Optimal Damping for Improved Controllability of a Shock Test Fixture

Team #3

Sponsor: Naval Surface Warfare Center–Dahlgren Division

Sponsor Advisors: Dr. Luke Martin, Sloan Burns, Garrett Wiles

Advisor: Dr. John Ferris

Team Members:
David Lee - Team Facilitator
Kevin Matos
Atticus Rex
Daniel Masters
Nick Stukel

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Executive Summary

Naval antennas require extensive shock testing and evaluation before being deployed on surface warships. The purpose of this project is to design, simulate, validate, manufacture, and test a prototype that emulates shock impacts on naval communication antennas for the Naval Surface Warfare Center - Dahlgren Division (Dahlgren). The team will produce an active and a passive solution with priority on modeling sample shock, which is irregular, high-frequency and high-velocity. This report covers customer needs, concept generation, prototyping, concept down selection, designs, analysis, and general team attributes.

The essential customer needs include active damping, scalability, velocity, and maximum frequency of the prototype. The team disseminated the customer needs into engineering characteristics and target specifications for the fixture to meet. Two concepts came from concept generation and down selection. The team explored these early designs by experimenting with different configurations of electromagnets to mitigate potential inadequate force generation and overcome the complexity of active damping. Based on results of the tests, electromagnetic simulation, and analysis, the optimized damping solution combines Lorentz force configurations of permanent magnets and conductive wire to generate linear force. The first concept generated was determined infeasible with displacement requirements of the beam.

The final design is covered in detail in this report. This design involves a hybrid of active and passive damping. Active damping consists of an array magnet-wire configuration to control its displacement. Passive damping of the system involves viscous damping and a linear spring. Active damping is controlled by a closed-loop control system that measures acceleration.

Fabrication, manufacturing, and assembly were completed in February. Coding development was completed in January. The team spent approximately $500 on initial subcomponent testing during the fall and spent approximately $5,400 on the final design and validation testing equipment. Approximately $1,000 went unused. Validation testing was completed in March to ensure design meets the established target specifications identified in the fall semester. All target specifications except velocity were met in the team's design. All deliverables were provided and presented to Dahlgren in April once the team completed validation testing.

Table of Contents

Introduction

The United States Navy is essential to global maritime trade and defending the United States and its interests. Communication is a vital part of carrying out the US Navy's mission. When a surface ship is under attack, shock waves are transferred from the ordnance through water onto the ship. These shock waves vibrate the whole ship, damaging key systems such as communication. The Naval Surface Warfare Center, Dahlgren Division (Dahlgren) created a resonant fixture for an antenna to match the shock absorbed by the ship. Dahlgren created the resonant fixture using a 17-PH Stainless Steel cantilever beam which did not match the desired damped test. The desired damped test is shown in Figure 1. Dahlgren asked Team 3 to create another prototype using creative solutions to match the desired damped test.

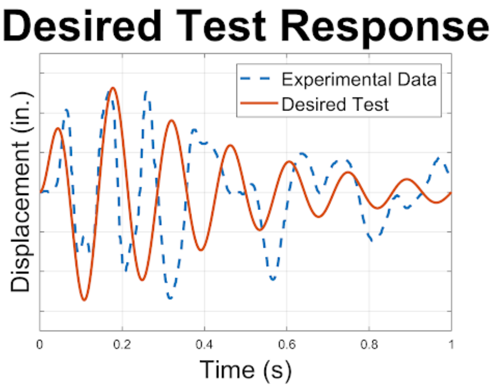


Figure 1: Comparison of Field Data and Desired Damped Shock Test

Team 3 understands the complexity of the desired damping and plans to use a hybrid between an active and passive damping solution. An ordinance produces irregular shock waves which can be challenging to dampen which is why active damping was necessary. Research was also completed, and Team 3 decided to pursue an electromagnetic damping system to have the most flexibility in controlling the resonant fixture. Team 3 used Dr. Henry Sodano (2005) as a close reference to creating a functional design using eddy currents. After experimentation, Team 3 decided to use the Lorentz Force as the foundation of the active damping system. The team completed testing and validation, and all target specifications were met except velocity. Team 3 successfully delivered a working prototype to Dahlgren.

Customer Needs, Engineering Characteristics, and Target Specifications

Team 3 created a customer needs table based on what was requested by Dahlgren. The table can be seen below in Figure 2. These customer needs were concluded based on past knowledge in vibrations and communication with our customers, Dahlgren. A weighted score of 5 shows the customer needs are essential, and a weighted score of 1 shows the customer needs have the least importance. The marginal and ideal values in the target specification table were generated in cohesion with Naval Surface Warfare Center, Dahlgren Division. Team 3 also did calculations from Dr. Sodano's dissertation (2005). Engineering characteristics were created and given a correlation rating with 9 having a strong correlation, 3 having a moderate correlation, and 1 having a weak correlation. Each engineering characteristic was ranked by taking the sum of the customer needs in each engineering characteristic. The engineering characteristic, maximum velocity, had high correlation ratings with customer needs 1, 2, 3, 4, 5, 6, and 7. In addition, 8 and 9 had moderate correlations with maximum velocity. The ideal and marginal values in Table 2 were carefully considered with Dahlgren and their initial description. The ideal values are the values that would be produced in perfect conditions; the marginal values are values that are more realistic. Tables 1 and 2 were both reviewed and approved by Dahlgren.

Table 1: Customer Needs for Shock Test Fixture

Customer Needs		
	Description	Weighting
1	Achieve desired test frequency	5
2	Durable	3
3	Variable damping	4
4	Amplification	3
5	Effective damping	5
6	Tunable active damping	4
7	Passive damping	2
8	Cost effective	1
9	Scalable	4
10	Modularity	3
12	Flexible text fixture	1

Table 2: Target Specifications Based On Customer Needs

Eng. Characteristic	Units	Marginal Value	Ideal Value
Maximum Frequency	Hz	15	25
Maximum Displacement	in	1.57	2.00
Maximum Velocity	ft/s	14.8	19.7
Acceleration	G's	10.0	15.0
Transmissibility	#	2	3
Damping Ratio	%	> 4	> 8
Volume	in^3	3000	2300
Surface Area Footprint	in^2	600	300
Cost	$	<10,000	<5000
Weight	lb	1100	110
Temperature	°C	<50	<30
Power	W	1800	1000
# of Components	#	<50	30

Concept Generation

To begin concept generation, the team generated a mind map to help identify certain aspects that the concept needs to include. The team added any and all aspects that are included in the problem statement to generate a giant mind map. We then discussed every branch of the mind map and identified seven different functions that the design must include. With this, the team collectively generated five concepts to help visualize possible solutions. With some general solutions, the next step was to generate multiple concepts to critique. The team decided that the best way to generate these concepts was to utilize the 6-3-5 method. Since our team has five team members, we used a modified 5-3-5 method. This method involves five people sketching three concepts onto a piece of paper that satisfy the problem, however unique or impractical they may be. Then each person passes the paper around for a few minutes, critiquing each concept or adding to the sketch until everyone gets their own paperback. With this, the team was able to identify some solutions to the functions of the concept.

These solutions were then put into a morphological chart to help organize each function. The team identified seven functions based on the customer needs and several solutions from the concept generation. With the chart below, each team member then generated two more concepts, making sure to include one solution for each function. These concepts were then presented to Dahlgren for feedback for improvements and eliminating less-probable concepts. Based on their feedback, the team was able to eliminate some designs and make improvements to others.

Table 3: Morphological Chart of Key Test Fixture Functions

Functions	Solutions				
Active Damping	Electromagnetic System	Pneumatic	Table Damper	Mass Damper	
Passive Damping	Viscous Damping	Aerodynamic Damping	Frictional Damping	Pneumatic Damping	Seismic Invisibility Cloak
Amplification	Cantilever Beam	Pendulum	Helical Spring	Torsional Spring	
Modularity	Combined Active/Passive	Separate Active/Passive			
Mounting	Bolts	Glue / Epoxy	Weld	Adhesive	
Shock Input	Shaker Table	Hammer	Heavy Mass Impact	Projectile	
Heat Management	Coolant	Heat Sink	Fan	Polymers	None

Analysis, Prototyping, and Risk Assessment

This section will detail the mathematical, virtual, and physical modeling for the prototypes as well as the risk assessment results and mitigation plans. Before examining the simulation results and methodology, it is important to reiterate the problem in the simplest terms possible. This project is to simulate an inexpensive way to simulate shock vibrations on antenna test fixtures. The vibrations examined in this project will be strictly one-dimensional. Thus, the team needs to find a way to model one-dimensional vibrations in multiple degrees of freedom to achieve the accelerations, velocities, and displacements with an accurate representation of the torpedo shocks given by the customer. The true shock graphs will not be disclosed in this report for confidentiality reasons.

A. Computational Modeling

This section will begin with examining the simplest transient response of vibration with one degree of freedom. This is defined by the canonical differential equation:

$$m\ddot{x} + b\dot{x} + kx = F(t) \tag{1}$$

where *m* is the mass of the vibrating object, *b* is the damping constant, *k* is the stiffness and *F(t)* is an external forcing component. The response, *x(t)*, is the displacement of the object over time. The team began with this model to begin analysis. However, the team has been asked to use a shaker table to vibrate the system at resonance. Thus, we can use the following model, detailed in Figure 2.

