

BRIDGE SHAKER

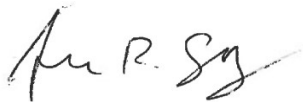
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A. Preface

A.1. Executive Summary

The Adaptive Real-Time Systems (ARTS) Lab is a research lab that develops sensor packages for structural health monitoring. They want a product that continuously excites different structures to permit continuous time testing of bridges to validate their vibration sensor packages.

Needs of the ARTS Lab were determined by identifying and independently ranking a list of needs, and after detailed analysis, it was determined that testing vibration data, operating at different frequencies, being safe to operate, and leaving the bridge undamaged were critical to satisfying those needs. It was furthermore determined that a product to satisfy their requirements would need to test vibration data and be usable by future researchers. It was thus determined that the product mission should be to create a bridge shaker that needs to test vibration data, operate at different frequencies, be safe to operate, and leave the bridge undamaged.

Given the above requirements, multiple concepts were researched and considered, as described in this report. The ultimate concept selected to best satisfy the ARTS Lab's needs was excitation via an AC motor and gear train for linear actuation. Details related to concept selection and subsequent product architecture are supplied.

The bracket stress, output force, and motor temperature are critical to functionality, and detailed engineering analyses are provided, demonstrating how bracket stress, output force, and motor temperature were modeled, under conditions of high frequency operation, and the design was optimized for a maximum bracket stress of 17.91 MPa, a maximum force output of 6000 N, and a maximum motor temperature of 316K. As a result, the system was able to output more than enough energy to excite the structure and stay within safe operating temperatures, though some of the 3D brackets experienced failure along the layer lines, which could not have been simulated and predicted in Fusion 360.

Because parameters safety, durability, and ease of use are high priorities for production of the product, the design was optimized for these parameters as well, which consisted of adding additional weight to secure the shaker, sourcing high quality materials, and making the project entirely open source.

The prototype was tested by measuring vibration output accuracy, testing the shaker's operation at a wide range of frequencies, operating the shaker at small step sizes and comparing the bridge response, weighing the shaker, inspecting any failed components after high frequency testing, and measuring the displacement of the shaker before and after operation. These tests were performed outdoors in 60-80 degree Fahrenheit weather on a pedestrian bridge with a high stiffness value.

Economic analysis of the scope of expenses associated with development of the prototype indicate that, for a \$4,736 investment, the ARTS Lab will recover costs within 7.7 years if they chose to sell units rather than earn profit from research grants.

The bridge shaker presented in this work meets the majority of the customer needs and product specifications, falling short on robustness and bridge contact. Robustness is increased by substituting higher quality brackets and bearings into the design, and bridge contact is improved through adding additional weight to the shaker during high frequency operation. Both issues have been addressed and require further formal testing to validate the design changes.

A.2. Background

The Adaptive Real-Time Systems Lab is a research lab at the University of South Carolina under Dr. Austin R.J. Downey. One specialization of the ARTS Lab is unmanned aerial vehicle deployable sensor packages for structural health monitoring. The lab has developed a sensor package to measure vibrations in bridges. A challenge the lab is facing is being able to perform continuous time testing of vibrations in bridges, as they would need a modal shaker to excite the bridge for minutes at a time. The lab can perform impulse testing, which involves striking the bridge just once to measure the decay signal, but there is a need

for continuous time testing to further the lab's research on structural health monitoring applications of its sensor package.

The purpose of this project is to design and develop a bridge shaker that will provide the lab with an instrument to perform continuous time testing with its vibration sensor package. The shaker is intended to be used by the lab for expanding the type of testing they can perform, which will further their research and entice new grants.

B. Customer Needs

B.1. Introduction

The goal of this project is to create a bridge shaker that, when placed on a bridge, excites multiple frequencies and modes within that bridge. Dr. Austin Downey wishes this device to test a wide variety of bridges and gather information on the structural integrity and health of the bridge. The purpose of this chapter was to begin the design process by determining and ranking the sponsor needs. The conceptualized needs were listed and defined in relation to the scope of the project. They then underwent two rounds of independent ranking in order to identify which were the highest priority needs. Finally, the project mission statement was formed based on the critical needs.

B.2. Interpretation of Needs

This section outlines the 36 needs that were brainstormed by the design team and defines each need to promote clarity.

1. Needs to be used to test vibration data – the bridge shaker must be able to shake the bridge being tested at a high enough frequency to match our control data.
2. Needs to ideally excite the fourth or fifth mode – the shaker needs to be able to shake the bridge well enough that the fourth and fifth mode can be seen on an FFT diagram.
3. Needs to have a max range based on experimental data gathered by accelerometers – testing data from normal bridge activity must be recorded to create a baseline for the shaker to operate at.
4. Needs to be robust – the design of the shaker needs to be simple and easy to put together, must not be too complex.
5. Needs to be usable in the future – the shaker needs to remain a useful tool for future experiments even after the conclusion of this project.
6. Needs to be site flexible – it must be applicable to a multitude of different bridge sizes and dimensions; needs to be simple enough for a wide range of applications.
7. Needs to be portable – by making the shaker light and easy to carry, the shaker is able to be used in a variety of different locations.

8. Needs to be user friendly – the controls and functionality of the shaker need to be simple enough so that someone with a little experience can operate the machine.
9. Needs to run off a portable power supply – some bridges may not have an outlet nearby for us to supply power to the shaker, therefore it will need some sort of internal power system.
10. Needs to tell the frequency it is operating at – a display for the current frequency the shaker is operating at so the value can be checked with a control test.
11. Needs to have feedback control – it needs feedback control on the responsiveness of the shaker and operating parameters; needs to be easily adaptable.
12. Needs to have a screen to monitor parameters – some sort of LCD needs to be incorporated to keep track of operating parameters.
13. Needs to transfer energy to bridge – a good connection to the bridge is required so that the energy of the shaker is transferred into the bridge and not dissipated elsewhere.
14. Needs to have high efficiency – must create minimal losses from the shaker itself or any other factors; needs to exert an equal value of energy to that it is using.
15. Needs to have good contact to bridge – needs good contact to the bridge so that the shaker will not tear itself apart or damage the bridge.
16. Needs to leave the bridge undamaged – the bridge's integrity needs to be upheld in an equal condition to which it started.
17. Needs to be minimally invasive – these bridges are community bridges, so the shaker and accelerometers need to be as convenient as possible for all foot traffic pedestrians.
18. Needs to be small enough to not affect vibration data – the size of the shaker needs to be small enough and light enough so that it does not dampen the vibrations in the bridge.
19. Need accelerometers to capture very high/low frequencies for validation – a wide range of frequencies must be accommodated in the design parameters.
20. Needs user controllable speed – the shaker must have some sort of controllable speed input to control the frequencies being created.
21. Needs to be replicable by other researchers – the shaker must be simple enough so that others interested in this work are able to recreate the design.
22. Needs to be easily repairable – the shaker must be easily repairable. Since the shaker is under continuous stress, anything that fails must be easily fixed.
23. Needs to be cost-effective – the shaker must not be extremely expensive, and the operating costs need to be low as well.
24. Needs to withstand the stress of operation – no matter the design, the shaker needs to produce extreme forces to create vibrations, therefore it must withstand its own energy output.
25. Needs to record data - accelerometer placement needs to be strategic to record the best and most useful data.
26. Needs to be aesthetically pleasing – since the experiments take place in public, the shaker must not be threatening-looking.

27. Needs to operate at different frequencies – frequency design parameters need to be set to ensure the shaker can operate in a full range of frequency.
28. Needs a resolution of at least 1 Hz – the shaker must be programmable within a 1 Hz resolution.
29. Needs to be power efficient – needs to output as much energy as it is taking in, ease of energy calculations.
30. Needs to be validated with data at different times of day – vibration data across the bridge in a normal day's time needs to be recorded to find the full range of vibrations experienced by the bridge.
31. Needs to operate at a variety of temperatures – the effect of temperature on the performance of the bridge is also of interest so the shaker needs to operate in extreme heat and cold.
32. Needs to be well documented (GitHub repository) - all data and documents need to be stored so that the public can see and recreate our experiment.
33. Needs to have clear operation instructions – the shaker must have instructions that allow someone with little experience to operate the shaker effectively.
34. Needs to be safe to operate – the shaker will operate in a public space; therefore, it needs to be safety tested before it is introduced into the public environment.
35. Needs to have a failsafe – a safety switch must be installed for an automatic stopping system.
36. Needs to have time control – the testing will take place over extended periods of time; therefore, it will need a timer to operate on.

