials consisted of just parts for the vibration damping system. From discussing with our client the concrete base as well as the acoustic box had been added. The testing system was the last piece added to the bill of materials as they were needed for our final testing procedure.

1.4 Manufacturing Plan

To begin the manufacturing process the team created a plan that included five parts. These parts were the manufacturing of the top triangle of the STM structure, the bottom triangle of the STM structure, concrete base, steel disc damping system, and acoustic system. The plan can be seen in the following figure that details time, method, and progress.

Picture	Part	Time [hours]	Manufacturing Method	Progress Percent		
	Top Triangle	2	3d Printed	100%		Completed
	Bottom Triangle	2.5	3d Printed	100%		In Progress
	Concrete Base	6	Cast	100%		No Progress
	Dampening System (Steel)	5	Machined on Lathe	100%		
	Acoustic System	6	Carpentry	100%		
	Total	**21.5**		**100.00%**		

Figure 28: Manufacturing Plan

The first part of manufacturing that occurred this semester came with changes to the STM structure. From the previous semester the team had an elongated base that was embedded into concrete. However, this resulted in some issues with noise from the water mixture in the concrete. This resulted in changing the bottom triangle of the STM structure. The change included adding three spots to mount the STM to a steel disk. This was done to separate the STM structure from the concrete. The STM structure was manufactured by 3D printing it with PLA.

The team also implemented steel discs into the design this semester. The team initially had steel stock that was planned to be manufactured on the lathe. The team began this process attempting to get four discs out of the stock. However, issues came with parting on the lathe. The parting tool was not big enough to part the entire stock so the team decided to purchase discs from McMaster. One of the steel discs purchased was drilled into to assemble the bottom STM structure to it. The team was still able to slave one disc from the stock by welding a piece of metal to it and cutting with a bandsaw. The disc that was faced down was used as the disc that the team embedded in the concrete. The team also acquired four viton o-rings from McMaster to insert between each steel disc to aid in damping vibrations.

The next part of manufacturing was making the concrete base. The first step was making the casting mold for the concrete. A triangular casting mold was made using three pieces of wood then blue masking tape was used to prevent the concrete from getting into any gaps created by the wood. Then six coupling nuts were put in the corners of the triangle for rubber feet after the concrete was set. The steel disc that was manufactured was also placed in the middle then the concrete was cast around it. Once the concrete was set the team drilled into the bottom of the concrete and attached the rubber feet to it.

Furthermore, the team had to manufacture the acoustic damping system. To manufacture this the team acquired furring strips, MDF panel, spray glue and 1.5 inch screws from Home Depot. This was along with acoustic foam that was provided by the team’s client. The team made a frame using the two furring strips that were purchased that were cut into eight pieces and screwed them together. Then the MDF wood panel was cut into five that were then screwed to the frame. Then upon request from the client the team spray glued five 12x12 inch squares of aluminum foil onto the walls of the box to help prevent electrical noise. Then the five acoustic panels were stapled on top of the aluminum foil. Lastly, the team made a faraday cage to put on top of the STM structure. This was done by acquiring a five inch duct pipe and cap from Home Depot and cutting it down to size.

Upon reflection the areas the team feels like could have done better are with the steel discs. When the team went to the machine shop to manufacture the four discs there were a lot of issues mostly due to the type of steel. The steel stock the team purchased was 4340 steel which is classified as medium carbon steel. This made it very difficult to machine along with the size of the stock being almost too large for the lathe. This inevitably delayed the team as the discs were not manufactured when the team thought and had to be purchased from McMaster. To prevent this the team would have purchased steel stock that was low carbon to begin with.

Final Hardware

1.5 Final Hardware Images and Descriptions

The final design consisted of 3D printed STM structure, concrete block, steel discs, viton o-rings, and acoustic box. With all these parts together the team successfully mitigated vibrations to eventually take images with the microscope.

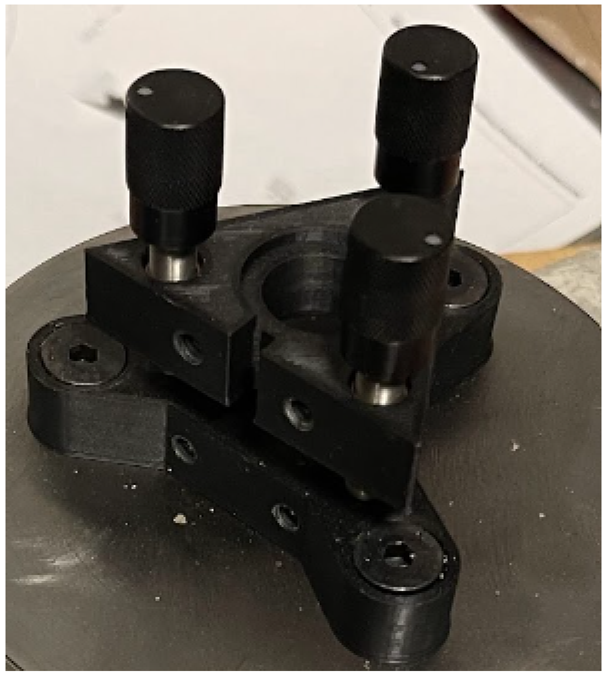

Figure 29: STM Structure

The first part of the team's hardware was the STM structure. This consists of two 3D printed parts with PLA that will hold the electrical components. The top part has a slot for the piezo disk to go into where a snap ring will be inserted to hold it in place. This part also has three brass inserts and three fine adjustment thumb screws. These allow the STM to move the height and adjust to the sample. Both pieces have six screw holes to insert screws to hold them together with rubber bands. Then the top part also has a slot in the side for the electrical wire to easily be run out of the device. The bottom piece has three holes for bolts to be put into to tighten it to a steel disc.

Figure 30: Steel Discs

The next part of the hardware was the steel discs and viton o-rings. The purpose of the steel discs is to apply mass to the system. Then separate them with the viton o-rings that are made to dampen vibrations. The team used the combination of mass and damping rings to mitigate the vibrations. There are in total four steel discs and three viton o–rings. Three of the steel discs are interchangeable with one larger one being embedded in concrete.

Figure 31: Concrete

Furthermore, the team made a concrete block to further help in damping vibrations. This was used in combination with the steel discs to add more mass to the system. This concrete block was also accompanied by three rubber feet to the bottom to further mitigate vibrations.

Figure 32: Acoustic Box

Lastly, the team created an acoustic damping box. This box consists of five MDF wood panels to help prevent noise while using the STM. This is aided with five acoustic foam pieces on the inside. Then between the foam and MDF were sheets of aluminum foil to help prevent electrical noise from ruining images taken by the STM.

1.6 Design Changes in Second Semester

1.6.1 Design Iteration 1: Change in STM structure discussion

The first main change to the design this semester was the STM structure. The final design from last semester had an extended bottom piece so it could be embedded into the concrete. This is shown in the figure below. However, this design was changed due to the electrical engineering team having issues with getting images, possibly due to the close proximity to the concrete. This resulted in the team changing the bottom piece. The team changed the design to have the bottom of the STM mount to a steel disc rather than have it embedded in the concrete. This change made the team remove the extended part of the original and add spots for screws. This can also be seen below the original design figure.

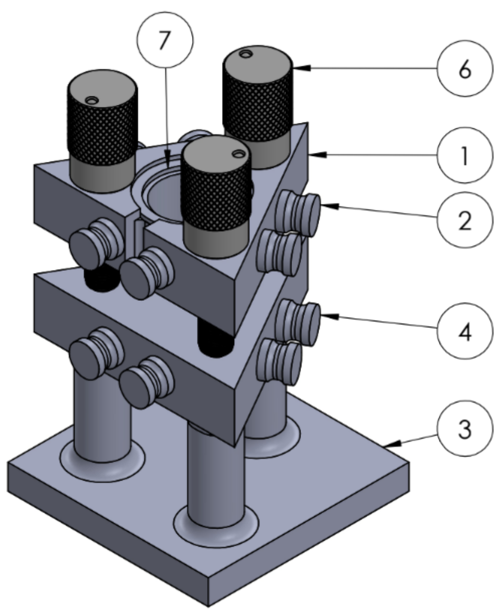

Figure 33: Original Design

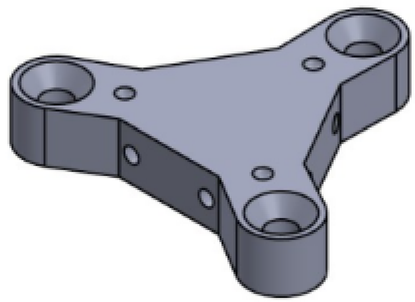

Figure 34: New STM Bottom

This change also allowed the team to have better control over the placement of the bottom piece. When the piece was embedded in the concrete it was hard to make sure it was fully flat and flush with the concrete. Using the new design will give more accuracy with it being held flat with the bolts.