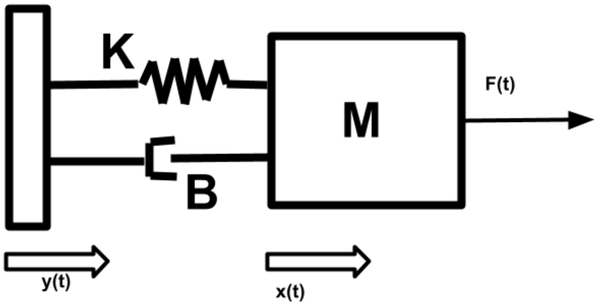


Figure 2: Visual Representation of Spring System

In this case, the external shake table will be modeled with the *y(t)* term while the response is modeled with the *x(t)*. The external force on the mass is the *F(t)* term. This reduces to the following differential equation:

$$m\dot{x} + B(\dot{x} - \dot{y}) + K(x - y) = F(t) \tag{2}$$

The team modeled the shock input using the following:

$$y(t) \ = \ \alpha \ \cdot Sin(\omega t) \tag{3}$$

The team is able to control α and ω within reasonable bounds. Using this approach, the team employed the following cost function:

$$C(B, K, \alpha, \omega) = ||x_{shock} - x_{sim}||_2 \tag{4}$$

Then, the team optimized the parameters *B*, *K*, α, and ω to produce a simulated response that matched the shock response as closely as possible with zero external forcings. The team generated non-confidential sample shocks to produce an irregular response in Figure 3.

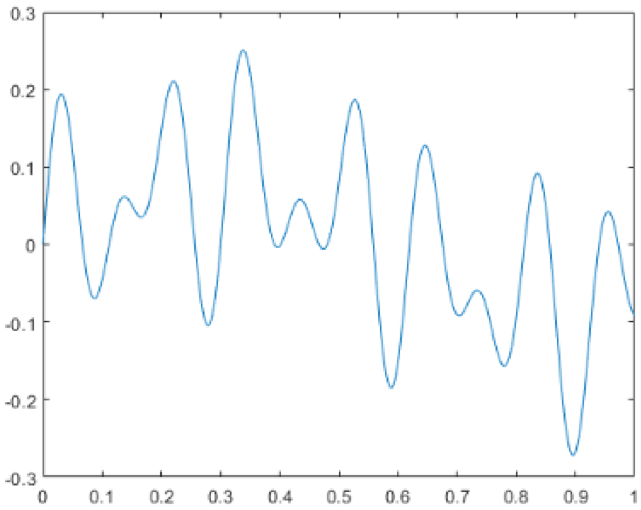


Figure 3: Sample Shock Generated in MATLAB

From this shock, the parameters were optimized to produce an ideal passive response. From this, the team then implemented a PID controller to actively control the simulated response to match the target response in Figure 4.

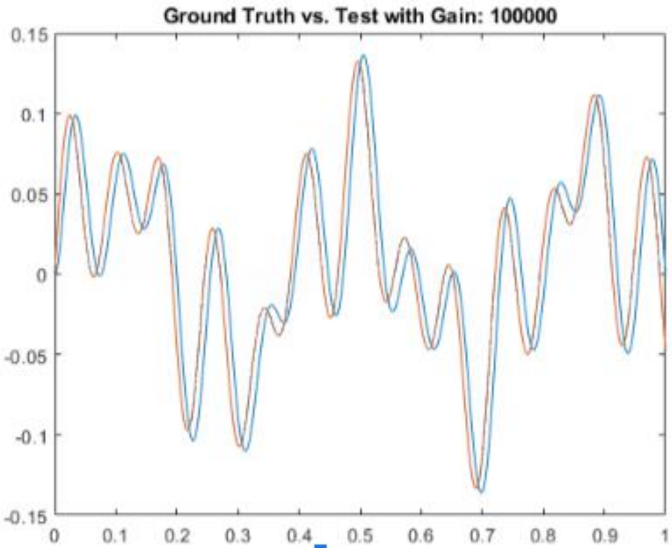


Figure 4: A Sample Shock With the Response Optimized With a High Controller Gain

This methodology gave the team an idea of how to use a controller to provide explicit force onto a vibrating mass. However, this did not tell the team how to apply electromagnetic force to an object. This will be discussed more thoroughly in the Experimental Testing subsection.

B. Computer-Aided Design (CAD)

The team produced three CAD models of the final two prototype designs. This design consists of a cantilever beam fixed to a shake table, with an aluminum frame around the beam fitted with electromagnets that control the displacement of the beam. Figure 5 is the CAD for the first prototype concept.

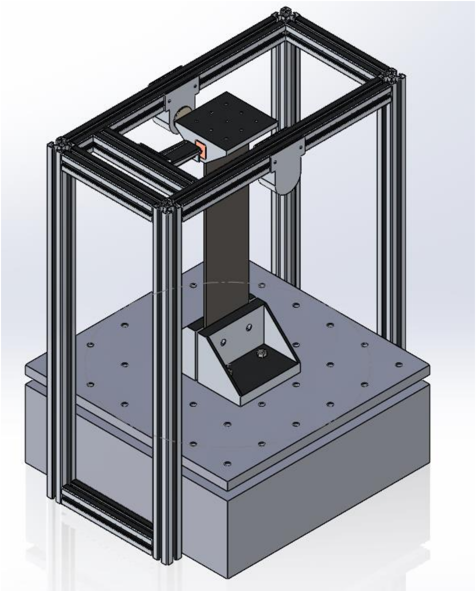


Figure 5: Concept 1 CAD Model On Top of Slip Table

The team also produced a second prototype concept which consists of a test fixture on two rails that vibrate longitudinally between rollers. This test fixture is passively sprung and damped while having an electromagnet produce the forcing for the control system. This can either be fitted with a cantilever beam for amplification or can be used as-is to produce the desired velocities. Figure 6 is the CAD model for the second design.

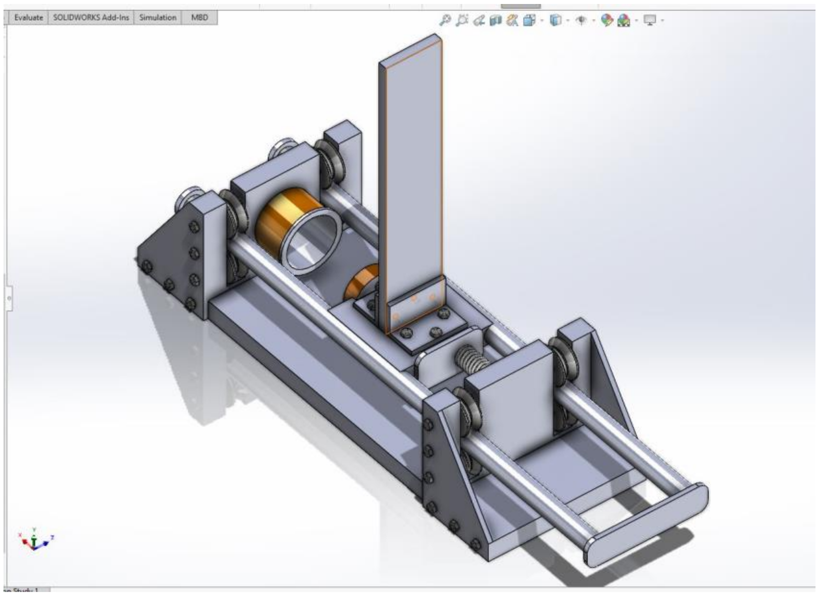


Figure 6: Concept 2 CAD model to be Mounted to a Slip Table

C. Physical Prototyping

Below are physical prototypes that were made to represent the basic functionality of the chosen design concepts. These prototypes assisted the team with scale and the structural integrity of designs #1 and #2, including the preliminary sub-component test rig. Figure 7 is a representation of design #1, Figure 8 is a representation of design #2, and Figure 9 represents the preliminary sub-component test rig. Figure 7 demonstrates the modularity of the 8020 aluminum frame. The top of the frame can be adjusted lower so the permanent and electromagnet have the most optimal damping force. Also, the permanent magnets in Figure 7 show how the permanent magnets can be adjusted along the top frame. Figure 8 shows how the aluminum rods can move in one dimension which allows the cantilever beam to oscillate and dampen. Figure 9 demonstrates how the test mount can move because of the aluminum rods.

Figure 7: Design #1 Physical Prototype

Figure 8: Design #2 Physical Prototype

Figure 9: Physical Prototype of Sub-Component Test Rig

D. Experimental Testing

The team designed an experiment to test various electromagnetic damping schemes. There are four electromagnetic forcing configurations that the team would like to investigate:

- Electromagnet with Permanent Magnet
  - In this configuration, an electromagnet with a variable current will be actively opposing a permanent magnet to produce a forcing term. This will almost indefinitely produce eddy currents in the electromagnets, which will need to be quantified.

- Electromagnet with Ferromagnetic Plate
    - In this configuration, an electromagnet with a variable current will be actively attracting a ferromagnetic plate located on the test fixture. Depending on the material, this conductor may carry eddy currents, and act as a damping mechanism in addition to the forcing mechanism.
- Permanent Magnet with Electric Coil
    - In this configuration, an enameled copper coil is wrapped around a permanent magnet, leaving a small gap, and a current is sent through the wire which produces the forcing term.
- Lorentz Force
    - In this configuration, two magnets are attracted to each other, but a small gap is created between the magnets. Enameled copper wire is then wrapped in between the small gap and magnet. This creates a force perpendicular to the magnetic force which can be used as a damping mechanism.