B.3. Affinity Diagram

Round 1 consisted of 50 points per person voting on all 38 needs and is shown in Table B1. For the first round, each need was independently given a score pulled from the 50 points based on how important it appeared to be. More points indicate a more critical need. The total points for each need were added up and the top seven needs were identified to move forward in a second round of voting. The top seven needs were chosen because they represent the 80th percentile of the 36 needs.

Table B1. First round of needs ranking

Needs	Points (50 total)				Total Points
	Alex Toth	Ryan Brown	Corinne Smith	Ryan Yount	
Category I Primary Functionality					
Needs to be used to test vibration data	3	3	3	2	11
Needs to ideally excite the fourth or fifth mode	2	2	0	1	5
Needs to tell the frequency it is operating at	2	2	3	3	10
Needs to have a max range based on experimental data gathered by accelerometers	2	3	2	1	8
Needs to have feedback control	1	2	2	2	7
Needs to transfer energy to bridge	3	3	3	3	12
Need accelerometers to capture very high/low frequencies for validation	2	2	1	1	6
Needs to operate at different frequencies	3	3	1	3	10
Needs a resolution of at least 1 Hz	1	2	0	3	6
Needs to operate in a variety of temperatures	0	0	0	0	0
Needs to have a time control	0	0	0	0	0
Needs to record data	1	0	2	0	3
Category II User Friendliness and Safety					
Needs to be user friendly	0	0	1	0	1
Needs to have a screen to monitor parameters	0	0	0	1	1
Needs user controllable speed	2	0	2	1	5
Needs to have clear operation instructions	0	1	1	1	3
Needs to be safe to operate	3	3	3	1	10
Needs to have a fail safe	3	3	3	1	10
Category III Documentation					
Needs to be usable after we leave	0	0	0	2	2
Needs to be replicable by other researchers	0	1	1	1	3
Needs to be easily repairable	0	1	1	1	3
Needs to be well documented (GitHub repository)	1	1	1	1	4
Category IV Packaging					
Needs to be robust	2	2	2	2	8
Needs to be site flexible	1	1	1	3	6
Needs to be portable	2	3	1	2	8
Needs to run off of a portable power supply	1	1	0	2	4
Needs to have good contact to bridge	3	3	2	1	9
Needs to leave bridge undamaged	3	3	3	2	11
Needs to be minimally invasive	0	0	1	0	1
Needs to be small enough to not affect vibration data	2	0	3	3	8
Needs to withstand the stress of operation	2	2	3	2	9
Needs to be aesthetically pleasing	0	0	0	0	0
Needs to be power efficient	1	0	1	1	3
Needs to have high efficiency	2	2	1	1	6
Category V Miscellaneous					
Needs to be cost-effective	2	1	2	2	7
Needs to be validated with data at different times of day	0	0	0	0	0
Total Points	50	50	50	50	200

The top seven needs from round 1 moved on to round 2, shown in Table B2, where they were ranked from highest priority to lowest, with 1 as the highest priority and 7 as the lowest. The voting was conducted similarly to the first round, but each team member had only 28 points to distribute in round 2. The top four from round 2 were used to form the product mission statement.

Table B2. Second round of needs ranking.

	Needs	Alex Toth	Ryan Brown	Corinne Smith	Ryan Yount	Total Points	Rank	
Round 2								
	Needs to leave bridge undamaged	1	1	3	2	7	1	Rank the needs listed 1-7, 1 being the most important, 7 being least important
	Needs to be safe to operate	4	3	2	3	12	2	
	Needs to have a fail safe	5	5	7	6	23		
	Needs to operate at different frequencies	2	4	6	4	16	4	
	Needs to transfer energy to bridge	3	6	4	5	18		
	Needs to tell the frequency it is operating at	7	7	5	1	20		
	Needs to be used to test vibration data	6	2	1	7	16	3	
		28	28	28	28	112		

B.4. Product Mission Statement

Dr. Austin Downey needs a bridge shaker that needs to test vibration data, operate at different frequencies, be safe to operate, and leave the bridge undamaged.

C. Project Specifications

C.1. Introduction

The product specifications phase of the design process determined ways to quantify the previously identified critical needs into specific engineering characteristics for the product. The needs list was consolidated to eliminate redundancies and the 15 most important needs based on the affinity diagrams in section B.3. are assigned metrics and units in the needs matrix. Engineering characteristics are then assigned for each customer requirement and the correlation of each with the needs is shown in the needs metrics matrix. Finally, target and fallback specifications for each important metric are assigned. The value of this section for the design process was the identification of critical specifications.

C.2. Needs Matrix

When deciding the needs for the bridge shaker, redundancies in the previously defined needs were identified to create a more concise list. Fifteen out of the original 36 needs were kept. Each need was evaluated individually to determine the importance of the characteristic for the final product. Some needs such as site flexibility, minimal invasiveness, and small size were cut in favor of portability as an umbrella need. Ways to validate the performance of each customer need were brainstormed to produce metrics and their corresponding units. Each metric and unit were collectively discussed in relation to each specific need.

The client requires an accurate way of measuring the desirable characteristics for excitation over an extended period to test structural integrity of a bridge. This means that the shaker needs to operate at different frequencies to recreate the modal frequencies of the bridge. This project is well documented, with data while using the shaker being recorded, as well as a time control on the shaker to supply timed testing. The client also recommended safety and ease of use so that

researchers could comfortably use the shaker for vibration experiments. After further discussion, the bridge shaker needs to be robust, have good contact with the bridge, and leave the bridge undamaged. These characteristics were clear needs for the shaker to meet the purpose of a long lasting and useful experimental tool. All the needs discussed were organized into Table C1 with the units and metrics included.

Table C1. Needs matrix.

Needs	Units	Metric
Test vibration data	N	Force
Operate at different frequencies	Hz	System output range
Resolution of at least 1 Hz	Hz	Measurement precision
Time control	s	Test run time
Record data	boolean	DAQ
Screen to monitor parameters	boolean	User interface
Clear and safe operation instructions	boolean	Usability by others
Usable after project	boolean	Adaptability
Well documented	boolean	Product details
Robust	N	Withstanding the abuse of operation
Portable	kg	Weight
Good contact to bridge	m ²	Surface area contact between device and bridge
Leave bridge undamaged	boolean	Minimally invasive
Power efficient	%	Power out / power in
Cost-effective	\$	Economically feasible

C.3. Needs Metrics Matrix

The needs metrics matrix is presented in Table C2 as a method of determining relationship strengths between customer requirements (CRs) and engineering characteristics (ECs), as well as determining which engineering characteristics are most significant.

Table C2. Needs metrics matrix.

Customer Requirements	Importance Weight Factor	System functionality	System output range	Measurement precision	Test run time	DAQ	User interface	Usability by others	Adaptability	Product details	Withstanding operation	Weight	Contact area	Minimally invasive	Power out / power in	Economically feasible
Test vibration data	2	9	3	3	3	9		1			1			1		
Operate at different frequencies	3	9	9				3	1			1					
Resolution of at least 1 Hz	2	3	1	9			1	1								
Time control	1				9	3	3			3						
Record data	4	3	3	3	3	9									1	
Screen to monitor parameters	2						9	3	1	3					3	
Clear and safe operation instructions	5					1		9	9	9					1	
Usable after project	3				1	1	3	9	9	3	3	1			1	
Well documented	4				1	1	1	3	9	9						
Robust	4						1		3		9					
Portable	4								3	3		9		3		
Good contact to bridge	3					1					1		9	1		
Leave bridge undamaged	4	1									1		1	9		
Power efficient	1						1						1		9	3
Cost-effective	2													1	1	9
Raw Score (1028)		67	47	36	34	73	50	109	134	99	57	39	32	55	29	21
Relative Weight (%)		7.60	5.33	4.08	3.85	8.28	5.67	12.36	15.19	11.22	6.46	4.42	3.63	6.24	3.29	2.38
Ranking		5	9	11	12	4	8	2	1	3	6	10	13	7	14	15
Legend																
1: Slight Correlation																
3: Moderate Correlation																
9: Strong Correlation																

After the list of needs was refined and each need translated into a CR, an importance weight factor was assigned to each CR. This weight factor ranged from 1-5 with 5 being the most important, and needs were ranked relative to one another. This was done as a group to consider all factors collectively. Next, the corresponding ECs and metrics were listed along the top of the matrix and the improvement direction of each EC was determined, which contextualized each need relative to the entire project. After this, the ECs were divided among the team members and the correlation of each EC with the different CRs was ranked with a 0, 1, 3, or 9 for no, low, medium, or high correlation. The ranking was divided up here to consider each EC independently from the other ECs and reduce group member influence on the scores, as the strength coefficients were scored more objectively than the importance weight factors. The EC strength coefficients were limited to 0, 1, 3, or 9 to reduce the subjectivity of the scoring method by eliminating “in-between”

scores. Once all strength coefficients had been assigned, the raw value and relative weight of each EC was calculated and ranked to determine the most significant ECs. It was found that the most significant ECs, which were ranked 1-3 and represent the 80th percentile, were the system's environmental adaptability, its usability by others, and the documentation of product specs. The priority CRs were found to be the ability to test vibration data and the usability of the system by future students.