1.6.2 Design Iteration 2: Change in Concrete design discussion

The second main change made to the design was the modification of the concrete block used for the base platform of the STM. Originally, the concrete was square-shaped, with four feet on the bottom. When making changes to the STM over the course of the past semester, the team found it fit to change the shape to a triangular base. This would remove the fourth foot off the base, effectively making the structure more stable and less prone to rocking. The triangular shape also matches the structure of the STM, and allows the entire base to take up less space overall compared to the previous base the team had made.

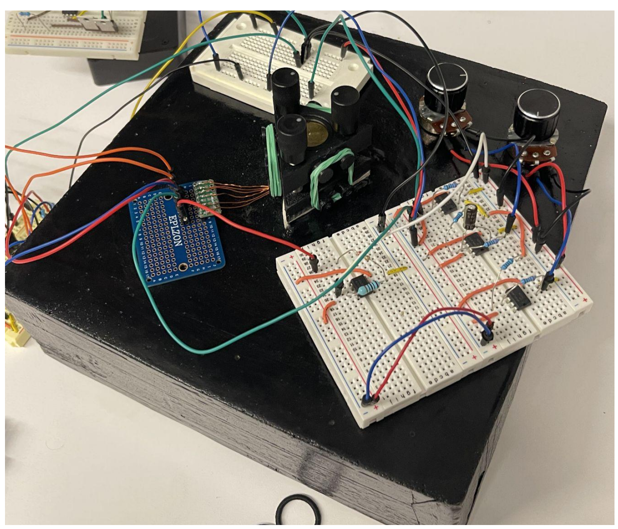

Figure 35: Original Concrete Block

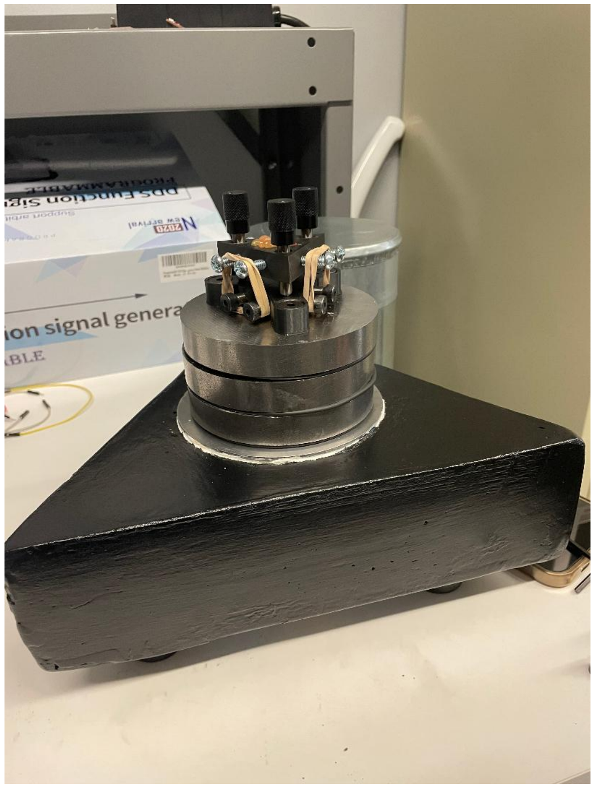

Figure 36: Triangular Concrete Block

This change overall had large benefits to the stability of the STM structure while also making it more aesthetically pleasing. The amount of space being taken up by the base overall was lowered as well, which could make it easier for the client and future users of the STM to place it in different locations.

1.7 Hardware Challenges Bested

Our team only had one real major challenge within our design changes. This challenge was to get parts ordered and showing up on time. All the design iterations besides the last one were able to be completed on our own without having to have our client order new parts for us. This was accomplished by having the design largely be 3D printed. The challenge came when it was time to make our final design, which required many components that were not locally available. This required our team to work with our partner electrical engineering team to place the online McMaster-Carr parts order. This process ended up needing approval from our client, the purchasing department, and the EE team. The order ended up being placed 3 weeks after it was submitted putting our final build behind schedule. Our team was able to recover by working on the weekends to get caught up. Besides this one issue the rest of our hardware and parts came in a timely manner.

1.8 Testing Plan

Ex1 - Vibration Test

This will test the customer requirement of Dampen Vibrations (CR2) and engineering requirement of isolating the structure from the surface (ER2) and limiting resonant frequency to 2 Hz (ER4). The test will be done by utilizing an Arduino and ADXL335, 3-axis accelerometer. The accelerometer measures in millivolts which can be converted into acceleration. This test will isolate movement by keeping the structure still then making disturbances that may occur while using the device. This will be done by performing three tests on four different structures of the STM. The three tests will be an active, semi-active, and non-active test. The active test will be done by bumping the table, moving things in the room, and walking around the room. A semi-active will involve everything from the first test except bumping the table the STM is on. Then the non-active test will result in no movement in the room at all. These three tests will be done on four different structures. One with the full structure including the cement block, steel discs, and acoustic box. Then with just cement block, and steel discs. Then with just the steel discs and finally with just the STM body structure. This will allow the team to see which performs best. The results the team is looking for are a minimum of 4dB in average difference between the STM and Table vibrations.

Ex2 - Measurement Test

This test will verify the customer requirements one, three, four, and engineering requirement 1 (CR1, CR3, CR4, ER1). The test will be done by using both a set of calipers as well as a tape measure.

This test will be completed by measuring the length of multiple components of the STM structure. The first part of this test will be testing the compactness of the STM body, the client requires the STM body to be less than 2.5” long or wide. This test will be completed with calipers and will result in a pass or fail.

The second part of this test will validate that there is adequate space on the concrete base to mount the electrical components. The client's requirement is that there is a minimum of 2” square flat area for the circuitry to rest, this will be measured using a tape measure and will be a pass or fail test.

The next part of this test will be ensuring that the STM body has a minimum of 0.5” of vertical movement to account for the changes in height of the multiple material types. This test will be completed by lowering the adjustment screws to the lowest setting and measuring the gap between the top and bottom triangles. Then the adjustment screws will be raised to the highest setting and the gap between top and bottom triangles will be measured for a second time. Those two measurements will be compared to ensure that there is a minimum of 0.5” of vertical travel.

Ex3 - Magnetism Test

This test will verify the customer requirement six and engineering requirement five (CR6, ER5) have been met. This test will verify that there are no magnetic fields present within the structure. This test will be completed using a ferris metal rod (steel rod). This rod will be placed around the STM base and then lifted away from the structure. If there is any resistance in movement in the rod our team will know that there are magnetic fields present within the structure. This test will be a pass fail test with passing being that there are no magnetic fields present and failing being that there are magnetic fields present. This test will also include a pass fail verification that there are no magnets used within the assembly.

Ex4 - Budget Analysis

This will test the customer requirement of being cost-effective (CR5) and the engineering requirement of affordable material selection (ER5). This will be done by comparing the amount spent in the bill of materials to the budget. If this value is less than the budget then it passes the test.

Ex5- Fine Threaded Screw Test

This test will check the customer requirement of precise adjustment of structure (CR7) and engineering requirement of integrating fine threaded screws with a minimum of 50 threads per inch. This will verify that the fine threaded screws are implemented in the STM body.

1.9 Testing Results

The first test completed was the vibration test. Our team conducted the experiment as described above and gathered the data from the two accelerometers.The setup of the vibration test can be seen in Figure 37. From the raw data the team needed to convert the voltage output into acceleration data then display this data in the time and the frequency domain. Appendix C shows the matlab script that imports the raw data files and outputs the needed graphs. Figure 38 shows the acceleration data on the time domain from the tests that were conducted with the full design configuration. Figure 39 displays the results from the tests that were conducted with the full design configuration, however these graphs show the data in the frequency domain.