The objective of this experiment was to determine which configuration will maximize forcing while minimizing eddy currents and to produce an approximate function of current and distance which can then be scaled to the actual prototype. This helped the team validate and refine prototypes and gain valuable experiments implementing the electronic components before the manufacturing cycle of the project. Figure 10 depicts a CAD design of the prototype that was assembled in the first two weeks of October. Most parts were 3-D printed in PET plastic through the Virginia Tech library.

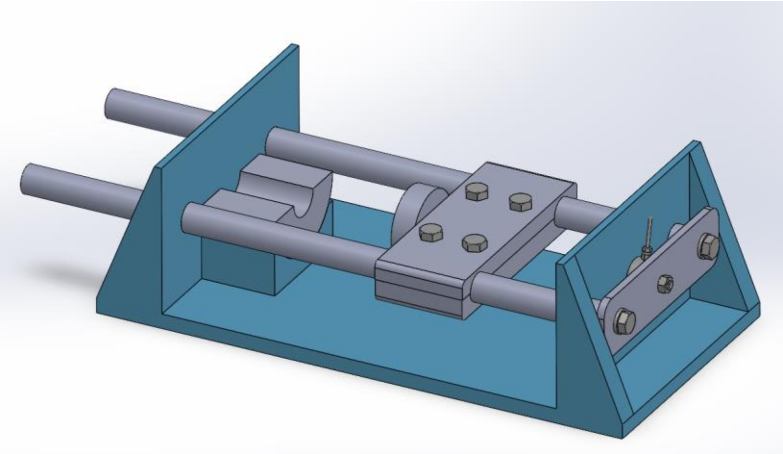


Figure 10: Preliminary Sub-Component Test Rig CAD Model

E. EMS for Solidworks

The team used the electromagnetic simulation add-on in Solidworks to analyze the amount of force that can be created from each subcomponent for the electromagnet. The Lorentz force model and the radial magnet were both analyzed.

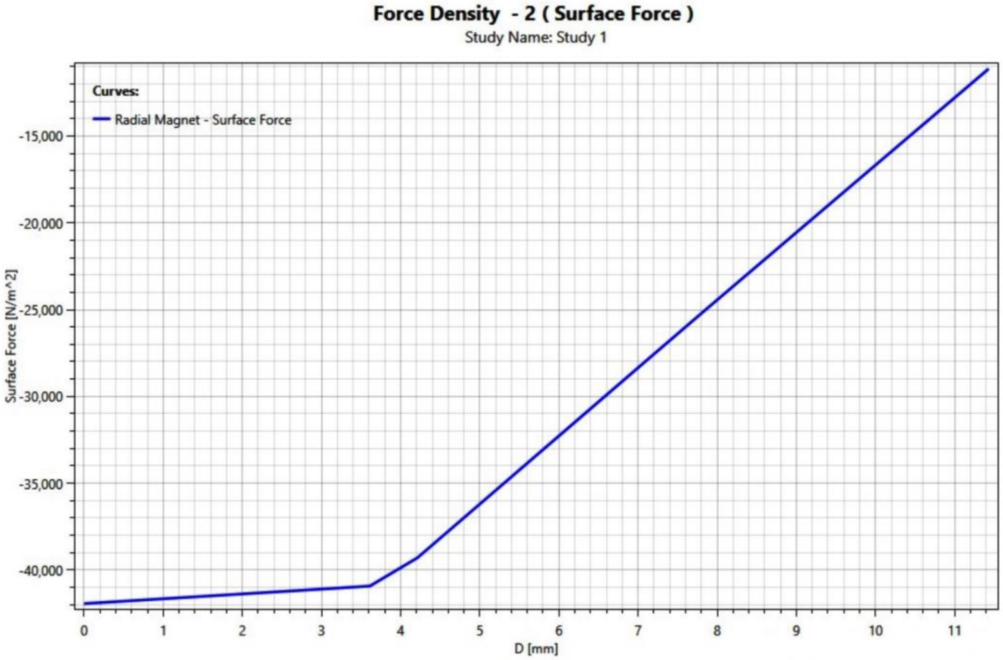


Figure 11: Results from EMS for Radial Magnet

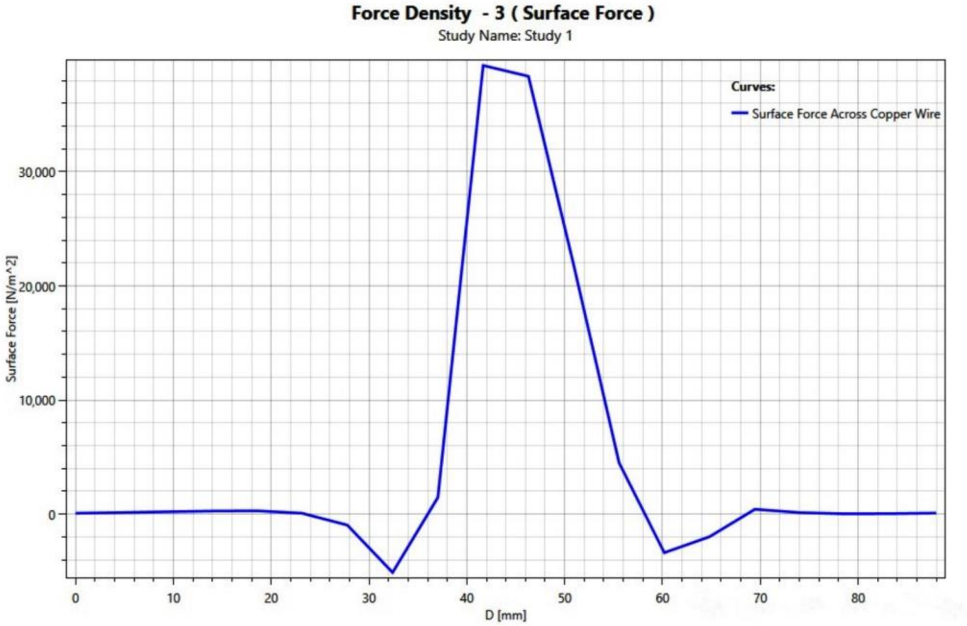


Figure 12: Results from EMS for Lorentz force model

The amount of force was found based on the integration of the surface pressure over the area of the coil wire. When comparing the radial magnet and Lorentz force model, the radial magnet produces a significantly larger force causing Team 3 to use a radial magnet as our active damping solution. However, the radial magnet was determined to be too challenging to manufacture. The team decided to use the Lorentz force as the active damping solution.

F. FEA

Team 3 completed FEA for the spring holder and outer bracket to ensure it is capable of the stress induced by the vibration. In Figure 13, the yield strength came out to $2.75 * 10^8\ N/m^2$ which translates to a factor of safety of 2.5. This factor of safety shows that the cantilever beam should not yield. The maximum displacement of the cantilever beam is 12.51 mm which can be seen in Figure 14, and 12.51 mm is below our marginal value for maximum displacement.