C.4. Target and Fallback Specifications

Determining target and fallback specifications is vital to the success of the product. Finding values or parameters that suit the sponsor's needs is time-intensive and important so that the satisfaction of the sponsor is met. All metrics, units, target, and fallback specifications can be found in Table C3.

Table C3. Target and fallback specifications.

Metric	Units	Target	Fall Back
Vibration data accuracy	mean % error	2%	6%
System output range	Hz	0-20 Hz	0-15 Hz
Measurement precision	Hz	1 Hz	2 Hz
DAQ	boolean	Yes	Yes
User interface	boolean	Yes	Yes
Usability by others	boolean	Yes	Yes
Adaptability	boolean	Yes	Yes
Product details	boolean	Yes	Yes
Robustness	# failed brackets	0	0
Weight	kg	73 kg	80 kg
Displacement	cm	2 cm	5 cm
Minimally invasive	boolean	Yes	Yes
Economically feasible	\$	< \$1000	< \$2000

For the shaker, multiple sources were found that had identical or similar experimental ideas and setups. From these, several target and fallback specifications were determined. Some specifications came from the direct wants of the sponsor and others came from researchers in the

field. Lastly, a few came from theoretical ideas that are ingrained in the basis of engineering. Specific reasons for why the target and fallback specifications were chosen can be found next to the source in the **References** section.

C.5. Conclusions

This project focuses on the creation of a bridge shaker with the ability to excite bridges to the target frequencies specified in table C3. The primary requirement of this project is the adaptability of the shaker for other engineering projects. Therefore, the shaker must be well-documented and intuitive to use by others. One of the main challenging specifications for this project is to ensure the vibrations and forces generated by the shaker do not damage its own components. One critical specification worth noting is to ensure the shaker produces adequate force to induce an output range with a maximum of 20 Hz.

D. Functional Concepts

D.1. Introduction

The next step in the design process was functional decomposition, an analysis method that broke down the needs and specifications into components grouped together by broader functions. From functional decomposition, design concepts were generated to satisfy each functional group. A variety of ideas were put together in a group setting on what the functions of a finished product would be. Then, ideas on how to complete each function were brainstormed. Finally, five concepts were created for a finished product using concept ideas that would correctly complete each function.

D.2. Functional Decomposition

Functional decomposition involves using the customer needs as a basis for determining the required functions of the product. These functions are not solutions, but rather abstract project requirements to fill with solutions later. Functions of the product were brainstormed based on the critical needs and engineering concepts previously discussed. Identified functions for the bridge shaker project in approximate order are listed below:

- a. Attach to structure
- b. Receive energy
- c. Regulate power
- d. Receive input on the desired frequency and time limit to vibrate at
- e. Determine set frequency
- f. Show parameters on screen
- g. Receive input to start vibration procedure
- h. Convert electrical energy to mechanical energy
- i. Increase or reduce frequency
- j. Transfer energy to the bridge
- k. Vibrate the bridge
- l. Receive input to stop vibration of the bridge
- m. Detach from structure

Once functions were identified, they were condensed and broken up into three categories: energy, material, and information. A functional decomposition diagram is shown in Figure D1 and was used to organize the functions and visualize interactions. The arrows identified preceding and subsequent functions depending on the head direction, and the order of functions increased from left to right. For example, receive energy preceded regulate power as indicated by the arrowhead and its position to the left of the other function blocks. As described by the functional decomposition diagram, the product must first attach to the bridge and receive electrical energy before regulating that energy and converting it into mechanical energy. That energy is used to manipulate the frequency depending on set parameters acquired from a user. The user input is measured and displayed after an initiation signal is received, and energy is transferred to the bridge to induce vibration.

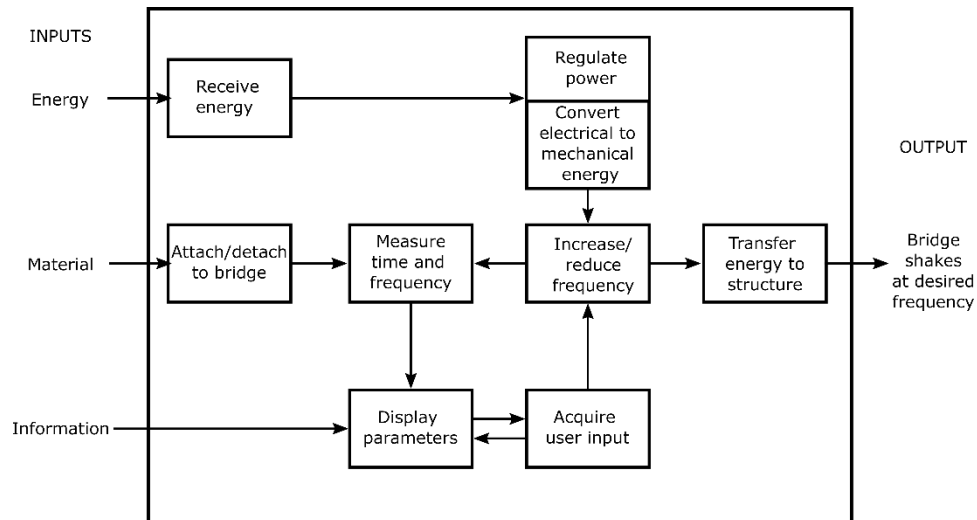


Figure D1. Functional decomposition diagram.

D.3. Concept Combinations

The Concept Combination Table (CCT) shown in Table D1 served to organize the practical solutions to the functional requirements of the project.

Table D1. Concept Combination Table, CCT.

Recieve Energy	Regulate Power	Convert Electrical Energy to Mechanical Energy	User Input	Reduce/Increase Frequency	Attach/Release from Bridge	Transfer Energy to Bridge
Battery	PMIC	Motor w/ Offset Weight	Buttons	Arduino (microprocessor)	Secured by Bolts	Through the Bolts
Wall Outlet	Microcontroller	Hydraulic Pistons	Remote Control	Motor Driver	Epoxy Adhesive	Sandbagged
Generator	MOSFET	Gravity with Weight	Keypad Entry		Tie down with Ratchet Straps	Counter Weights
		Electromagnetic Solenoids	Touchscreen		Welded to Structure	Shaker Weight
		Motor w/ Linear Weight	Hard Code		Velcro	
			Voice Control		Clamps to sides of Bridge	

With the subproblems and solutions listed out, it was easier to combine functional solutions to generate a total solution for the project. The CCT allowed for ease of development in creating five design concepts for the bridge shaker project.

For most of the functions, several solutions were generated for the functional requirements that were broader in scope. However, for some functions, only limited solutions remained such as “Reduce/Increase Frequency”, “Receive Power”, and “Regulate Power”. For “Reduce/Increase Frequency”, an Arduino or Motor Driver was the best option, as other solutions were either overly complex or expensive. The “Receive Power” function in the CCT had so few solutions because there were not many ways to solve this apart from the most convenient options such as wall outlets, generators, and batteries. A similar thought process guided the creation of the “Regulate Power” function of which the Power Management Integrated Circuit (PMIC), microcontroller, or Metal Oxide Semiconductor Field Effect Transistor (MOSFET) seemed to be the most viable options. The other functions with more solutions had some with greatly desired methods and some that are not. For instance, attaching the bridge shaker via epoxy was greatly undesired due to the difficulties inherent in working with epoxies such as the mess and effort in application. Other solutions seemed to be no-brainers in their use, but there were some solutions where choosing the best option is not

as simple. For instance, the method to convert electrical energy to mechanical energy had several options. The motor with an offset or linear weight and solenoids were both great methods, but the choice influenced the remaining solutions of other functions like “Receiving Power”.