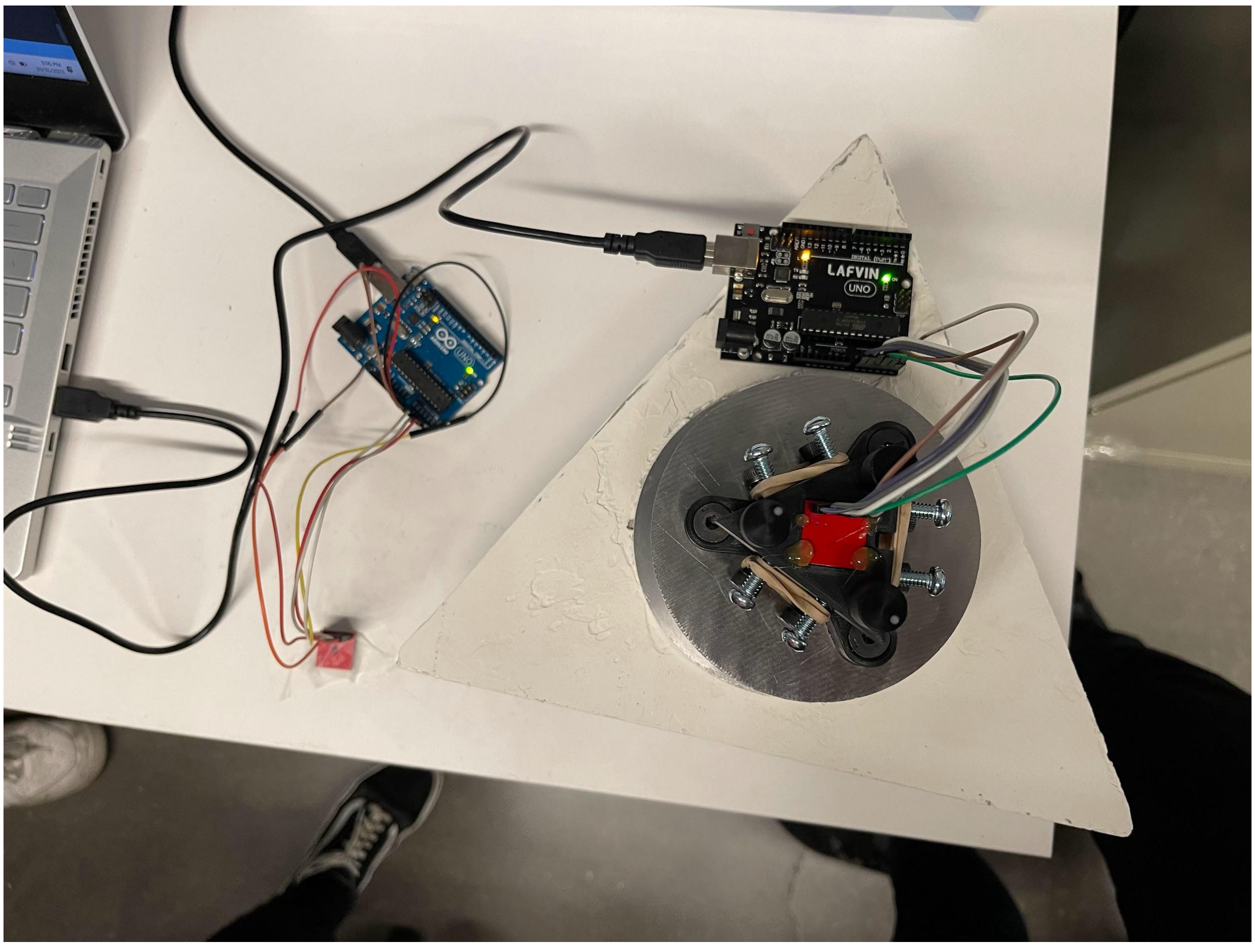

Figure 37: Vibration Test Setup

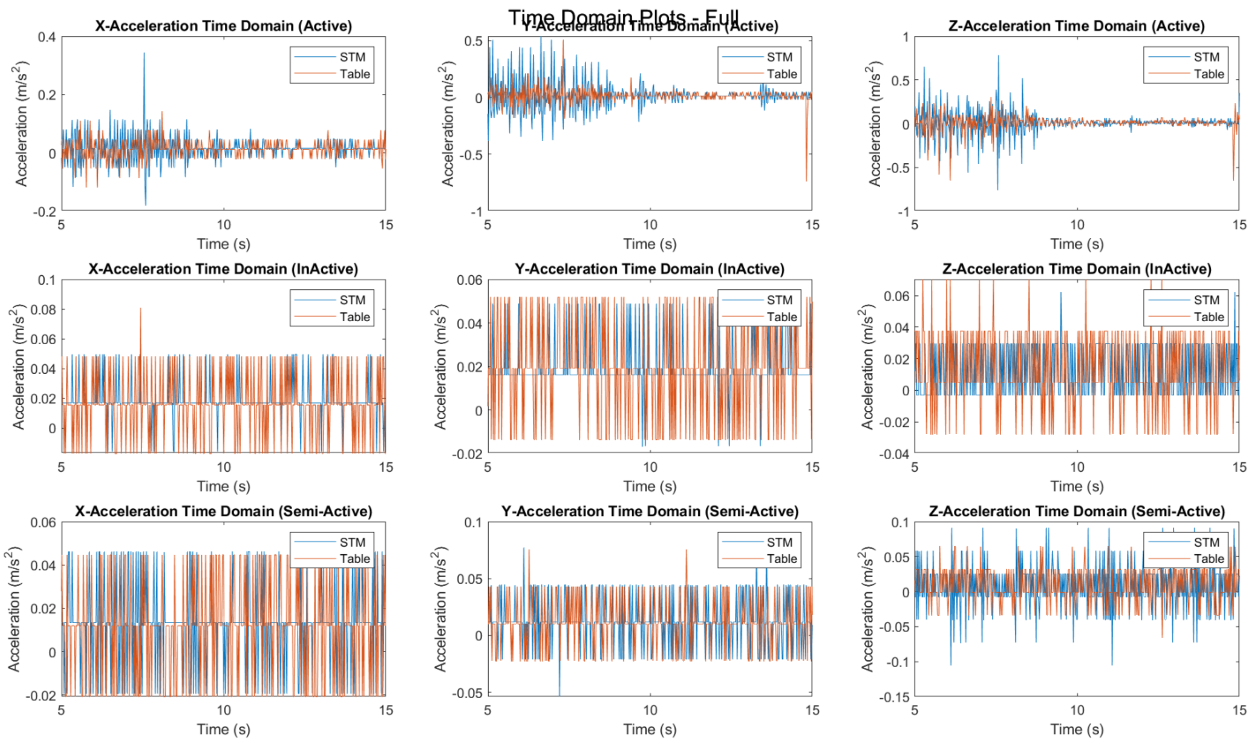

Figure 38: Time Domain Plots - Full

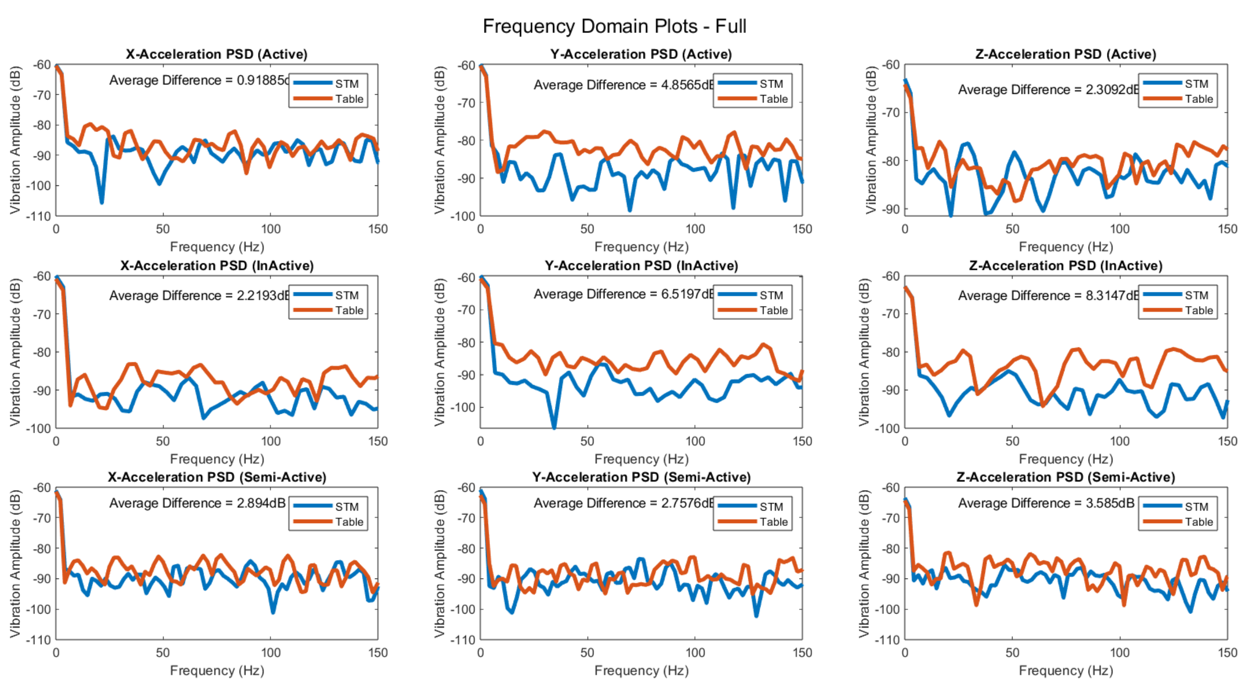

Figure 39: Frequency Domain Plots - Full

From Figure 38 and 39, the team was able to interpret the results and verify that the dampening structure was adequate for the STM to operate and obtain clear images. The goal of our team was to obtain an average difference of 4 dB with a tolerance of 2dB between the table and the STM. Looking at Figure 39 it can be seen that the inactive test passes this constraint in all 3 directions. The inactive test with the full setup is the most accurate configuration that the STM will be operating in; therefore, these are the results that the team is basing the verification on. The results from the other configurations are shown in Appendix D.