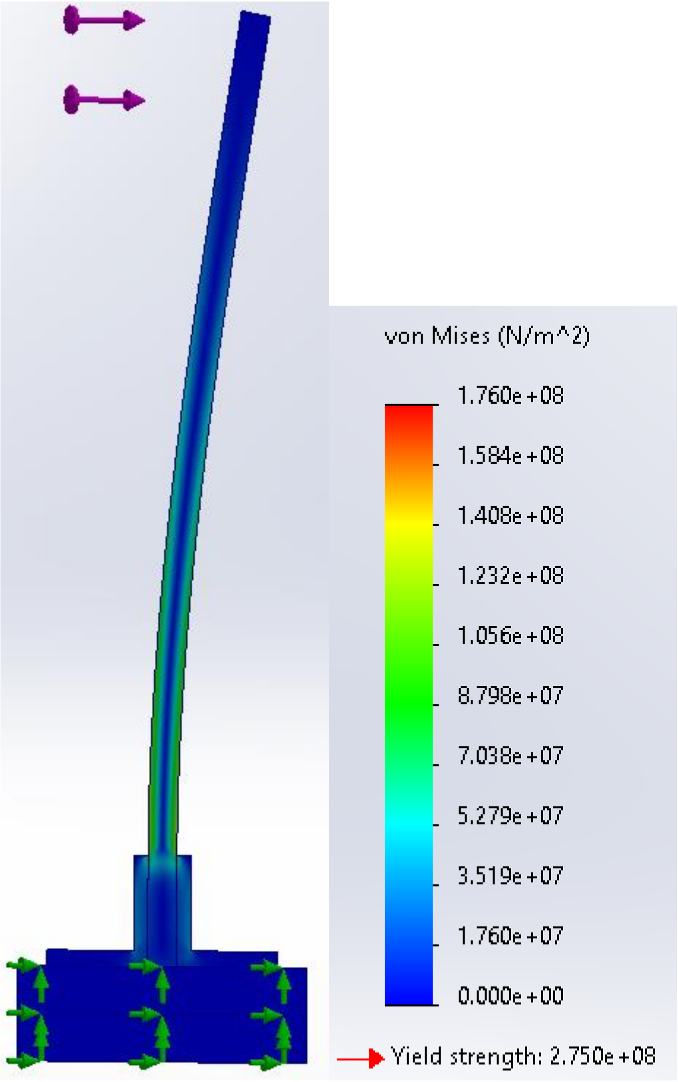


Figure 13: von Mises Stress using FEA

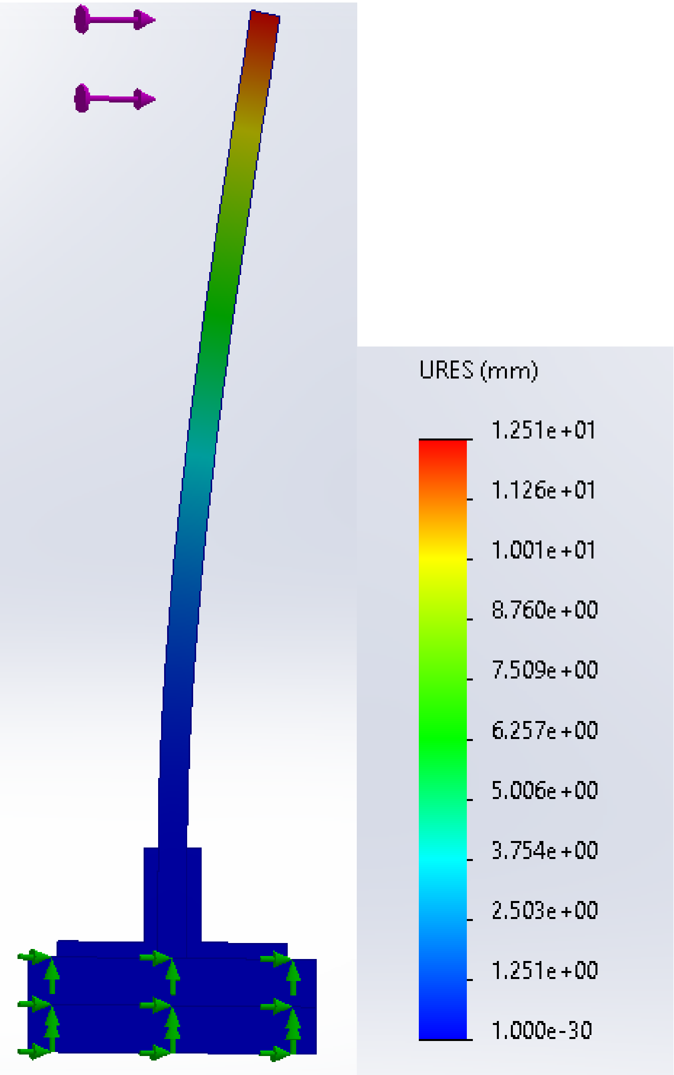


Figure 14: Displacement using FEA

In the spring semester, further FEA was done on the spring holder and outer bracket. Figure 15 shows the spring holder with a factor of safety of 11.5 The spring holder's material was Aluminum. Figure 16 shows the outer bracket where the damper is attached using a bolt. The factor of safety of the outer bracket part came to be 2.1.

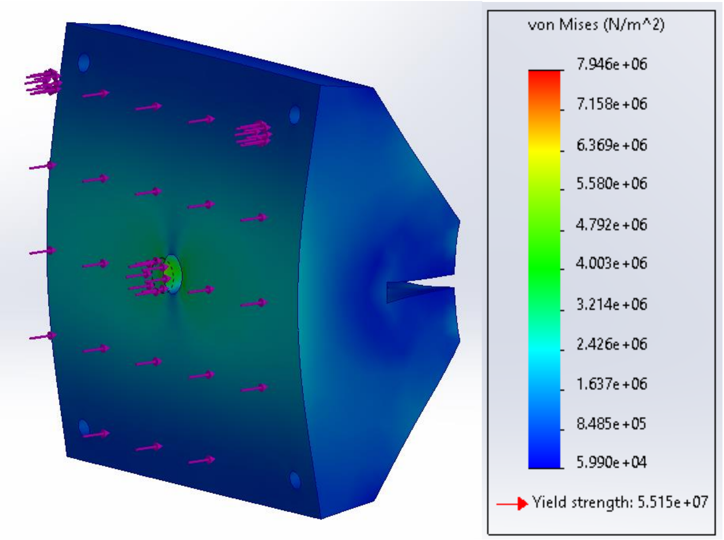


Figure 15: Spring Holder FEA

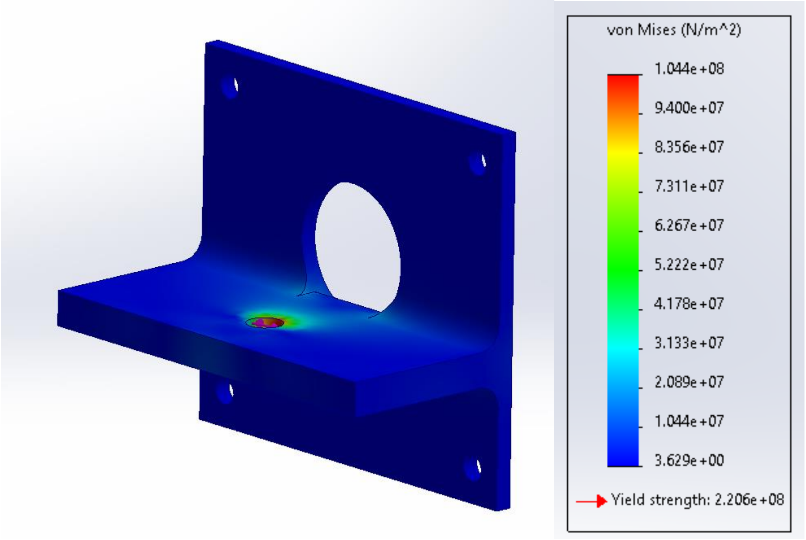


Figure 16: Outer Bracket FEA

G. Thread Hand Calculations

Thread hand calculations were conducted to determine the factor of safety for the bolts in tension and compression. The following equation was used to determine screw stress area:

$$J = \frac{A_S \text{ x tensile strength of external thread material}}{A_n \text{ x tensile strength of internal thread material}} \qquad (5)$$

Figures 17 and 18 show the screw locations. The internal threads in Figure 17 were determined to have a 17 factor of safety with a force input of 2250 lbf. The internal threads in Figure 18 were determined to have a 7 factor of safety with a force input of 560 lbf / thread.

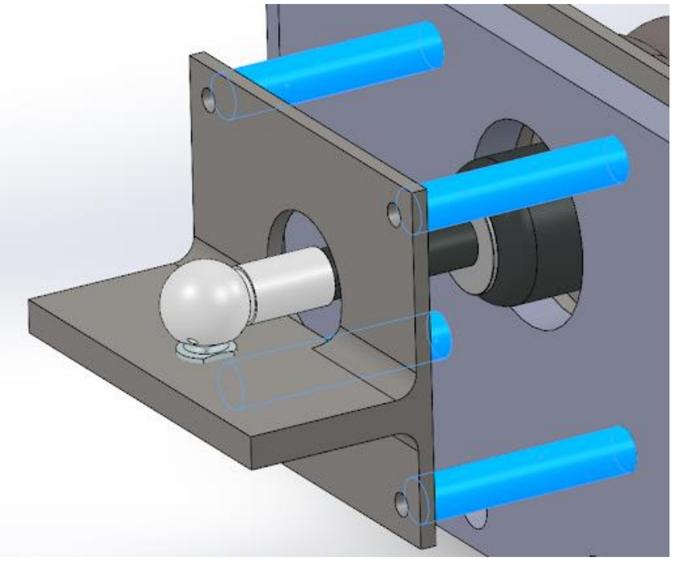


Figure 17: Passive damping bracket threads

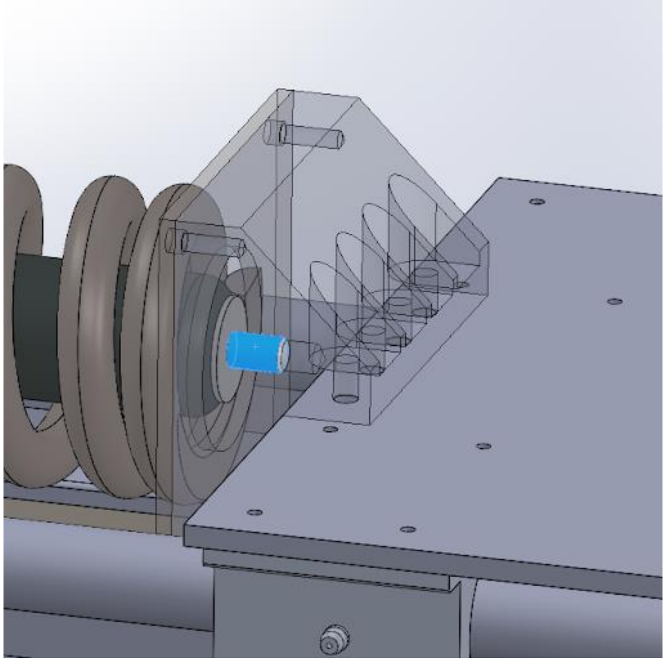


Figure 18: Sled clamp threads

H. Risk Assessment and Mitigation

Team 3 discovered five different risks which were analyzed to increase the success of the design. Identifying the different risks also shows the team what the priorities are for the design. The risks identified were inadequate force generation, inability to get an active position reading, insufficient input amplification, excessive forces applied to assembly, and not finalizing the design by end of the semester. The risk table summary can be seen in Appendix A.3. The likelihood scale ranges from 1 having a low probability and 5 having the most probability. The consequence scale ranges from 1 being a minimal consequence and 5 being an unacceptable consequence. As is shown in the risk table summary, all our risks are medium and one is low. The mitigation plan can be seen also in the risk table summary. Each risk has its own mitigation plan to evade any risk from occurring. The likelihood of each mitigation plan being successful is medium-high or high.

Concept Down Selection

Concept down selection occurred over several stages, Criteria & Datum Screening, Pairwise Comparison, and the Down Selection Matrix. The team used the information compiled from the engineering characteristics, target specifications, morphological chart, and generated concepts to determine which concepts were lacking and which stood out as feasible solutions.