D.4. Concept Generation

Five concepts were generated using the Concept Combination Table. A basic schematic and description of each concept was developed by the group. The following concepts were developed:

Concept 1 (Table D2): A motor is powered by a wall outlet with power regulated by a microcontroller. The motor rotates an asymmetric offset weight to induce vibration by converting electrical energy into mechanical energy. User input on frequency and test time is gathered through buttons read by a microcontroller, which increases or decreases the frequency by altering the power. Energy is transferred to the bridge with a shaker weight. The shaker is attached and released from the bridge using clamps to the sides of the bridge. A sketch of the concept is shown in figure D2.

Table D2. Concept Generation; Concept 1.

Recieve Energy	Regulate Power	Convert Electrical Energy to Mechanical Energy	User Input	Reduce/Increase Frequency	Attach/Release from Bridge	Transfer Energy to Bridge
Battery	PMIC	Motor w/ Offset Weight	Buttons	Arduino (microprocessor)	Secured by Bolts	Through the Bolts
Wall Outlet	Microcontroller	Hydraulic Pistons	Remote Control	Motor Driver	Epoxy Adhesive	Sandbagged
Generator	MOSFET	Gravity with Weight	Keypad Entry		Tie down with Ratchet Straps	Counter Weights
		Electromagnetic Solenoids	Touchscreen		Welded to Structure	Shaker Weight
		Motor w/ Linear Weight	Hard Code		Velcro	
			Voice Control		Clamps to sides of Bridge	

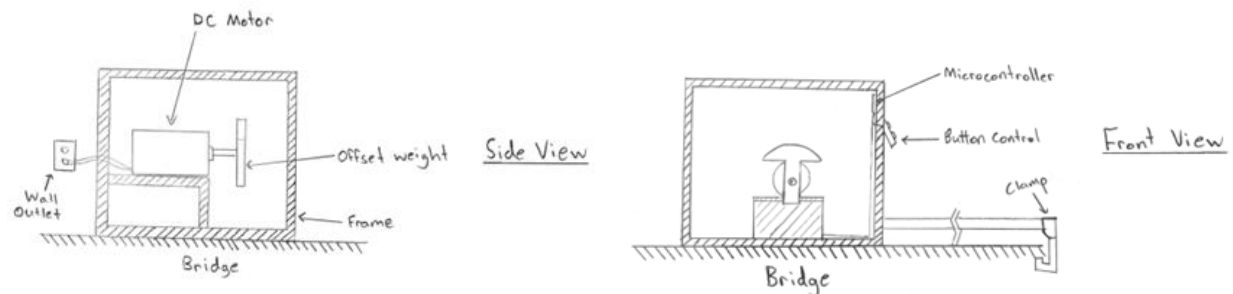


Figure D2: Concept sketch 1.

Concept 2 (table D3): The power from the battery is put through a PMIC and goes to an Arduino. The Arduino takes keypad entries from the user to control the speed of the solenoids which impact the platform and induce vibrations in the bridge. The apparatus is connected to the bridge with bolts, and energy is transferred to the bridge through this connection. A sketch of concept 2 is shown in figure D3.

Table D3. Concept Generation; Concept 2.

Recieve Energy	Regulate Power	Convert Electrical Energy to Mechanical Energy	User Input	Reduce/Increase Frequency	Attach/Release from Bridge	Transfer Energy to Bridge
Battery	PMIC	Motor w/ Offset Weight	Buttons	Arduino (microprocessor)	Secured by Bolts	Through the Bolts
Wall Outlet	Microcontroller	Hydraulic Pistons	Remote Control	Motor Driver	Epoxy Adhesive	Sandbagged
Generator	MOSFET	Gravity with Weight	Keypad Entry		Tie down with Ratchet Straps	Counter Weights
		Electromagnetic Solenoids	Touchscreen		Welded to Structure	Shaker Weight
		Motor w/ Linear Weight	Hard Code		Velcro	
			Voice Control		Clamps to sides of Bridge	

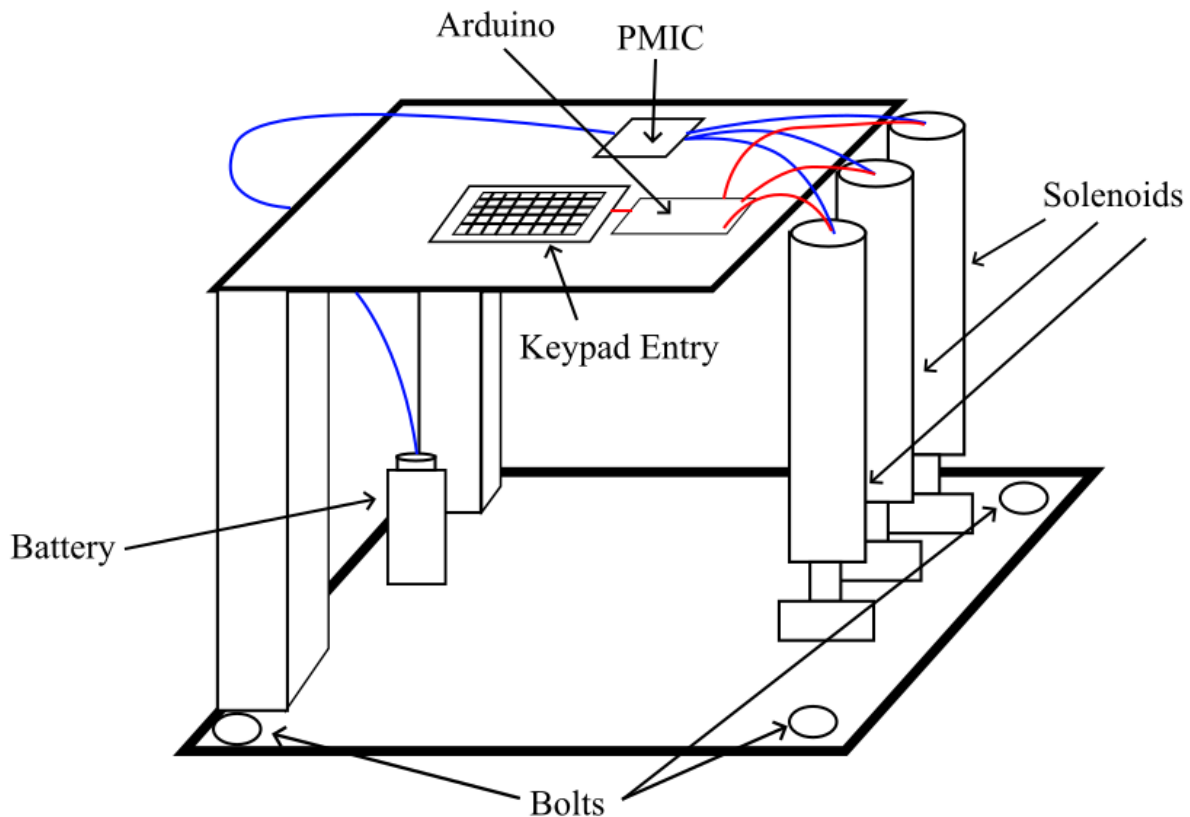


Figure D3. Concept sketch 2

Concept 3 (table D4): A motor is powered by a separate generator. The voltage from the generator is regulated via a MOSFET. The DC Motor turns a pulley that draws the weight upward towards the top of the frame. Then, by control of the microprocessor, when given an input from the remote control, the device will drop the weight and pick it back up repeatedly until instructed to stop. The entire apparatus will be held down by ratchet straps connected to the bridge and the mode of energy transportation will be via the counterweight. A sketch of concept 3 is shown in figure D4.

Table D4: Concept Generation; Concept 3.