The second test completed was the measurement test. This simply was done by taking calipers and measuring the size of the STM top triangle to verify that it was below 2.5 inches. The length of the sides were measured to be 2.25 inches which met the customer requirement of minimizing the dimensions of the structure and engineering requirement of under 2.5 inches. The next part of this test required was to measure the room on the concrete block to verify that there is enough room for the electrical components. This was done with a tape measure and it was approximately 4 inches of space. This meets the technical requirement of having 2 inches of space for the electrical components. Then finally the team measured the space between the top and bottom triangle. This was done with calipers and measured to be half an inch which meets the requirement exactly.

The third test was done to test if there was a magnetic field present in the STM structure. This was completed by taking a ferris metal rod (steel rod) and putting it near and pulling away from the structure. When doing this to the teams design there was no resistance felt on any part of the structure meaning that the team completed the requirement. The purpose of having no magnetic materials in the STM is to prevent issues with images.

The fourth test completed was the budget analysis. This was simply a pass or fail test completed by checking the teams bill of materials and comparing it to the budget given. The budget given for this project was 500 dollars and the total cost of the design was 305.44 dollars. Giving the team a surplus of 194.56 dollars and completing the requirement.

The final test was the fine thread screw test. This test was done to verify that the team had at least 50 threads per inch. It was verified that the fine adjustment screws being used were 80 threads per inch meeting the design requirement. To summarize the design requirements and the test the team put together two tables shown below.

Table 2: Customer Requirement Specification Sheet

Customer Requirement	CR met? (Yes or No)	Client Acceptable (Yes/No)
CR1 - Compact Design	Yes(<2.5in)	Yes(<2.5in)
CR2 - Dampen Vibration	Yes (~4dB)	Yes
CR3 - Space for Electrical Components	Yes	Yes
CR4 - Adjustable Height	Yes	Yes
CR5 - Cost-effective	Yes (<$500)	Yes(<$500)

CR6 - No Magnetic field present in STM	Yes	Yes
CR7 - Precise adjustment of structure	Yes (80tpi)	Yes (80tpi)

Table 3: Engineering Requirement Table

Engineering Requirement	Target	Tolerance	Measured Value	ER met? (Yes or No)	Client Acceptable (Yes or No)
ER1 - Minimize dimensions of structure	<2.5 inches in length and width	$\pm 0.005\ in$	2.25 inches	Yes	Yes
ER2 - Isolate structure from surface	<4dB difference	-2dB	2.2dB 6.52dB 8.31dB	Yes	Yes
ER3 - Integrate fine threaded screws	>50 TPI	N/A	80 TPI	Yes	Yes
ER4 - Affordable material selection	< $500	$100	$305.44	Yes	Yes
ER5 - No magnets used within structure	0	N/A	0	Yes	Yes

These two tables summarize if each customer and technical requirements are met. The technical sheet also shows the target and the measured value. Each one of the team's design requirements were met and the client was satisfied with the product the team provided.

1.10 Testing Challenges Bested

While most of the tests went smoothly for the team the vibrations testing was where issues arose. The first issue that happened when testing was the team had a faulty accelerometer. The team had run multiple tests and collected data however when the team checked the results the Z direction for one of them was giving unexpected results. For the raw data the expected accelerometer output is between 200 and 500 millivolts. However, for one of the accelerometers it outputted a value between 1-5mV for the Z direction.

Therefore, all the data collected had to be thrown out due to the broken accelerometer and get another one to continue testing.

RISK ANALYSIS AND MITIGATION

When designing the STM, risks involved with the design process were heavily considered to ensure the process of the STM's construction went smoothly. During the first semester of the project, many risks were considered to identify how the STM could fail. Below will be a number of potential failures identified by the team as well as how to avoid these failures.

1.11 Potential Failures Identified First Semester

9.1.1 Potential Critical Failure 1: Unaligned or Uneven Structure

One concern when designing the STM is proper alignment of the structure. If the structure were to become unaligned due to repeated use, the piezoelectric sensor responsible for imaging may yield inaccurate results. Because of the importance of stability within the structure, the adjustment screws within the STM allow for easy adjustment of the top platform while keeping the sensor aligned with the specimen, resulting in more accurate imaging.

9.1.2 Potential Critical Failure 2: Sample Instability

When considering a specimen resting on the surface of the STM, it is important to make sure the sample does not move. If the sample were to move while imaging is taking place, the imaging process will yield inaccurate results, and the piezo sensor will have trouble recording any data. Any vibrations caused by movement of the sample in question would also drastically affect the results of imaging, possibly causing all data to be unusable and imaging impossible. Because of the importance of stability when considering the imaging process, the bottom triangular platform of the STM was designed to have plenty of space for the sample without interacting with any components of the structure.

9.1.3 Potential Critical Failure 3: Inaccurate Imaging Due to Piezo Sensor

Accurate imaging results with the piezo sensor are the most important objective when creating the STM, and results can be affected by a variety of methods. Sources of vibration within the testing apparatus as well as lack of control over the piezo sensor will drastically affect results if not carefully considered. If the piezo sensor is not able to be directed towards the sample properly or adjusted in a fine manner, the process of imaging will be much more difficult. To aid in the process of imaging, the use of a ring to hold the piezo sensor in place as well as adjustment screws to move the top base of the structure will allow the team to easily move the sensor and increase the accuracy of our results.

1.12 Potential Failures Identified This Semester

When making changes to the design of the STM, potential failures became more apparent throughout the design process. For one, an example of a potential failure would be the cement block we had originally created in the first semester. If the feet of the cement block were not leveled properly, the entire structure of the STM would be affected accordingly. Changing the number of feet and shape of the cement block allows us to mitigate that form of failure and allow the structure of the STM to stay stable under the expected testing conditions.

Another potential failure that was identified by the team was the effect of noise on the structure of the STM. Because of this, an acoustic box was constructed to place over the STM when testing. This acoustic box will allow the STM to operate without noise from outside factors affecting the imaging process and results. This potential failure was crucial to identify, as it could impair the overall performance of the STM and its results.

Risk Mitigation

When considering each method of failure mitigation, the effectiveness of each method as well as how they would affect each other was inspected to ensure the design would function properly. The team also wanted to make sure that any changes made to the design to avoid further failures would not cause additional ones. One example is the sample stability of the STM and how it would affect the design as a whole. If the space designed to hold the sample was made too large, an interference between other parts would occur, and the functionality of the STM would diminish. Another case would be the use of the piezo sensor ring to hold the sensor in place. If the ring did not hold the sensor in a proper position or in a compact manner, it is possible that the sensor could move or be obstructed. A close observation of the ring's measurements and its interaction with the sensor were considered heavily when designing this aspect of the STM.

LOOKING FORWARD

1.13 Future Testing Procedures

The main consideration for future testing procedures includes retesting the damping of the STM structure overall. As time continues, the testing process could further isolate potential solutions to damping and allow the STM to operate even more proficiently. The process could be iterative and allow the STM to gain accuracy over time.

1.14 Future Iterations

When considering the future of this project and how other teams may move forward with it, the most beneficial course of action would be to improve the damping system to allow the STM to be even more resistant to vibration. Improving the damping system could also make the STM more efficient as well as accurate, yielding better results as the damping system increases in proficiency.

CONCLUSIONS

The development of the STM with a specialized damping system will provide advancement in taking images on an atomic scale. The main goal of this project was to enhance the quality of images taken using the device. This led the team to making a damping system to prevent vibrations from ruining the quality of the images. This led to the team to apply the use of mass as well as known damping methods. The team manufactured a concrete block and purchased steel discs to supply the mass needed for higher quality images. Along with this were viton o-rings to dampen the system and an acoustic box to prevent noise from lowering the quality of the images. With all of these parts combined the team's design provided a difference of 2.22, 6.52, and 8.31 decibels between the accelerometer on the table and the accelerometer placed where the STM will be taking images from. This proves the STM will provide better images with the team's damping system than without it.