A. Criteria & Datum Screening

In this stage the team considered how each of the generated concepts compared to each other with regard to each of the 15 engineering characteristics. First, the team established an improvement direction and scale type for each characteristic. This was done in order to have a consistent value, 1, to mean “better than”, 0, to mean no meaningful difference, and -1, to mean “worse than”.

With the improvement direction defined, the team created several tables, like that shown in Table A.1. Here, the team was evaluating one of the functions decided upon in the morphological chart. One function solution was set as the datum (0 column), and each of the remaining function solutions was compared to it in regard to each engineering characteristic. This was done up to 4 times in some cases for each function. With this data collected the team was able to determine which function solutions could be ignored entirely and which ones showed promise.

Using the results for passive damping are shown in Table A.2 as an example. Looking at the normalized values, we can see that Aerodynamic damping and the Seismic invisibility cloak are poor choices shown by the negative value, while Viscous, Frictional, and Pneumatic damping are potentially worthwhile to explore further.

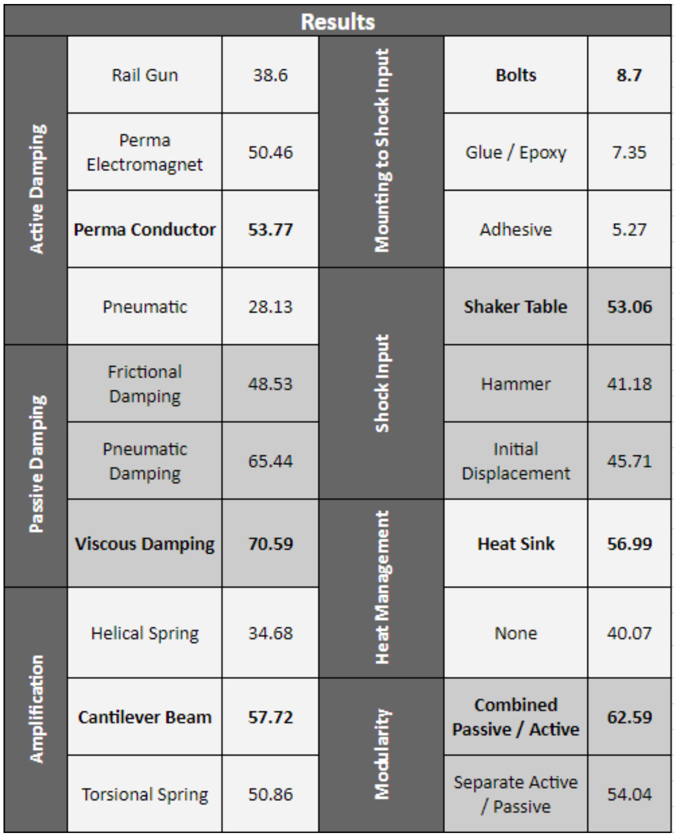
B. Pairwise Comparison

This stage was done to establish a relative weight for each of the 15 engineering characteristics for use in the down-selection matrix. The process was relatively straightforward. A matrix was created to compare each of the engineering characteristics with each other to determine which ones were more important. Here, the scale went from 0, less important, to 1, more important. From there each row was summed, averaged, and converted to a percent relative weight.

C. Down Selection Matrix

With several worthwhile function solutions determined and a relative weighting of engineering characteristics, the team was able to do one more comparison. This time the team scored how well each function solution would be able to meet each of the engineering characteristics. Using the relative weighting, and summing each solution’s weighted score, the team was able to determine a theoretical “best” solution for each function. These “best” solutions are bolded in Table 4 below. It should be noted that down-selection is not a perfect system. There may be slight nuances to each solution that the team didn’t account for in the matrix that comes up during further development. This does however give the team a ballpark of solutions to focus our attention on.

Table 4: Down Selection Matrix for Key Test Fixture Functions



Results					
Active Damping	Rail Gun	38.6	Mounting to Shock Input	**Bolts**	**8.7**
	Perma Electromagnet	50.46		Glue / Epoxy	7.35
	Perma Conductor	**53.77**		Adhesive	5.27
	Pneumatic	28.13	Shock Input	**Shaker Table**	**53.06**
Passive Damping	Frictional Damping	48.53		Hammer	41.18
	Pneumatic Damping	65.44		Initial Displacement	45.71
	Viscous Damping	**70.59**	Heat Management	**Heat Sink**	**56.99**
Amplification	Helical Spring	34.68		None	40.07
	Cantilever Beam	**57.72**	Modularity	**Combined Passive / Active**	62.59
	Torsional Spring	50.86		Separate Active / Passive	54.04

Detailed Design

The final design solution, shown in Figure 19 below, is an iteration of Concept 2. It implements three major changes including a system of support rails with “frictionless” bearings along with an array of bar magnets that surround a loop of copper wire, and the mount for the spring and viscous damper.

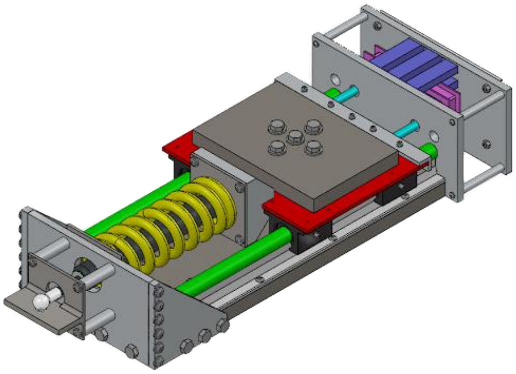


Figure 19: Final Concept 2 design

I. Support Rail & Linear Bearings

The support rail system was decided upon after several experimental tests. The team found that having a smooth straight surface for the sled to slide upon would be critical to success. Without the required freedom to move, the team found that the sled frequently got bound during its travel making repeatable setup and data collection near impossible. With this new support rail system, the team will be able to assemble the fixture quickly and easily, and have a respectable degree of consistency during testing.

II. Bar Magnets & Copper Coil

The other issue found from experimental testing was that the copper coil was difficult to maintain at a consistent distance away from the magnets. To maximize output force from the bar magnets and copper coil, we found we needed the coil as close to and fully surrounding the magnets as possible without touching which would risk stripping the protective enamel from the copper wire. With this in mind, the team decided to loop the wire between the bar magnets so that they are always exposed to the magnetic field. This can be seen in Figure 18 below. As these two components will be moving during testing, stiffness of the magnet holder throughout the travel is key here to avoid any accidental contact from unwanted vertical motion. The support rail system in conjunction with the standoffs connecting the sled plate and the copper coil gives the team confidence that will be maintained and magnet-coil separation will be minimized.

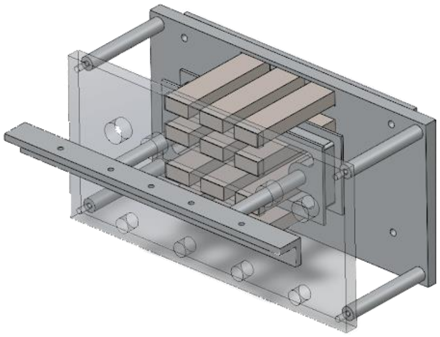


Figure 20: Final Concept 2 magnet & copper coil drum configuration

III. Spring and Viscous Damper Mounting

The main issues with the passive damping system were how to mount the spring to the sliding sled plate and how to minimize space without causing any excess bending. Because of the dimensions of both parts, the team found it beneficial to place the viscous damper inside of the spring. To achieve this, there were multiple steps that had to take place. The first being the spring mount. The team decided to weld the spring onto two steel plates so that it can be screwed into place. Two holes were cut into these plates so that the viscous damper could be placed through the spring. The main component for connecting these two parts is a custom clamp that the team ordered. This piece has holes on one side to screw in the spring and the damper, and a tight tolerance slot for the sled plate to fit in which is then bolted into place. The team also chose this configuration for two reasons. One, to increase the linearity of the system simplifying calculations. Two, having the spring and damper connected separately from each other allowed for a high degree of modularity. The system could be tested with just the spring, just the damper, or both very easily. These parts are shown in the figure below.

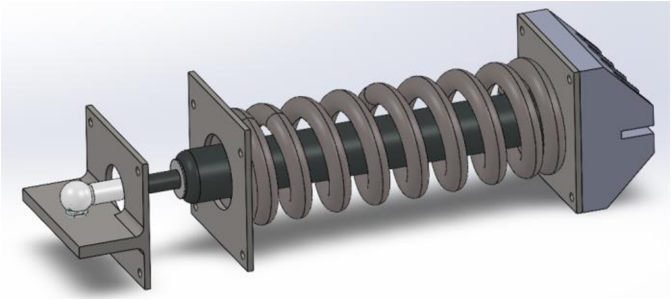


Figure 21: Configuration for passive damping system

IV. Electrical Component Setup

The way the active damping components were wired is shown in the figure below. The power supply sends current through the two 1 ohm resistors that are in series, and those are connected to two sets of solid-state relays. Each of the relays are connected to the breadboard and Arduino to control the switches in the relays to actively control the direction of the current going through the wire. All of these components are then placed inside an electrical box.

Figure 22: Setup of Electrical Components

Consideration of Multiple Factors in Your Design Solution

A. Public Health, Safety, and Welfare Factors

The fixture could cause projectiles to launch due to high frequencies up to 25 Hz and acceleration up to up to 15 G’s from shock input testing. Projectiles could hit and injure people in the direction of input. The team detailed assembly instructions that ensure every component is tightly mounted to the fixture, and encourage users to wear proper personal protective equipment (PPE) during testing.