Recieve Energy	Regulate Power	Convert Electrical Energy to Mechanical Energy	User Input	Reduce/Increase Frequency	Attach/Release from Bridge	Transfer Energy to Bridge
Battery	PMIC	Motor w/ Offset Weight	Buttons	Arduino (microprocessor)	Secured by Bolts	Through the Bolts
Wall Outlet	Microcontroller	Hydraulic Pistons	Remote Control	Motor Driver	Epoxy Adhesive	Sandbagged
Generator	MOSFET	Gravity with Weight	Keypad Entry		Tie down with Ratchet Straps	Counter Weights
		Electromagnetic Solenoids	Touchscreen		Welded to Structure	Shaker Weight
		Motor w/ Linear Weight	Hard Code		Velcro	
			Voice Control		Clamps to sides of Bridge	

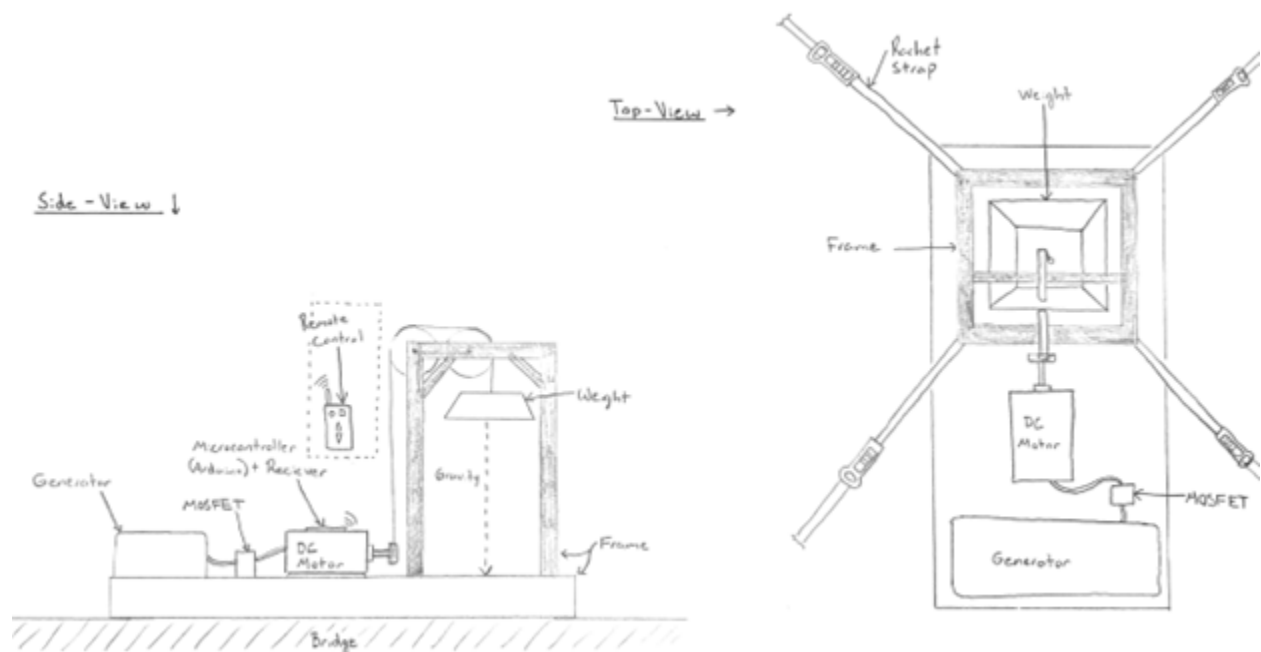


Figure D4: Concept sketch 3.

Concept 4 (table D5): A wall outlet supplies power which is regulated by a microcontroller to an air compressor. This compressor powers a hydraulic actuator with a large surface area on the end to strike the bridge to induce vibration. The user inputs frequency and testing time via a touchscreen, which is read by an Arduino to increase or decrease the frequency by controlling the air compressor. The system is secured by ratchet straps, and energy is transferred to the bridge from the weight of the system. A sketch of concept 4 is shown in figure D5.

Table D5: Concept Generation; Concept 4.

Recieve Energy	Regulate Power	Convert Electrical Energy to Mechanical Energy	User Input	Reduce/Increase Frequency	Attach/Release from Bridge	Transfer Energy to Bridge
Battery	PMIC	Motor w/ Offset Weight	Buttons	Arduino (microprocessor)	Secured by Bolts	Through the Bolts
Wall Outlet	Microcontroller	Hydraulic Pistons	Remote Control	Motor Driver	Epoxy Adhesive	Sandbagged
Generator	MOSFET	Gravity with Weight	Keypad Entry		Tie down with Ratchet Straps	Counter Weights
		Electromagnetic Solenoids	Touchscreen		Welded to Structure	Shaker Weight
		Motor w/ Linear Weight	Hard Code		Velcro	
			Voice Control		Clamps to sides of Bridge	

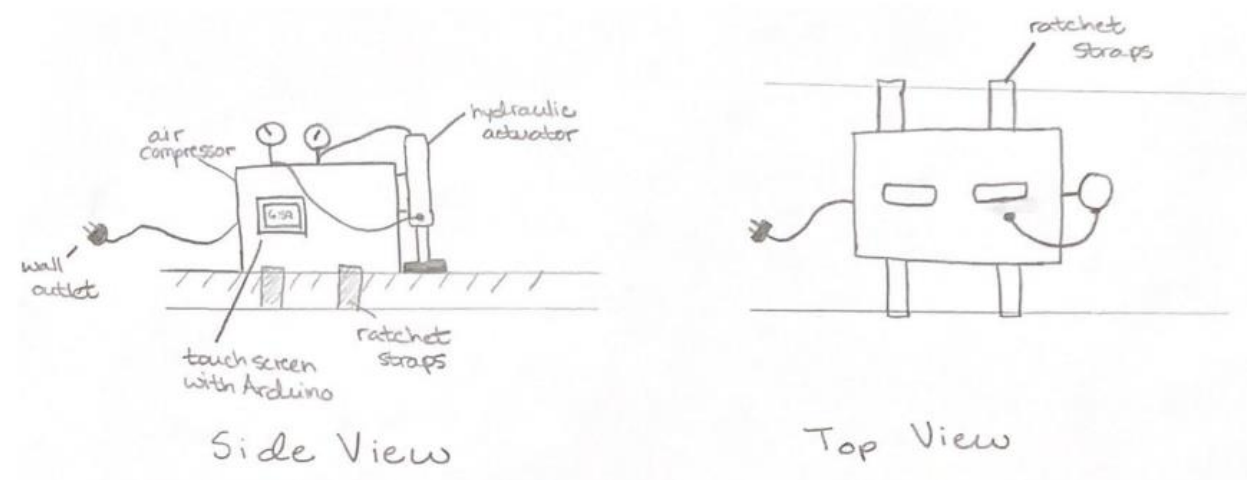


Figure D5: Concept sketch 4.

Concept 5 (table D6): A generator is regulated by a MOSFET and powers a motor with a linear weight. The motor is controlled by an Arduino which takes input from a keypad. The device is encased to protect the parts and the whole device is tied down with ratchet straps. The energy is being transferred to the bridge through the linear weight being driven up and down by the motor and links. A sketch of concept 5 is shown in figure D6.

Table D6: Concept Generation; Concept 5.

Recieve Energy	Regulate Power	Convert Electrical Energy to Mechanical Energy	User Input	Reduce/Increase Frequency	Attach/Release from Bridge	Transfer Energy to Bridge
Battery	PMIC	Motor w/ Offset Weight	Buttons	Arduino (microprocessor)	Secured by Bolts	Through the Bolts
Wall Outlet	Microcontroller	Hydraulic Pistons	Remote Control	Motor Driver	Epoxy Adhesive	Sandbagged
Generator	MOSFET	Gravity with Weight	Keypad Entry		Tie down with Ratchet Straps	Counter Weights
		Electromagnetic Solenoids	Touchscreen		Welded to Structure	Shaker Weight
		Motor w/ Linear Weight	Hard Code		Velcro	
			Voice Control		Clamps to sides of Bridge	

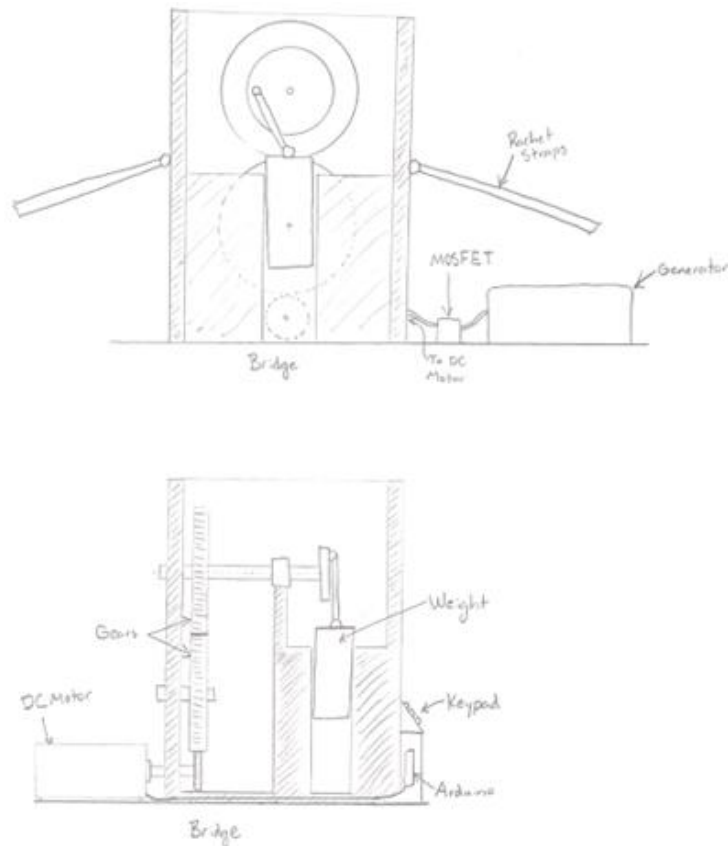


Figure D6: Concept sketch 5.