1.15 Reflection

While the team's project isn't directly dealing with the public it still has an impact.The STM is used to better technology by understanding the structure of semiconductive and conductive materials. This will allow technology to continue to become smaller, more powerful, and more accessible to the public. The team's design is also environmentally conscious with minimal use of materials. The design is concise by not using a lot of material and inexpensive. The team also limited the use of 3D printed parts to just the STM structure to not produce more plastic waste. The design is also going to be used for educational purposes. The design will be distributed to schools in Arizona that are partnered with Raytheon to experiment with taking images with the STM as well as creating their own damping system. This is why the most important part of the design was to make it inexpensive so it can be accessible and easily produced for education,

1.16 Project Applicability

This project had many aspects that will help prepare each of our group members for our future careers. One of the major skills our team learned and improved upon was teamwork. Each team member had to work with team members, clients, and other groups. Working with team members taught how to delegate work and how to pick up the slack to make sure that all the assignments were completed on time. Working with our client taught team members how to present our updates and data to our client and have a meaningful conversation about future work and what direction the client wants to take their project. Working with the electrical engineering team taught our team members how to work with other groups to complete one common goal, this required lots of communication of how to get our vibration damping system working with their electrical STM componentry. Working with these multiple groups allowed our team to learn how to ask the right questions and get the needed information to continue our progression on completing the project.

Another aspect of this project that will greatly benefit our future selves is the independent nature of this project. Our team had to make many choices on our own to figure out the best way to complete this project. The design process required our team to do research and make informed decisions that did not have a correct or incorrect answer. This helped teach our members the best way to make independent choices to help progress the project. Another aspect that taught our team how to work without guidance was the testing and validation process for our design. This required our team to design a testing system from scratch that we could use to quantify that our design was providing adequate damping. For this our team had to come up with a valid procedure and testing methodology that would prove that our structure was passable.

Overall this project prepared each team member to work in a small group setting as well as in a large multigroup environment. It also helped prepare team members to have problem solving skills for problems that other people have not encountered and there is no information on what the correct answers are. This project helped each team member gain the knowledge and skills needed to fulfill a demanding role as a mechanical engineer.

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APPENDICES

Appendix A: FMEA Sheet

STM	Development Team: Spring 2023 STM Team				
Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)
Unaligned or uneven	Less control over piezo	10	Less-detailed imaging	7
Too thick or thin	Less control over piezo	10	Less-detailed imaging	8
Damaging 3D Printed Material	Inaccurate control over piezo	9	Less-detailed imaging	7
Misalignment of screws	Inaccurate control over piezo	9	Less-detailed imaging	7
Sample instability	Sample moves as screws are adjusted	10	Less-detailed imaging	6
Not enough size for a sample	Not able to take images of sample	10	Less-detailed imaging	5
Prone to vibrations	Not able to take accurate images of sample	10	Less-detailed imaging	6

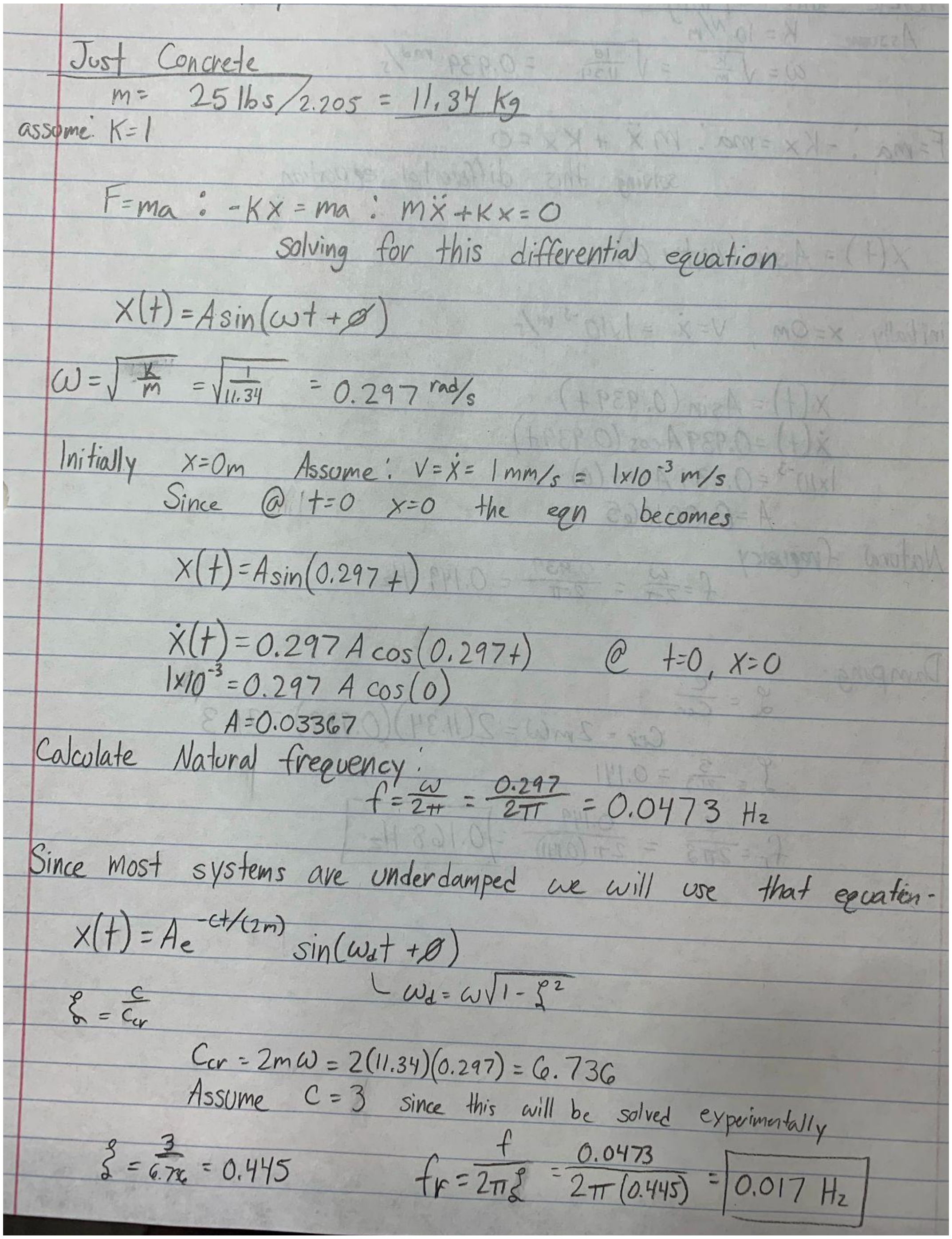
Figure 40: Full FMEA Sheet (Pt. 1)

Page No 1 of 1
FMEA Number 1
Date 4/30/23

Detection (D)	RPN	Recommended Action
2	140	Measure and adjust part to our needs without affecting neighboring parts
2	160	Measure and adjust part to our needs without affecting neighboring parts
2	126	Use stronger/longlasting 3D printed material (resin)
2	126	Divets added to bottom tringle for easy alignment
2	120	Adjustment screws are adjusted slowly
2	100	Make the platform large enough to hold sample
2	120	Create the design out of more dense material/ no loose wiring or structures

Figure 41: Full FMEA Sheet (Pt. 2)

Appendix B: Cement Block Vibration Analysis



Just Concrete

$m = 25\ lbs / 2.205 = 11.34\ kg$

assume: $K = 1$

$F = ma : -Kx = ma : m\ddot{x} + Kx = 0$

solving for this differential equation

$x(t) = A\sin(\omega t + \phi)$

$\omega = \sqrt{\frac{K}{m}} = \sqrt{\frac{1}{11.34}} = 0.297\ rad/s$

Initially $x = 0m$ Assume: $V = \dot{x} = 1\ mm/s = 1\times10^{-3}\ m/s$

Since @ $t = 0$ $x = 0$ the eqn becomes

$x(t) = A\sin(0.297t)$

$\dot{x}(t) = 0.297A\cos(0.297t)$ @ $t = 0,\ x = 0$

$1\times10^{-3} = 0.297\ A\cos(0)$

$A = 0.03367$

Calculate Natural frequency:

$f = \frac{\omega}{2\pi} = \frac{0.297}{2\pi} = 0.0473\ Hz$

Since most systems are underdamped we will use that equation-

$x(t) = Ae^{-ct/(2m)}\sin(\omega_d t + \phi)$

$\omega_d = \omega\sqrt{1 - \zeta^2}$

$\zeta = \frac{c}{c_{cr}}$

$c_{cr} = 2m\omega = 2(11.34)(0.297) = 6.736$

Assume $c = 3$ since this will be solved experimentally

$\zeta = \frac{3}{6.736} = 0.445$

$f_r = \frac{f}{2\pi\zeta} = \frac{0.0473}{2\pi(0.445)} = 0.017\ Hz$

Figure 42: Vibration Analysis Calculations

Appendix C: MATLAB Code for Analysis of Vibration Test

```
clear;
clc;
close all;
% Define the directory where the CSV files are located
dataDirectory = 'C:\Users\pkrig\OneDrive\School\Capstone\Acceleration Test\Actual Test\NEW';

% Get a list of all CSV files in the directory
csvFiles = dir(fullfile(dataDirectory, '*.csv'));

% Create figure for time domain plots
f1 = figure(1);
f1.Name = 'Time Domain Plots - Baseline';
sgtitle('Time Domain Plots - Baseline');

% Create figure for time domain plots
f2 = figure(2);
f2.Name='Time Domain Plots - Full';
sgtitle('Time Domain Plots - Full');

% Create figure for time domain plots
f3 = figure(3);
f3.Name = 'Time Domain Plots - No-Base';
sgtitle('Time Domain Plots - No-Base');

% Create figure for time domain plots
f4 = figure(4);
f4.Name = 'Time Domain Plots - No-Box';
sgtitle('Time Domain Plots - No-Box');

%Create figure for frequency domain plots
f5 = figure(5);
f5.Name = 'Frequency Domain Plots - Baseline';
sgtitle('Frequency Domain Plots - Baseline');

%Create figure for frequency domain plots
f6 = figure(6);
f6.Name = 'Frequency Domain Plots - Full';
sgtitle('Frequency Domain Plots - Full');

%Create figure for frequency domain plots
f7 = figure(7);
f7.Name = 'Frequency Domain Plots - No-Base';
sgtitle('Frequency Domain Plots - No-Base');

%Create figure for frequency domain plots
f8 = figure(8);
f8.Name = 'Frequency Domain Plots - No-Box';
sgtitle('Frequency Domain Plots - No-Box');
```

```
graph_num = [1 1 1 1];
graph_numf = [1 1 1 1];


% Load the first timetable data
for FileIDx = 2:2:length(csvFiles)
    data1 = readmatrix(csvFiles(FileIDx-1).name);

    % Load the second timetable data
    data2 = readmatrix(csvFiles(FileIDx).name);

    % Extract acceleration data from the timetables
    X_Voltage1 = data1(:,2);
    Y_Voltage1 = data1(:,4);
    Z_Voltage1 = data1(:,6);

    X_Voltage2 = data2(:,2);
    Y_Voltage2 = data2(:,4);
    Z_Voltage2 = data2(:,6);

    % Convert Voltage to acceleration
    X_acceleration1 = ((X_Voltage1-mean(X_Voltage1))/300)*9.81;
    Y_acceleration1 = ((Y_Voltage1-mean(Y_Voltage1))/300)*9.81;
    Z_acceleration1 = ((Z_Voltage1-mean(Z_Voltage1))/300)*9.81;

    X_acceleration2 = ((X_Voltage2-mean(X_Voltage2))/300)*9.81 ;
    Y_acceleration2 = ((Y_Voltage2-mean(Y_Voltage2))/300)*9.81;
    Z_acceleration2 = ((Z_Voltage2-mean(Z_Voltage2))/300)*9.81;

    % Create a time vector for both data
    t1 = data1(:,1);
    t1 = t1 / 1000;

    t2 = data2(:,1);
    t2 = t2 / 1000;

    start_time = 0;
    end_time = 7; % First 7 seconds
   max1 = X_acceleration1(1);
   max2 = X_acceleration2(1);
   for j = 1:length(t1)
      if(t1(j)>end_time)
          break
      end
   end
   for i = 1:j
      if X_acceleration1(i)>max1
          max1 = X_acceleration1(i);
          data1_start = i;
      end
   end
```

```
  for j = 1:length(t2)
     if(t2(j)>end_time)
        break
     end
  end
  for i = 1:j
     if X_acceleration2(i)>max2
        max2 = X_acceleration2(i);
        data2_start = i;
     end
  end

X_acceleration1(1:data1_start-1)=[];
X_acceleration2(1:data2_start-1)=[];
Y_acceleration1(1:data1_start-1)=[];
Y_acceleration2(1:data2_start-1)=[];
Z_acceleration1(1:data1_start-1)=[];
Z_acceleration2(1:data2_start-1)=[];
t1 = t1-t1(data1_start);
t2 = t2-t2(data2_start);
t1(1:data1_start-1)=[];
t2(1:data2_start-1)=[];

   if FileIDx == 2 ||  FileIDx == 10 || FileIDx == 18
      test_type = 1;
   elseif FileIDx == 4 ||  FileIDx == 12 || FileIDx == 20
       test_type = 2;
   elseif FileIDx == 6 ||  FileIDx == 14 || FileIDx == 22
       test_type = 3;
   elseif FileIDx == 8 ||  FileIDx == 16 || FileIDx == 24
       test_type = 4;
   end



   % Time domain plots with synchronized data
   if test_type == 1
      figure(f1);
   elseif test_type == 2
      figure(f2);
   elseif test_type == 3
      figure(f3);
   elseif test_type == 4
      figure(f4);
   end

   if graph_num(test_type)==1
      type = 'Active';
   elseif graph_num(test_type) == 4
      type = 'InActive';
```

```
elseif graph_num(test_type) == 7
    type = 'Semi-Active';
end

subplot(3, 3, graph_num(test_type));
plot(t1, X_acceleration1, t2, X_acceleration2);
title(sprintf('X-Acceleration Time Domain (%s)',type));
xlabel('Time (s)');
ylabel('Acceleration (m/s^2)');
legend('STM','Table');
graph_num(test_type) = graph_num(test_type)+1;
xlim([5 15])

subplot(3, 3, graph_num(test_type));
plot(t1, Y_acceleration1, t2, Y_acceleration2);
title(sprintf('Y-Acceleration Time Domain (%s)',type));