The fixture will be operating at high current input to the active damping system. Electrocution is a possibility if the operator touches open wires while the active damping system is in use. The wire has enamel insulation to prevent electrocution, but the team should secure the wires with electrical housing and tape to reduce risk. The team also considered timed shut-off of the active damping system so that operators do not accidentally come into contact with live wires while working on the control system.

B. Global Factors

The team is developing the fixture for the Navy who is a US-restricted customer. All parts should be sourced in the United States to comply with International Traffic in Arms Regulations (ITAR) to ensure the system can be properly scaled up with no sourcing issues. Dahlgren cannot rely on components that can only be sourced from foreign adversaries. The team has considered potential US-based supply chain shortages and determined part sourcing according to part availability. The team also considered how the control system could be exploited to prevent hacking and infiltration from foreign adversaries.

C. Cultural Factors

No cultural factors were determined. The fixture will be used for laboratory testing of Naval warship capabilities and does not overtly influence culture.

D. Social Factors

The fixture could protect sailors by ensuring stable communications in adverse scenarios. Communications are the bloodline of Naval warships. Antenna testing of antennas before fleet fielding ensures warships can withstand shock events and keep the people onboard safe. More broadly, American interests are protected by protecting the warfighter through robust testing and evaluation of military technology. The team considered the importance of test results that can accurately characterize real shock events in combat.

E. Environmental Factors

Dahlgren can reuse the components of the fixture through multiple test iterations. The fixture minimizes manufacturing footprint by keeping replacements minimal, ultimately producing less waste. The team has considered using sustainably-based lubricant for the linear actuation of the test platform and examined the lifespan of components.

F. Economic Factors

Dahlgren conducts testing for internal and external customers. Tests are quoted according to the cost of parts and labor. The team has considered the additional equipment costs for non-antenna tests where shock input could characterize other components.

Dahlgren does not profit from testing since Dahlgren is owned by the US government. Part replacements will determine the usage of the fixture if Dahlgren determines tests can be run without losing funding. The team has considered how the lifespan of parts will influence usage since the Navy cannot benefit economically from using the fixture.

Test and Validation

Sensing the dynamics was the largest challenge in the testing and validation stage of the design cycle. The team received a linear potentiometer and an accelerometer from Dahlgren for the sensing of displacement, velocity, and acceleration. The following table shows the target specifications that was validated with the linear potentiometer and accelerometer:

Table 5: Testing Characteristics measured with Linear Potentiometer or Accelerometer.

Characteristic	Pass	Fail	Device
Maximum Frequency	15 Hz	< 15 Hz	Linear Potentiometer/ Accelerometer
Transmissibility	≤ 100	>100	
Damping Ratio	≥ 0.04	< 0.04	
Maximum Acceleration	≥ 10 G	< 10 G	
Maximum Displacement	≥ 1.57 in	< 1.57 in	
Maximum Velocity	≥ 14.8 ft/s	< 14.8 ft/s	

For testing the dynamic measurements, the team used a shaker table in Durham to perform these tests. The table allowed us to perform two types of tests, a sine sweep and a shock test. The sine sweep allowed us to test a range of frequencies with the slip table while keeping the acceleration constant.

The team was in the process of determining whether the accuracy and workability of the laser vibrometer is a worthy investment. This would be the most expensive piece of test equipment that the team purchases. In comparison, the accelerometer would be one of the least expensive purchases on the bill of materials. Double integration of acceleration would be necessary if an accelerometer were used in place of a vibrometer. A vibrometer could be more difficult to integrate with an Arduino-based control system. Using Fourier Analysis, numerical integration, and differentiation, the team will be able to derive all of the measurements shown in Table 5. The team decided to borrow accelerometers and a Data Physics machine from Dahlgren so we could test and validate each characteristic shown in Table 5.

Table 6: Results from Linear Potentiometer/Accelerometer testing and Pass/Fail

Characteristic	Measured	Pass/Fail
Maximum Frequency	25 Hz	Pass
Transmissibility	5	Pass
Damping Ratio	≥ 0.04	Pass
Maximum Acceleration	12.5 G	Pass
Maximum Displacement	1.6 in	Pass
Maximum Velocity	4.30 ft/s	Fail

In addition to Table 5, the following target specifications must also be met in validation testing which are shown in Table 6. These characteristics are based on survivability and environment, whereas Table 5 conveys the fundamental dynamic measurements needed by Dahlgren in their original project intent. All the dynamic target specifications were met except maximum velocity. The maximum velocity could not be met due to design constraints in the active damping system. If the velocity was any higher, the inner bobbin would crash into the walls which could damage the system. All the dynamic target specifications were measured on the slip table and the sled.

Table 7: Testing Characteristics measured with other devices.

Characteristic	Pass	Fail	Device
Weight	< 1100 lb	> 1100 lb	Scale
Surface Area Footprint	< 3000 in^2	> 3000 in^2	Tape Measure
Temperature	< 50 °C	> 50 °C	Laser Thermometer
Power	< 1800 W	> 1800 W	Digital Outlet Meter

Table 8: Results from other device testing

Characteristic	Measured	Pass/Fail
Weight	138.44 lbs	Pass
Surface Area Footprint	2.85 ft^2	Pass

Temperature	29 °C	Pass
Power	1800 W	Pass

All static target specifications were met with weight, surface area footprint, temperature, and power. The values can be found in Table 8 above. The weight and surface area footprint were measured using a scale and tape measure as well as solidworks. Overall, the team measured acceptable data for every target specification, and some target specifications passed the ideal value by margins like transmissibility and maximum frequency.

Project and Team Resource Allocation

The team has five members and is organized into two sub-teams of two people and a project facilitator. The sub-teams are responsible for hardware or software/electrical. Subteam #1 took the lead on the software and electrical side of the design. Subteam #2 took the lead on hardware and manufacturing. Members are organized in the following roles:

- Project Facilitator: Kevin Matos
- Subteam #1: Atticus Rex and Nick Stukel
- Subteam #2: David Lee and Daniel Masters

The sub-teams are responsible for the design, modeling, and simulation of their concepts. Each subteam is expected to develop a full CAD model of their concept and a comprehensive bill of materials. The designs will be justified by mathematical modeling and preliminary testing done in the Fall semester. In December 2022, subteams completed FEA and electromagnetic simulations of their designs. All aspects of the development process are split evenly between both members of the subteams. They are expected to provide weekly internal team updates and external Dahlgren updates. The project facilitator is responsible for the communication between the team, faculty, and Dahlgren. The project facilitator manages the project timeline, turns in assignments, and sends/receives deliverables between stakeholders. The project facilitator manages the budget and is responsible for preliminary testing equipment design changes, procurement, and 3D printing of materials.

Since the team developed one prototype, previous sub-team focuses will be reassigned focusing on hardware and software. Subteam #1 will focus on software during the spring semester, and Subteam #2 will focus on the hardware aspect of the prototype. Both subteams completed team assignments together and still met weekly to work cooperatively.

The following resources are available to individual team members:

- Personal laptop
- SolidWorks 2022 Educational License
- Electric and Magnetic Field Simulation (EMS) for SolidWorks 2022 Educational License
- MATLAB
- Microsoft Office products

The following workspace resources are available to the team:

- APPLIED lab
    - Workbench 7 and Basic Tool Kit
    - Manufacturing machines
    - 30 cubic inches ABS plastic
    - Misc. leftover hardware
- CENTIRE lab
- Durham Lab 181
    - Shaker for testing

Budget

Team 3 spent $5,919.21 in materials spending from the $7,000 in total funding provided by Dahlgren and the ME department. The breakdown of budget items is shown below.

A. Funding

This project is sponsored by Dahlgren who has provided the team with $5000.00. In addition, $2000.00 from the ME grant fund was awarded to the team. $6,486.99 remain after subcomponent test materials were purchased in the fall semester.

B. Preliminary Sub-Component Testing

Preliminary testing will be done at the sub-component level to determine the behavior and force output of the active and passive damping configurations used in the test fixtures. Excluding shipping costs, materials are $513.01 in total. The framework will be 3D printed at no cost and the control system is already in possession, while the electromagnet components, load cell, and hardware will be purchased. Table B.3 displays a bill of materials (BOM) for the fixture.

C. Design Bill of Materials

The team has created a BOM for the design. The BOM is located in the appendix, Table B2. The total cost of the design is $5,406.20.

D. APPLIED Lab

The team has access to the Advanced Product Prototyping Laboratory in Engineering Design (APPLIED) lab which includes a machine shop and maker space. As an industry-sponsored team, Team 3 has been assigned workbench 7.

E. Additional Resources

Dahlgren’s donated shaker in Durham 181 was borrowed by the team for testing.

Conclusion

Team 3 worked diligently this spring semester to deliver a validated prototype to Dahlgren. During this fall semester, Team 3 created two prototypes and a test configuration for the most optimal damping subcomponent. The damping subcomponent was completed. After further testing, Team 3 realized that Design 2 would only be successful in matching the customer’s needs. Two sub-teams were formed, hardware and software. Team 3 met regularly for updates and testing. The team met multiple challenges throughout the semester, but the team completed all testing and validation. The team delivered a successful and robust prototype for Dahlgren.