D.5. Literature Review

The keywords “mass shaker,” “structures,” and “test” were entered into the Google Patent search engine revealed some relevant patents that were useful in illuminating methods of inducing vibrations. Patent EP2589947B1 [2] presented a high-frequency vibration system that used the piezoelectric effect to induce vibration through a disk-shaped contact structure that the object sat upon. Patent SU325770A1 [3] was found that depicted a pneumatic vibrating device. This device used compressed air alternately pushed into opposite sides of the cylinder, creating a vibration. This patent resembled the hydraulic piston concept generated in the above section. Patent EP0566809A1 [4] showed a fruit harvester that clamped onto a tree trunk and used linear impact vibrations to shake fruit off the branches. Its primary method of vibration inducement was motors with offset weights that were connected to an excitation rod attached to the tree trunk by a clamp, and the vibrations transmitted through the rod and the impacts acting on the tree caused the fruit to fall.

D.6. Conclusion

Prior to concept generation, the functions of the device were laid out sequentially to give the team an idea of the technologies needed for each step. Next, the concept combination table was created to brainstorm ideas that could fulfill each function. Lastly, from this table concepts were generated that satisfy all stakeholders. In doing so, some technologies were found to be unrealistic, or would not necessarily suit the needs of the sponsor. An example of this was the use of hydraulic pistons to convert electrical energy into mechanical energy. Discussion led to the conclusion that the pistons would not be able to alternate fast enough to produce the vibrations desired and that the fluid inside of the pistons would dampen the vibrations. On the other hand, it was determined that the DC motor, in combination with either linear weight oscillation or offset weight, was the

likely conceptual design for any scenario. This kept the design comparatively simple and easily controllable by the user. In another interview with stakeholder Joud Satme, he expressed concerns about the functionality of single-frequency excitement. This conversation led to the development of concept 5. Each concept generated was used in the concept selection process detailed in section E.

E. Concept Selection

E.1. Introduction

The purpose of concept selection was to evaluate each previously generated concept and determine which was the most viable to advance in the design process. The significance of concept selection was that it utilized empirical measurements to select the best concept for the customer without interference from designer biases. This report presents a matrix-based down-selection of each concept using previously identified selection criteria. First introduced is the concept screening process, which assessed positive or negative concept criteria performance relative to a baseline concept. Once concept screening was completed, concept ranking assigned quantitative values to the positive/negative performance of the top concepts from the concept screening. Finally, the chosen concept was presented as the design the team decided to advance to fabrication. All referenced concepts are detailed in section D and are referenced by their numbers throughout the report.

E.2. Concept Screening

The concept selection matrix's main function was to narrow down the options by eliminating concepts that scored too low in addressing customer requirements. The selection criteria were based on the customer requirements formulated in the functional decomposition and concept generation processes in section E. Each concept was rated relative to the reference, concept 1, to decide which concepts would be desirable to move forward with. The reference concept was decided unanimously as the best "middle path" due to its simplistic design and intuitive nature, but other concepts could outperform it due to issues inherent with a spinning weight on a moment arm. In the matrix, a "+" indicated that the given concept would outperform the reference in the customer requirement, while a "-" indicated it would underperform in relation to the reference. A

“0” meant that it would perform the same as the reference concept. It should be noted that when the table was first created, more selection criteria existed (as shown in the Needs Metrics Matrix in section C) but were removed due to similar performance across concepts. This would have given a result of “0” along the entire column, and therefore would not have had any factor in changing the comparative scores. The results of each concept performance are shown in Table E1.

Table E1. Selection Matrix

Selection Criteria	Concepts				
	REF (1)	2	3	4	5
Test vibration data	0	+	-	+	+
Operate at different frequencies	0	+	-	+	+
Resolution of at least 1 Hz	0	+	-	+	+
Clear and safe operation instructions	0	+	0	+	+
Usable after project	0	+	-	+	-
Robust	0	+	-	-	+
Portable	0	-	-	-	0
Good contact to bridge	0	-	+	+	+
Leave bridge undamaged	0	-	-	-	0
Power efficient	0	0	+	-	0
Cost-effective	0	-	-	-	-
Sum (+)'s	0	6	2	6	6
Sum (-)'s	0	4	8	5	2
Net Score	0	2	-6	1	4
Rank	4	2	5	3	1
Continue?	No	Yes	No	Yes	Yes

The final score for each concept was calculated by subtracting the sum of “-”s from the sum of “+”s. The concepts were then ranked based on these scores and the top three scoring concepts moved on to the second round of concept ranking. The ratings were given based on analysis and a vote of each group member comparing each concept with the reference. The top three concepts based on Table E1 were concepts 2, 4, and 5. Concept 2 was the design with solenoids inducing vibration, concept 4 was the hydraulic actuator-based design, and concept 5 was the linearly oscillating weight that was moved up and down with a crank. Concepts 1 and 3 did not have a high

enough score to move on to the second round. Concept 1 underperformed in multiple areas, including contact to bridge, and operating at different frequencies. Concept 3 underperformed in the categories of clear and safe operation instructions and resolution of at least 1 Hz.

E.3. Concept Ranking

The top three out of five concepts proposed were used to create a concept ranking matrix to condense the list of candidates for a final concept. The concept ranking matrix further derived which design was the best to move forward with. Each concept was given a rating between 1 and 5 based on how well it met each selection criterion of the project. A rating of 5 indicated a significant improvement from the reference design while a 1 indicated a severe deficit. The importance weight factor was determined in the product specifications section with the Needs Metrics Matrix. The importance weight factors were normalized across the selection criteria and multiplied with the rankings, resulting in a weighted score for each criterion. All the weighted scores for a concept were added together for a total score. The highest total score was the concept deemed the best to move on with for the project.

Table E2 shows the concept ranking matrix and concludes that concept 5, a linear weight with a DC motor, was the best option due to its vast improvement on the reference. It was decided that the linear weight with a DC motor better tested vibration and was easier and safer to use than the other concepts. The highest importance weight factors corresponded to the clear and safe operation instructions, robust, portable, and leave bridge undamaged selection criteria. Concept 5 ranked higher relative to the other concepts in three out of four of these categories, which explained its higher total score and designation as the best concept.

Table E2: Concept Ranking with Importance Weight Factors.

Selection Criteria	Importance Weight Factor	Concepts					
		2		4		5	
		Electromagnetic Solenoid		Hydraulic Cylinder		Linear Weight w/ DC Motor	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Test vibration data	0.061	4	0.242	4	0.242	5	0.303
Operate at different frequencies	0.091	4	0.364	4	0.364	4	0.364
Resolution of at least 1 Hz	0.061	4	0.242	4	0.242	4	0.242
Clear and safe operation instructions	0.152	4	0.606	4	0.606	5	0.758
Usable after project	0.091	3	0.273	5	0.455	2	0.182
Robust	0.121	4	0.485	2	0.242	4	0.485
Portable	0.121	2	0.242	2	0.242	3	0.364
Good contact to bridge	0.091	2	0.182	4	0.364	4	0.364
Leave bridge undamaged	0.121	2	0.242	2	0.242	3	0.364
Power efficient	0.030	3	0.091	2	0.061	3	0.091
Cost-effective	0.061	2	0.121	2	0.121	2	0.121
Total Score		3.091		3.182		3.636	
Rank		3		2		1	
Continue?		No		No		Yes	

E.4. Final Concept

The concept selection tables designated the highest-scoring concept as the best design. Concept 5, the linear weight powered by a DC motor shown in Figure E1, scored highest in both tables because of its ability to test vibration data at a wide range of values, as well as the ability to transfer energy more efficiently to the bridge.