xlabel('Time (s)');
ylabel('Acceleration (m/s^2)');
legend('STM','Table');
graph_num(test_type) = graph_num(test_type)+1;
xlim([5 15])

subplot(3, 3, graph_num(test_type));
plot(t1, Z_acceleration1, t2, Z_acceleration2);
title(sprintf('Z-Acceleration Time Domain (%s)',type));
xlabel('Time (s)');
ylabel('Acceleration (m/s^2)');
legend('STM','Table');
graph_num(test_type) = graph_num(test_type)+1;
xlim([5 15])

% Compute the FFT for each acceleration axis
N1 = length(X_acceleration1);
N2 = length(X_acceleration2);
max_N = max(N1, N2);
diff1 = zeros(N1,1);
for i = 2:N1
    diff1(i) = t1(i)-t1(i-1);
end
Fs1 = 60/mean(diff1);
frequencies1 = Fs1 * (0:round(N1/2)) / N1;

X_fft1 = fft(X_acceleration1);
Y_fft1 = fft(Y_acceleration1);
Z_fft1 = fft(Z_acceleration1);

% Compute the power spectral density (PSD) for each axis
X_psd1 = (1/(Fs1*N1)) * abs(X_fft1(1:round(N1/2)+1)).^2;
Y_psd1 = (1/(Fs1*N1)) * abs(Y_fft1(1:round(N1/2)+1)).^2;
Z_psd1 = (1/(Fs1*N1)) * abs(Z_fft1(1:round(N1/2)+1)).^2;
```

```
% Convert PSD to (G^2/Hz)
X_psd1_G2Hz = X_psd1 / 9.81^2;  % Assuming 1 g = 9.81 m/s^2
Y_psd1_G2Hz = Y_psd1 / 9.81^2;
Z_psd1_G2Hz = Z_psd1 / 9.81^2;

% Compute the FFT for each acceleration axis

diff2 = zeros(N2,1);
for i = 2:N2
   diff2(i) = t2(i)-t2(i-1);
end
Fs2 = 60/mean(diff2);
frequencies2 = Fs2 * (0:round(N2/2)) / N2;

X_fft2 = fft(X_acceleration2);
Y_fft2 = fft(Y_acceleration2);
Z_fft2 = fft(Z_acceleration2);

% Compute the power spectral density (PSD) for each axis
X_psd2 = (1/(Fs2*N2)) * abs(X_fft2(1:round(N2/2)+1)).^2;
Y_psd2 = (1/(Fs2*N2)) * abs(Y_fft2(1:round(N2/2)+1)).^2;
Z_psd2 = (1/(Fs2*N2)) * abs(Z_fft2(1:round(N2/2)+1)).^2;

% Convert PSD to (G^2/Hz)
X_psd2_G2Hz = X_psd2 / 9.81^2;  % Assuming 1 g = 9.81 m/s^2
Y_psd2_G2Hz = Y_psd2 / 9.81^2;
Z_psd2_G2Hz = Z_psd2 / 9.81^2;

if test_type == 1
   figure(f5);
elseif test_type == 2
   figure(f6);
elseif test_type == 3
   figure(f7);
elseif test_type == 4
   figure(f8);
end

if graph_numf(test_type)==1
   type = 'Active';
elseif graph_numf(test_type) == 4
   type = 'InActive';
elseif graph_numf(test_type) == 7
   type = 'Semi-Active';
end

% Apply a moving average filter to smooth the PSD data
window_size = 2;  % Adjust the window size based on your preferences
X_psd1_G2Hz_smoothed = movmean(X_psd1_G2Hz, window_size);
Y_psd1_G2Hz_smoothed = movmean(Y_psd1_G2Hz, window_size);
Z_psd1_G2Hz_smoothed = movmean(Z_psd1_G2Hz, window_size);
```

```
X_psd2_G2Hz_smoothed = movmean(X_psd2_G2Hz, window_size);
Y_psd2_G2Hz_smoothed = movmean(Y_psd2_G2Hz, window_size);
Z_psd2_G2Hz_smoothed = movmean(Z_psd2_G2Hz, window_size);

%Convert to dB
X_psd1_G2Hz_smoothed = 10*log10(X_psd1_G2Hz_smoothed);
X_psd2_G2Hz_smoothed = 10*log10(X_psd2_G2Hz_smoothed);
Y_psd1_G2Hz_smoothed = 10*log10(Y_psd1_G2Hz_smoothed);
Y_psd2_G2Hz_smoothed = 10*log10(Y_psd2_G2Hz_smoothed);
Z_psd1_G2Hz_smoothed = 10*log10(Z_psd1_G2Hz_smoothed);
Z_psd2_G2Hz_smoothed = 10*log10(Z_psd2_G2Hz_smoothed);

freq_max = 150; %Maximum frequency displayed
x_diff = zeros(freq_max,1);
y_diff = zeros(freq_max,1);
z_diff = zeros(freq_max,1);
for k = 1:freq_max
   x_diff(k) = X_psd2_G2Hz_smoothed(k)-X_psd1_G2Hz_smoothed(k);
   y_diff(k) = Y_psd2_G2Hz_smoothed(k)-Y_psd1_G2Hz_smoothed(k);
   z_diff(k) = Z_psd2_G2Hz_smoothed(k)-Z_psd1_G2Hz_smoothed(k);
end
x_ave_diff = mean(x_diff);
y_ave_diff = mean(y_diff);
z_ave_diff = mean(z_diff);

subplot(3, 3, graph_numf(test_type));
plot(frequencies1, X_psd1_G2Hz_smoothed,frequencies2, X_psd2_G2Hz_smoothed,LineWidth=3);
title(sprintf('X-Acceleration PSD (%s)',type));
xlabel('Frequency (Hz)');
ylabel('Vibration Amplitude (dB)');
legend('STM','Table');
text(25,-65,['Average Difference = ',num2str(x_ave_diff),'dB']);
xlim([0 freq_max])
graph_numf(test_type) = graph_numf(test_type)+1;

subplot(3, 3, graph_numf(test_type));
plot(frequencies1, Y_psd1_G2Hz_smoothed,frequencies2, Y_psd2_G2Hz_smoothed,LineWidth=3);
title(sprintf('Y-Acceleration PSD (%s)',type));
xlabel('Frequency (Hz)');
ylabel('Vibration Amplitude (dB)');
legend('STM','Table');
text(25,-65,['Average Difference = ',num2str(y_ave_diff),'dB']);
xlim([0 freq_max]);
graph_numf(test_type) = graph_numf(test_type)+1;

subplot(3, 3, graph_numf(test_type));
plot(frequencies1, Z_psd1_G2Hz_smoothed,frequencies2, Z_psd2_G2Hz_smoothed,LineWidth=3);
title(sprintf('Z-Acceleration PSD (%s)',type));
xlabel('Frequency (Hz)');
ylabel('Vibration Amplitude (dB)');
```

```
    legend('STM','Table');
    text(25,-65,['Average Difference = ',num2str(z_ave_diff),'dB']);
    xlim([0 freq_max])
    graph_numf(test_type) = graph_numf(test_type)+1;
end

for fig_num = 1:8
    fig = figure(fig_num);  % Get the figure by its number

    % Specify the size of the image (width and height in inches)
    width = 15;  % Adjust to your preferred width
    height = 8;  % Adjust to your preferred height
    set(fig, 'PaperPosition', [0 0 width height]);

    % Save the figure as an image (e.g., in PNG format)
    saveas(fig, fig.Name, 'png');
end
```