References

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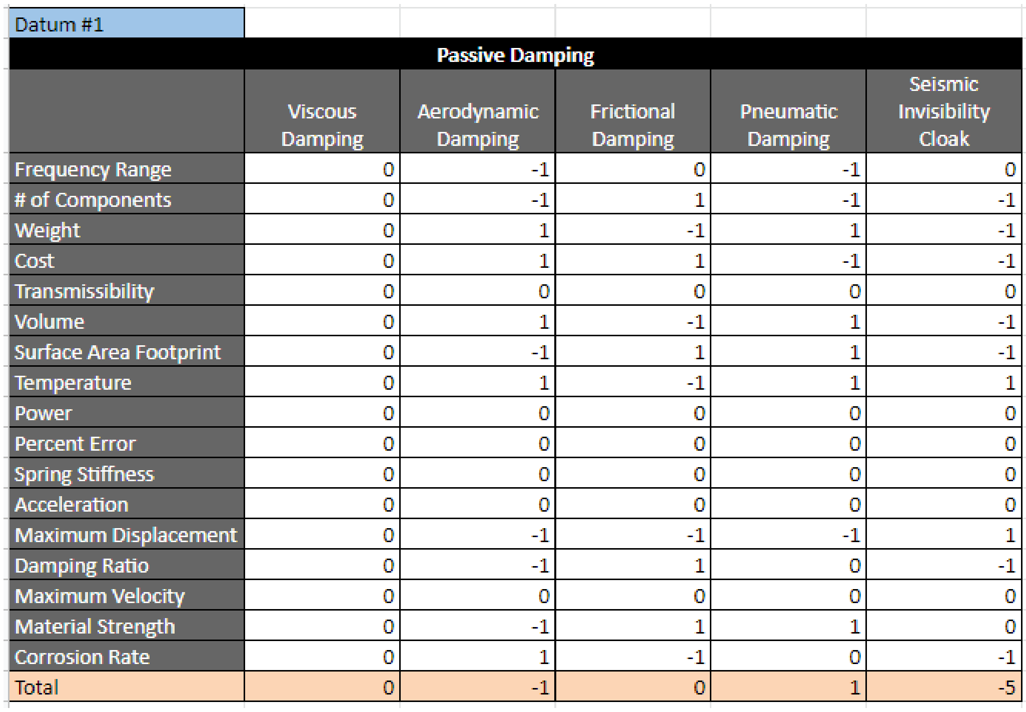
Appendix A

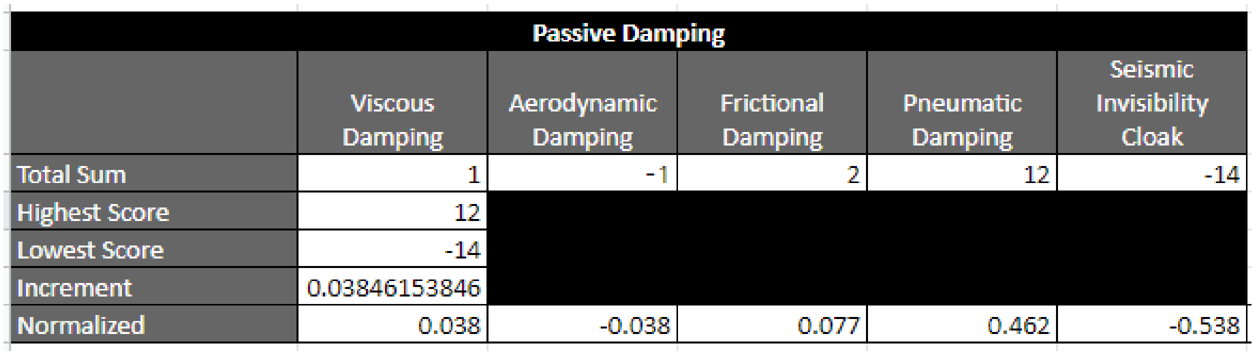
Table A.1: Criteria & Datum Screening Passive Damping Example



Datum #1

Passive Damping	Viscous Damping	Aerodynamic Damping	Frictional Damping	Pneumatic Damping	Seismic Invisibility Cloak
Frequency Range	0	-1	0	-1	0
# of Components	0	-1	1	-1	-1
Weight	0	1	-1	1	-1
Cost	0	1	1	-1	-1
Transmissibility	0	0	0	0	0
Volume	0	1	-1	1	-1
Surface Area Footprint	0	-1	1	1	-1
Temperature	0	1	-1	1	1
Power	0	0	0	0	0
Percent Error	0	0	0	0	0
Spring Stiffness	0	0	0	0	0
Acceleration	0	0	0	0	0
Maximum Displacement	0	-1	-1	-1	1
Damping Ratio	0	-1	1	0	-1
Maximum Velocity	0	0	0	0	0
Material Strength	0	-1	1	1	0
Corrosion Rate	0	1	-1	0	-1
Total	0	-1	0	1	-5

Table A.2: Criteria & Datum Screening Passive Damping Results



Passive Damping	Viscous Damping	Aerodynamic Damping	Frictional Damping	Pneumatic Damping	Seismic Invisibility Cloak
Total Sum	1	-1	2	12	-14
Highest Score	12				
Lowest Score	-14				
Increment	0.03846153846				
Normalized	0.038	-0.038	0.077	0.462	-0.538

Table A.3: Summary Risk Assessment & Mitigation Plans (RAMP)

Risk ID #	Risk Description	Risk Category	Likelihood	Consequence	Risk Level	Owner	Mitigation Plan	Mitigated Likelihood	Mitigated Consequence	Mitigated Risk Level	Status
1	Inadequate Force Generated	Technical	3	4	7	Atticus Rex	We have a preliminary fall-semester test plan between October 2022 and November 2022 to prevent an inadequacy of force from occuring. The testing plan is to gauge force strength and reliability from various electromagnetic damping methodologies that will account for magnetic material, permanent magnet strength, and current supply limitations. Furthermore, preliminary testing will allow the team to pursue alternative active damping methods if electromagnets are determined to be infeasible by designing the two test fixtures as modular--replacing one damping method with another without having to redesign the entire system.	4	3	7	Open
2	Inability to get Active Position Readings	Technical	3	4	7	Atticus Rex	We are implementing a testing plan between October 2022 and November 2022 to determine the frequency and accuracy by which we can sense position of the test fixture. We have access to an accelerometer, high speed camera, and laser vibration sensor that will all provide opportunities position readings. Each method will be tested and validated for accuracy at the frequencies and velocities targeted by NSWC.	5	2	7	Open
3	Insufficient Input Amplification	Technical	3	4	7	Kevin Matos	The team will use preliminary testing in the fall semester to develop mathematical models and test the chosen amplification methods so that the final design does not lack sufficient amplification. Testing will begin before the end of October and last until November 2022. We will also use pre-existing research from Virginia Tech using aluminum beams and NSWC's existing amplification method of 17-4 steel at a specified geometry to ensure no insufficiency in attaining target velocities in the system.	4	3	7	Open
4	Excessive forces applied to assembly	Technical	2	4	6	Daniel Masters	Proper calculation of applied forces and the resulting stress is mandatory to mitigate and prevent this risk. With known forces and stress esspecially at key vulnerable locations, determining the correct material will be as simple as looking through a material properties table. To guarantee safety, a sufficient safety factor will be set such that even small discrepencies will not cause any undue risk. Finite element analysis (FEA) will be used to validate the structure by simulating the force input in late November 2022 / early December 2022.	4	2	6	Open
5	Not finalizing design by end of semester	Program	2	3	5	Kevin Matos	Team 3 is delegating tasks to subteams so that the designs are only informed and not hindered by the test plan. The test plan is considered separate from the main project timline so that other tasks are not dependent on our results. We will halt preliminary testing if the task interferes with the final design by December 2022. All preliminary testing will be completed by Thanksgiving break.	5	1	6	Open