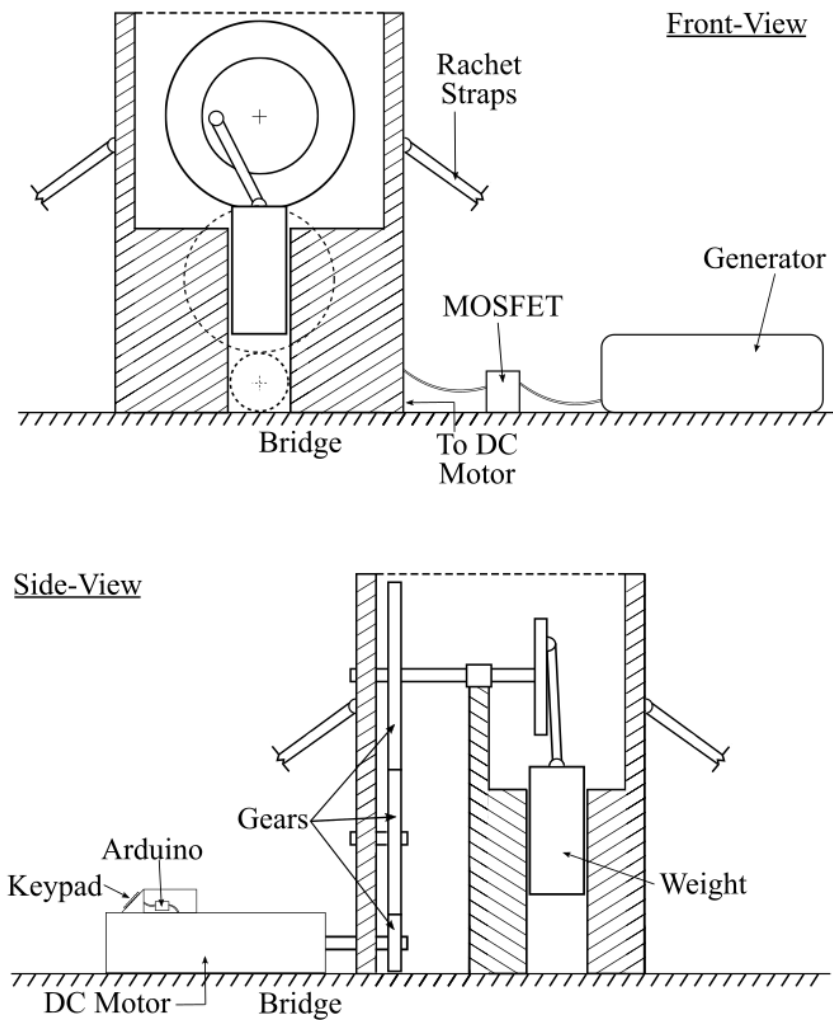


Figure E1: Excitation via DC Motor and powertrain for linear actuation.

The generator provides enough power to the system while still maintaining an ease of portability. The MOSFET controlled the flow of power from the generator to the DC motor and Arduino. Desired values for frequency and time were be input via the keypad, and the Arduino controlled the speed to match the desired frequency. It is important to note that in the final design, detailed in section L, this power control system is greatly simplified through the use of a variable frequency drive, which allows user input via a knob and screen to set frequency and control the output speed. This adaptation eliminates the need for an Arduino, keypad, and MOSFET. The energy of the DC motor is translated through the gears and into the weight to create linear motion, which is transferred downwards via the shaker's weight into the bridge, inducing vibration. Concept 5 does this efficiently by using gears to convert rotational motion to linear motion to move a weight up and down to localize and create a one-dimensional force. This force is better suited for testing vibration data because there is minimal wasted energy. This design is more complicated than some of the other concepts, but when evaluating the criteria for a productive shaker, concept 5 prevailed. The power train added elements of difficulty in the design process, specifically trying to find an efficient gear ratio to excite all frequencies needed while not stalling the motor. To address this challenge, the team sourced outside expert advice on gear train design.

F. Product Architecture

F.1. Introduction

The product architecture encompassed product layout creation, schematic element clustering, simple geometric layout creation, and interactions identification, especially any unintended consequences. The product architecture was considered to note possible flaws or issues which may arise down the line, as well as find an ergonomic placement of components and systems, specifically the gear train. In this project, the ergonomics of the project are put above the aesthetics, as its only use is for research purposes. Compactness and portability are two important qualities this project must have, therefore the placement of components and moving parts were prioritized.

F.2. Product Layout

The product layout is shown in figure F1 and contains all the functions of the original functional decomposition, however it has translated the action statements into functional components. As such, additional components have been added to elaborate on how the function will be carried out, such as the extra boxes in the vibration mechanism cluster.

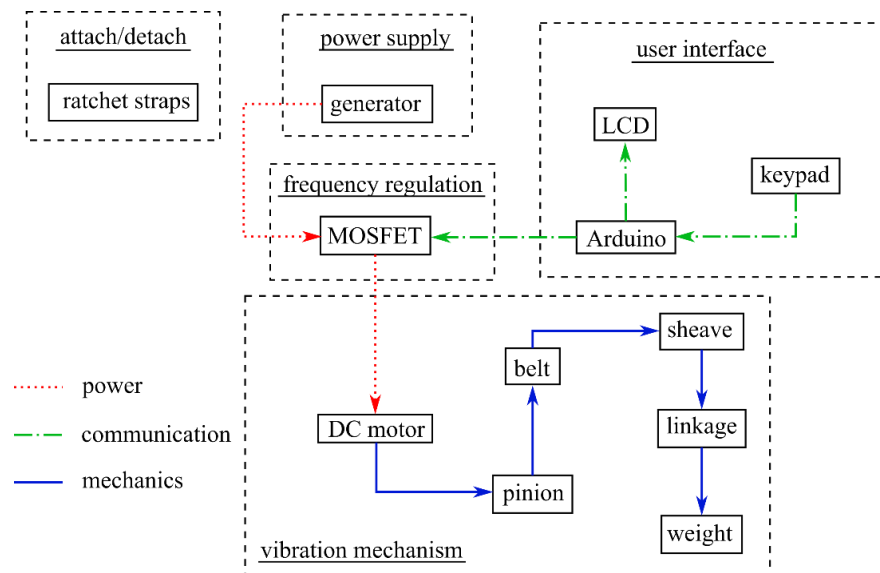


Figure F1. Product layout with functional clusters.

The functional components were divided into five clusters. The first cluster was the attach/detach cluster that only contained the ratchet straps, which were later replaced with sandbags in the final design, used to secure the shaker to the bridge. The second cluster was the power supply, which consisted of the generator to supply electrical energy to the system. The third cluster was the frequency regulation, which housed the MOSFET for power regulation, which in turn regulated the frequency. The frequency regulation cluster was tied to the user interface cluster, which involved all interactions between user input and system output. It consisted of the keypad entry into the Arduino microcontroller, which was displayed on the LCD screen. The Arduino was tied to the MOSFET to translate a physical output from the frequency user input. As previously discussed in section E.4., the final design implemented a variable frequency drive that eliminated the LCD, keypad, Arduino, and MOSFET. As such, the user interface and frequency regulation functional clusters are now consolidated and only contain the VFD. The output of the VFD was connected to the vibration mechanism cluster, which contained all components involved in mechanical energy generation and transfer. The VFD controlled the DC motor, which converted electrical to mechanical energy. This mechanical energy was transferred through a belted pinion to a sheave containing a linkage to a weight, which oscillated vertically to induce vibration. The belt replaced the gear chain in the original concept design in order to reduce stress induced back on the system from the weight, as suggested by Dr. Downey after the conceptual design review [5], but this was later changed back to a gear chain.

The clusters were chosen based on functional component and connection type. The power supply and frequency regulation clusters were distinct enough from one another that the team did not want to make them a modular component, however they both involved power signals, as indicated by the dotted red line. The user interface cluster is dominated by digital communications,

and the seamless interfacing between keypad, LCD, and Arduino made it easy to modularize. Particularly as the delicate electronics were mounted on the shaker, the team wanted to keep them separate and protected. The vibration mechanism cluster was created out of necessity, as all functional parts depended on one another to create the desired output. These parts are all related through mechanics, as indicated by the blue solid lines. The attach/detach cluster was the only isolated cluster, as it did not produce an output for another cluster but was still noteworthy.