Appendix D : Vibration Test Results

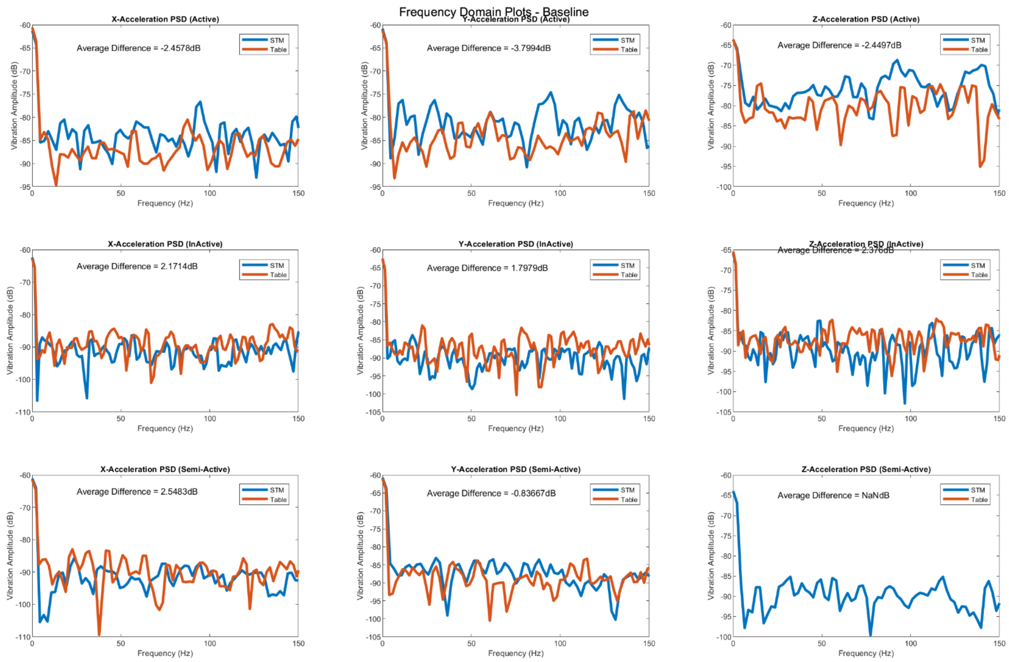


Figure 43: Frequency Domain Plots - Baseline

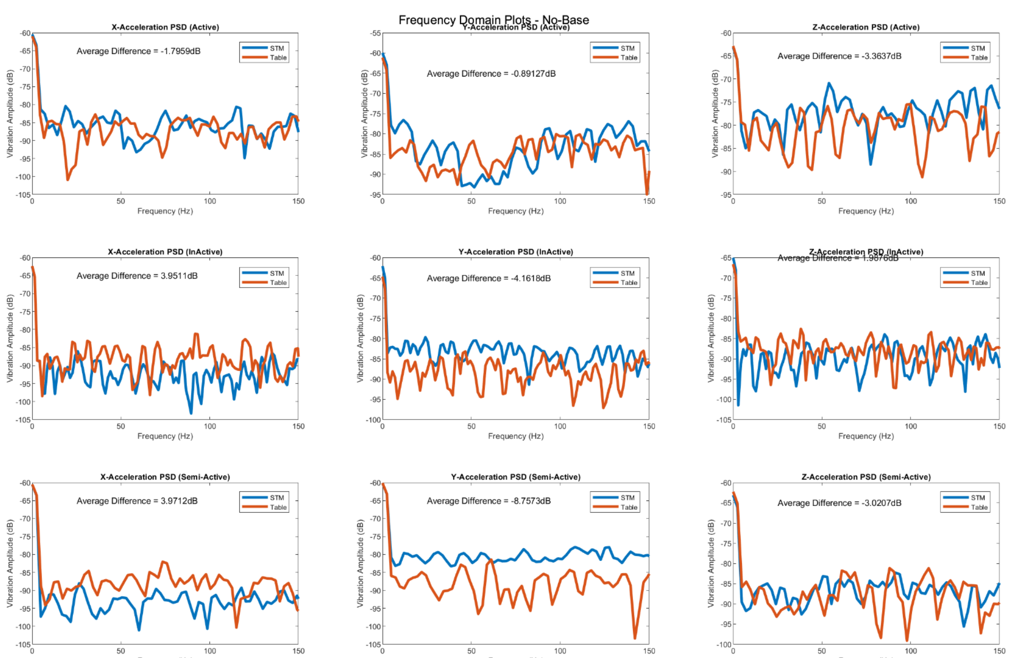


Figure 44: Frequency Domain Plots - No Base

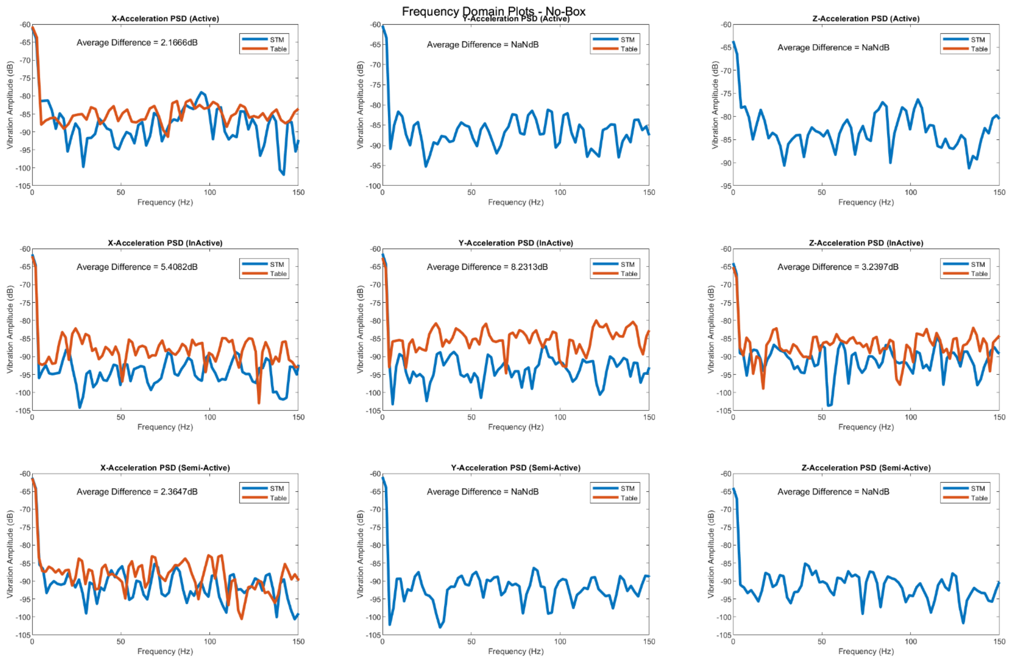


Figure 45: Frequency Domain Plots - No Box

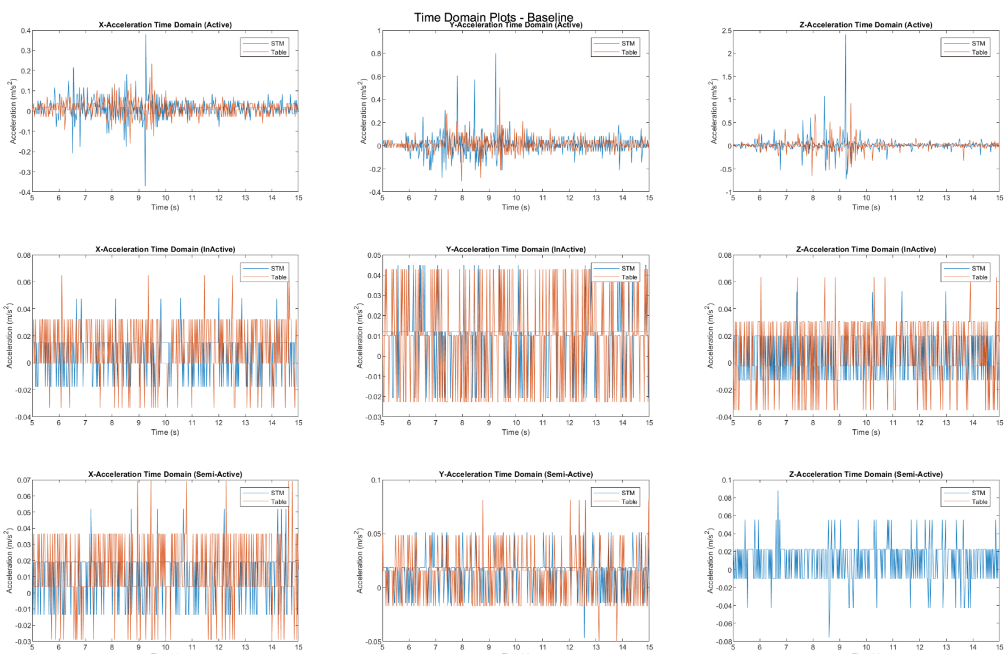


Figure 46: Time Domain Plots - Baseline

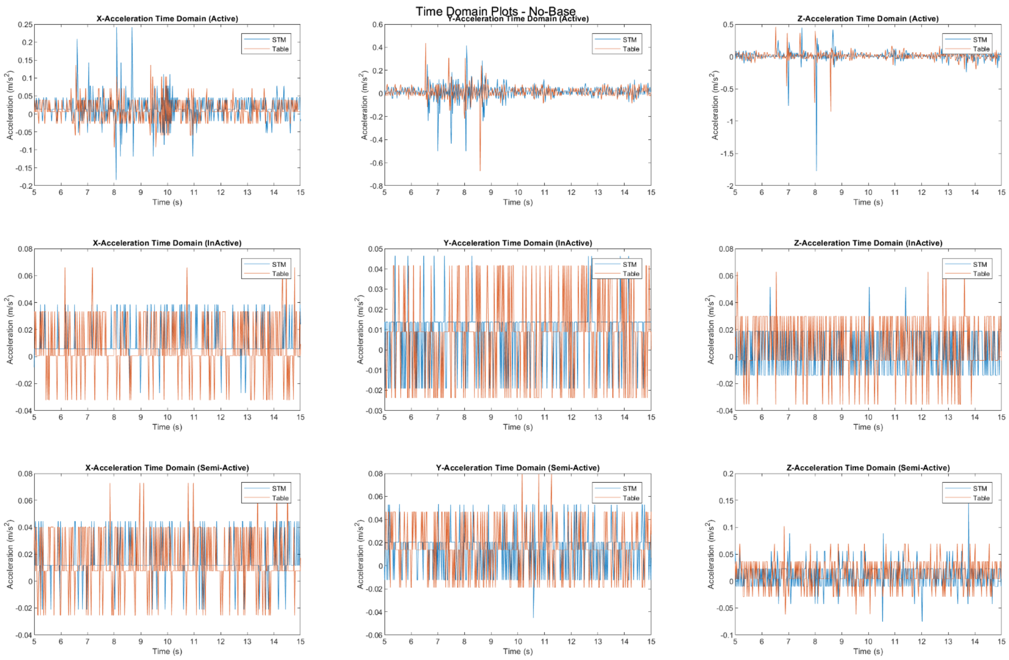


Figure 47: Time Domain Plots - No Base

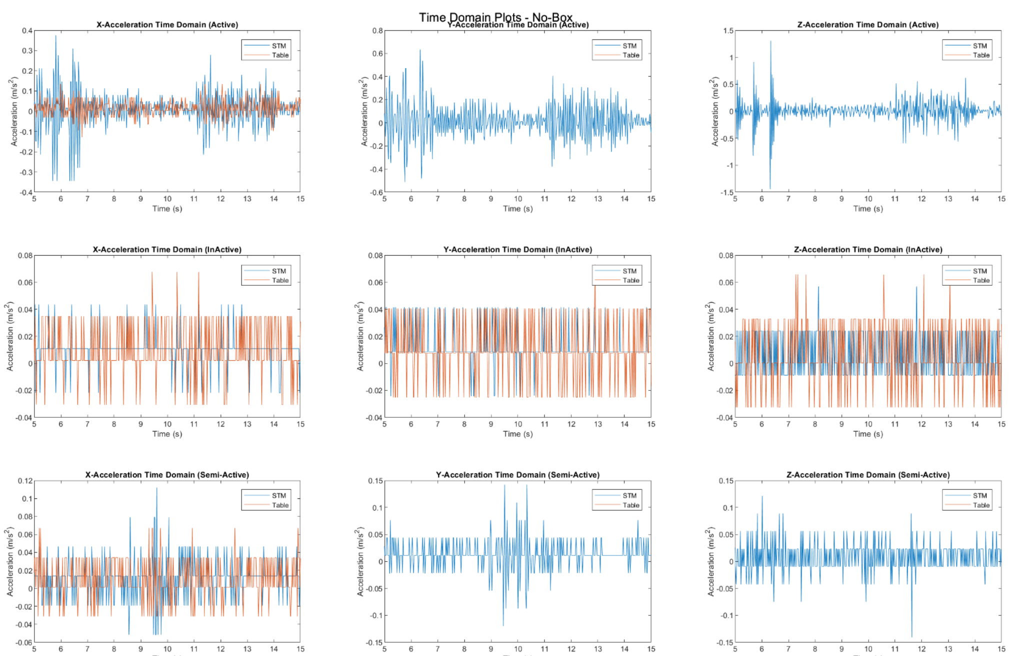


Figure 48: Time Domain Plots - No Box