Appendix B

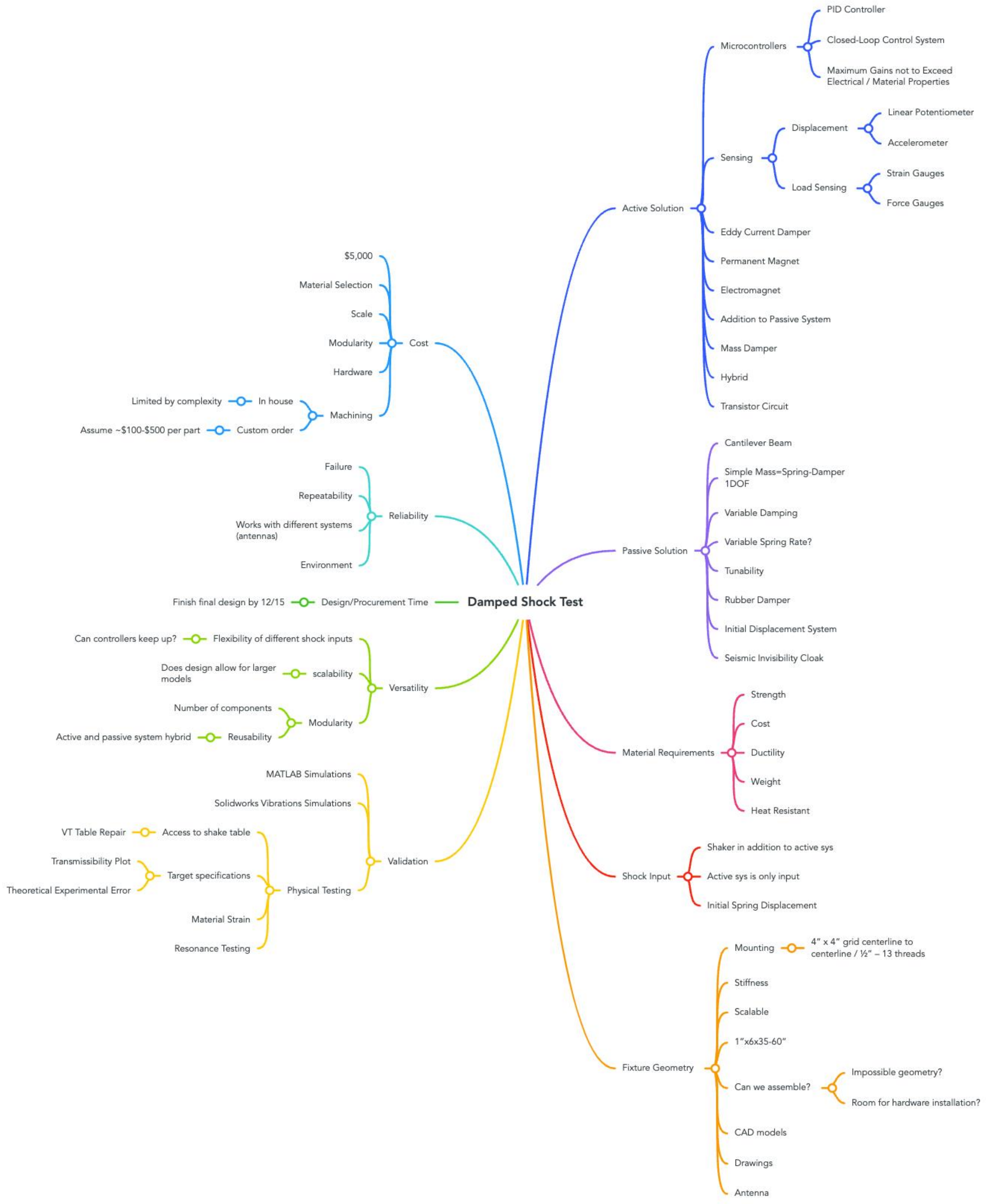


Figure B.1: Mind Map of Concept Generation Process

Category	Part Name	Material	Geometry	Misc Information	Quantity	Method of Acquisition	Cost
Fixture	Top Clamp	Plastic	15 x 7.5 x 5 cm	-	1	3D Print (PET)	-
	Bottom Clamp	Plastic	15 x 5.94 x 1.5 cm	-	1	3D Print (PET)	-
	Electromagnet Holder	Plastic	7.62 x 5 x 3.81 cm		1	3D Print (PET)	-
	Base	Plastic	27 x 18 x 9 cm	-	1	3D Print (PET)	-
	Rod	Aluminum	30 x 1.9 DIA cm	-	2	Purchase	$16.99
	Sled Connector	Plastic	15 x 0.5 x 4 cm	-	1	3D Print (PET)	-
	Hex Head Bolt	Steel	M8 x 3.5 cm	-	8	Purchase	$9.49
	Oversized Washer	Steel	M8	-	2	Purchase	$12.99
	Hex Nut	Steel	M8	-	4	Purchase	$5.98
	Hex Lock Nut	Steel	M6	-	2	Purchase	$6.99
Active Damper	Enameled magnet wire	Copper	30 AWG	155 deg C Temp Rating	4 oz (~250m)	Purchase	$11.70
	Iron rod	Iron	5.08 x 1.27 DIA cm	Soft Iron	1	Purchase	$19.99
	Round Electromagnet	-	3 in DIA x 2 in	Up to 500 lbs force	1	Purchase	$141.32
	Block Magnet	Neodymium	4" x " 1" x 1/2"		2	Purchase	$101.42
	17 AWG Magnet Wire	Copper	17 AWG		161 ft	Purchase	$23.99
Passive Damper	Permanent Magnet	Neodymium	0.3 x 3.2 DIA cm	80 N	2	Purchase	$11.00
Active/Passive Damper	Conducting plate	Iron	10 x 6 x 0.3 cm	Adhesive	1	Purchase	$9.99
Sensor	Load cell	-	M6	Tension & Compression, 200lbs force, dual-sided stud	1	Purchase	$75.00
Control System	Arduino MEGA microcontroller	-	-	-	1	In possession	-
	Misc. electrical components	-	-	-	-	In possession	-
Tools	Drill bit set	Cobalt steel	-	Metric	1	Purchase	$26.99
	Tap and die set	-	-	Metric	1	Purchase	$24.99
						Total	**$498.83**

Table B1: Bill of Materials for Preliminary Sub-Component Test Rig

Table B2: Bill of Materials for Design

Final Design							
Category	**Part Name**	**Material**	**Geometry**	**Misc Information**	**Quantity**	**Method of Aqcuisition**	**Cost**
Base	Steel Base Plate	A-36 Steel	1" x 10" x 24"	-	1	Purchase	$147.70
	Two-Piece Support Rail Shaft	Carbon Steel / Aluminum	24" x 1 1/2" x 1 1/8"	-	2	Purchase	$321.21
Sled	High-Speed Mounted Linear Sleeve Bearing	Aluminum	2 13/16" x 3 1/4" x 2 3/16"	-	4	Purchase	$107.22
	Sled Base	Aluminum	0.25" x 12" x 12"	-	1	Purchase	$57.12
	Mineral Oil	ISO Grade 100	1 gal	-	1	Purchase	$24.42
Cantliever Beam	Cantilever Beam	A-36 Steel	0.5" x 1' x 4'	-	1	Purchase	$142.72
Passive Damping	Compression Spring	MW Steel	3.5" OD 10" Free length	-	1	Purchase	$310.67
	Viscous Damper	-	in Compressed Lg, 22.24 in Extend	-	1	Purchase	$337.87
	Extra Weight for Point Mass	A36 Steel	1" x 10" x 24"	-	1	Purchase	$157.70
Electromagnetic Damping	Block Neodymium Magnets	N52 Neodymium	4" x 1" x 0.5"	-	14	Purchase	$46.10
	Enameled Magnet Wire	Copper	16 AWG	5 lb	628 ft	Purchase	$58.46
	Walls	Aluminum	6 " x 12" x 0.5"	-	4	Purchase	$31.63
	Inner Bobbin	Aluminum	-	-	-	Purchase	$441.83
	Aluminum Rods	Aluminum	0.5" x 12"	-	2	Purchase	$5.39
	Outer Coil Holder	Aluminum	1" x 6" x" 12"	-	1	Purchase	$60.91
	Spring Holder	Aluminum	Custom	-	1	Purchase	$501.34
Hardware	Sled Base Screws	Steel	10-32 x 1" Philips	25	2	Purchase	$14.83
	Washers	Alloy 20 Stainless	Inner Diameter 0.260"	5 count	2	Purchase	$6.94
	Magnet Holder Screws	Steel	8-32 x 1" Philips	10	25	Purchase	$7.90
	Nylon Insert Locknut	Steel	10-32	10 Count	1	Purchase	$4.89
	Screws	Steel	10-32 x 2" Philips	25	1	Purchase	$9.75
	Bolts	-	8-32 2.5"	-	6	Purchase	$0.37
	Lock Nut	-	8-32	-	6	Purchase	$0.17
	Wire 19GA 50 Galv Roll	-	-	-	1	Purchase	$4.59
Controllers	Arduino	-	-	-	1	Purchase	$29.95
	Raspberry Pi	-	-	-	1	Personal	-
Housing	Electrical Junction Box	Wood	15"x15"x6"	-	1	APPLIED	$113.00
Power Supply	MEAN WELL NSP-3200-48	-	-	-	1	Purchase	$551.00
Measurement	Accelerometer	-	-	5 count	1	Purchase	$12.99
Tools	Soldering Iron	-	-	-	1	Purchase	$18.99
	Short-Length Drill Bit	Black-Oxide High-Speed Steel		-	2	Purchase	$2.60
	Short-Length High Speed Drill Bit	Steel	-	-	1	Purchase	$44.89
	Short-Length Drill Bit	Cobalt Steel	-	-	2	Purchase	$4.35
	Short-Length Drill Bit	Cobalt Steel	-	-	1	Purchase	$15.30
	Short-Length Drill Bit	Cobalt Steel	-	-	2	Purchase	$5.10
	Short-Length Drill Bit	Cobalt Steel	-	-	2	Purchase	$2.68
	Short-Length Drill Bit	Cobalt Steel	-	-	1	Purchase	$13.82
	Short-Legnth Drill Bit	Black-Oxide High-Speed Steel	-	-	2	Purchase	$2.13
	High-Speed Chip-Clearing Tap	Steel	-	-	2	Purchase	$7.41
	High-Speed Chip-Clearing Tap	Steel	-	-	1	Purchase	$16.48
	High-Speed Chip-Clearing Tap	Steel	-	-	2	Purchase	$7.41
	Multipurpose 90 Angle with Round Edge	6061 Aluminum	.5" Thickness, 2.5" Outside Height	-	1	Purchase	$31.20
	Short-Length Drill BIt	Black Oxide	-	-	1	Purchase	$3.49
	High-Speed Drill	Steel	Size F	-	1	Purchase	$9.47
Electrical	High G Accelerometer with I2C and SPI	-	-	-	2	Purchase	$24.95
	STEMMA QT/Qwiic JST SH 4-pin	-	-	-	2	Purchase	$0.95
	MOSFET N-CH 60V	-	-	-	6	Purchase	$3.15
	Resistor	-	-	-	2	Purchase	$66.36
	CG Solid State Relay DC to DC 60A	-	-	-	8	Purchase	$12.90
		-				**Total**	**$5,406.20**