F.3. Interactions

For the fundamental interactions, the elements of the project were grouped together based on their relation to each other. In the second cluster, the power supply was included as a generator to provide electricity for the bridge shaker. The generator sent power to a MOSFET in the third cluster for frequency regulation. Then, in the fourth cluster, user interface, the Arduino sent a signal based on user input to the MOSFET as well. The signal sent to the MOSFET then went as power to the DC motor in the fifth cluster. These elements led into each other and were connected accordingly. The final design retains the same interactions as originally designed here, with the third and fourth clusters consolidated and consisting of the variable frequency drive.

As far as unintended consequences are concerned, there were a few that should be mentioned. First, the vibrations from the shaker were transferred to the electronics and the shaker frame. To minimize this effect, each element was secured to the frame to minimize any extra shaking of components. There was electrical noise affecting the MOSFET control signal due to the shaking of electronics. This was dealt with by adding a capacitor to smooth the voltage going to the MOSFET. Heat was generated from the electronics as well, which was lowered by allowing airflow to reach the components that may be affected. The shaker also presented a possible safety

hazard to any user as it had many moving parts and a moving weight. To fix this problem, steps were taken to make the shaker more user friendly like covering dangerous moving parts.

F.4. Geometric Layout

Laying out a geometric diagram was crucial in identifying where certain components resided inside the finished product. The geometric diagram helped the sponsor get an idea of the overall size and its relation to the component size. This also helped the team to understand what to research when finding the components to source based on power needs and size limitations. Since the specified need of portability was identified, the layout for the shaker was designed to be small enough and light enough to be portable by two people while still maintaining enough power to generate the needed vibrations.

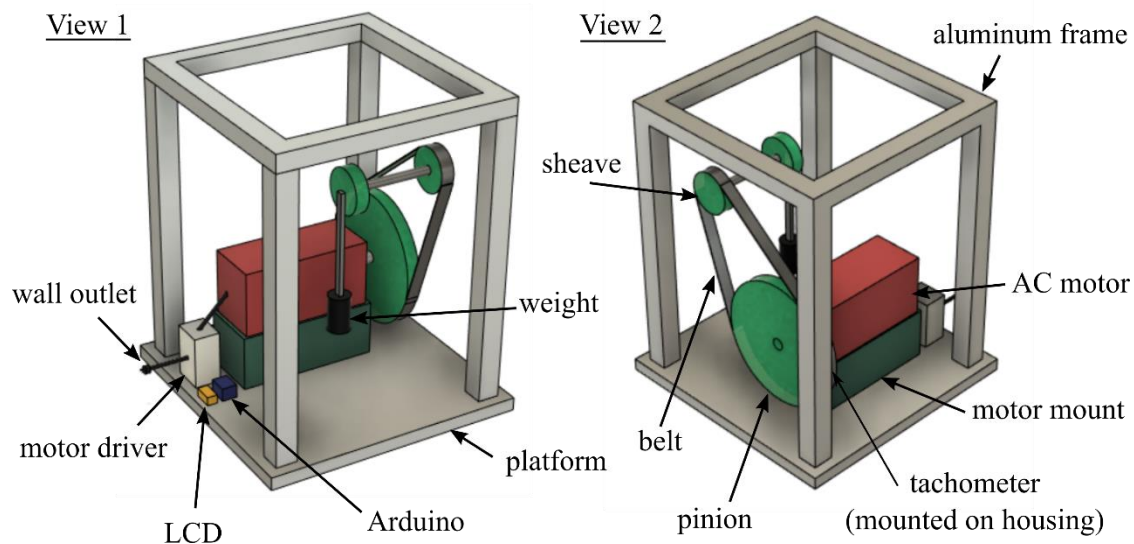


Figure F2: Geometric layout with color coding system.

Figure F2 shows the approximate 3D layout of the shaker. This diagram represented all the information from the product layout with functional clusters. The wall outlet and motor driver components made up the power supply and frequency regulation clusters, respectively. The Arduino and LCD screen were pictured together as they were part of the user interface cluster. The

motor driver, Arduino, and LCD were consolidated into the variable frequency drive later on. Originally the AC motor was outside of the frame, but in conversations with Joud Satme [6] it was determined that the motor could be placed inside of the frame. Also located inside of the frame were the pinion, sheave, chain, and weight. These six components made up the vibration mechanism cluster. Lastly, not pictured in the above diagram, is the attach/detach cluster which consisted of sandbags. This cluster was the main supporting device when connecting the shaker to the bridge. The idea behind creating these clusters was to separate the components into their individual tasks and add a functional advantage of making these parts modular.

G. Engineering Analysis

G.1. Introduction

This report contains details of engineering analyses performed to determine theoretical limitations of the bridge shaker at areas of concern. The team brainstormed ways that the bridge shaker could either underperform or fail to identify these areas of concern. Emphasis was placed on failure modes on the consumer end, rather than failure modes during manufacturing. The main concerns were as follow:

- A. The product could disassemble itself at the connection joints under the strain of vibratory loads, with either loosening the connection bolts or completely breaking the bracket.
- B. Friction in the shafts could lead to underperforming.
- C. Friction on the guiderails could lead to underperforming.
- D. The guiderail system might not be strong enough to withstand the forces of the weight at max speed, causing it to break and could cause catastrophic damage to the structure. Material selection is important.
- E. The VFD could underperform and output less voltage than is needed for the motor.
- F. A fuse might trip and cut power to the system.
- G. The motor could overheat.
- H. The motor might not produce enough speed to provide adequate force to the bridge.

Once the main concerns were identified, FMEA was used to determine how deeply each failure mode needed to be addressed. FMEA was chosen due to the complexity and diversity of subsystems, as well as its emphasis on safety issues. The results of the FMEA are shown in the table below, Table G1.

Table G1. Failure Modes and Effects Analysis

Failure Mode	Severity	Occurrence	Detection	RPN
A	10	8	2	160
B	4	6	3	72
C	4	6	3	72
D	10	7	1	70
E	7	4	1	28
F	6	2	3	36
G	7	9	3	189
H	7	7	2	98

The FMEA shows that the greatest concerns were that the product could disassemble itself at the connection joints under the strain of vibratory loads, with either loosening the connection bolts or completely breaking the bracket; the motor could overheat; and the motor might not produce enough speed to provide adequate force to the bridge. The corrective actions for each of these designs were determined by conducting engineering simulations. For failure mode A (referred to as failure mode #1), a stress analysis of the 3D printed joints was run to determine deflection caused by the force of vibration. For failure mode H (referred to as failure mode #2), a Simulink model of the motor drive train subsystem was created to test output force, speed, and effect of gear ratio. For failure mode G (referred to as failure mode #3), thermal ports were added to the existing Simulink model to test motor temperature.

G.2. Analyses performed

Failure mode #1: 3D printed joint failure.

The first analysis performed was the simulated stress on the bracketing assemblies in Fusion 360. This analysis was needed to ensure the 3D printed brackets could withstand the stress of operation, specifically the shear and bending stress. 3D printed brackets were requested by Dr. Austin Downey because they are cheaper than ordering the alternative metal brackets, and he felt that they should be strong enough to hold the frame together. With this information, the team tested the brackets with Fusion 360's simulation tool. The test was done using a few equations from the textbook Machine Elements in Mechanical Design (not all equations used in the simulation will be listed as the team has no way to find every equation used, the general equations for this type of engineering problem are assumed) [7]. The variable definitions for equations 1-4 are in table G2.

$$\sigma = \frac{F}{A} \quad \text{Eq - 1}$$

$$\sigma = \frac{MI}{c} \quad \text{Eq - 2}$$

$$\varepsilon = \frac{\sigma}{E} \quad \text{Eq - 3}$$

$$\Delta L = \varepsilon L_0 \quad \text{Eq - 4}$$

Table G2. Definition of variables for failure mode 1.

Variable symbol	Variable name/description	Variable units
σ	Stress	MPa
ε	Strain	--
E	Young's Modulus	GPa
ΔL	Change in length	m
L_0	Initial length	m
F	Applied force	Pa
A	Area	m ²
M	Bending moment	N·m
I	Moment of inertia	kg·m ²
c	Distance from neutral axis	m

Knowing these equations and an initial set of parameters based on the orientation of the bracket within the total assembly, the team constrained and placed force accurately within the simulation. The locked constraints belonged to the tops and bottoms of the screw holes in the bracket. The force was comprised of two components: the axial force from the side-to-side movement of the frame and a bending force created by the shaft and weight being supported from the top. Since the software performed a comprehensive analysis of the piece and evaluated every section of the bracket, the team could not give every input condition. Figure G2 displays the constraints placed on the bracket, and the forces and their numerical values that were used in the simulation are listed in section G.3.

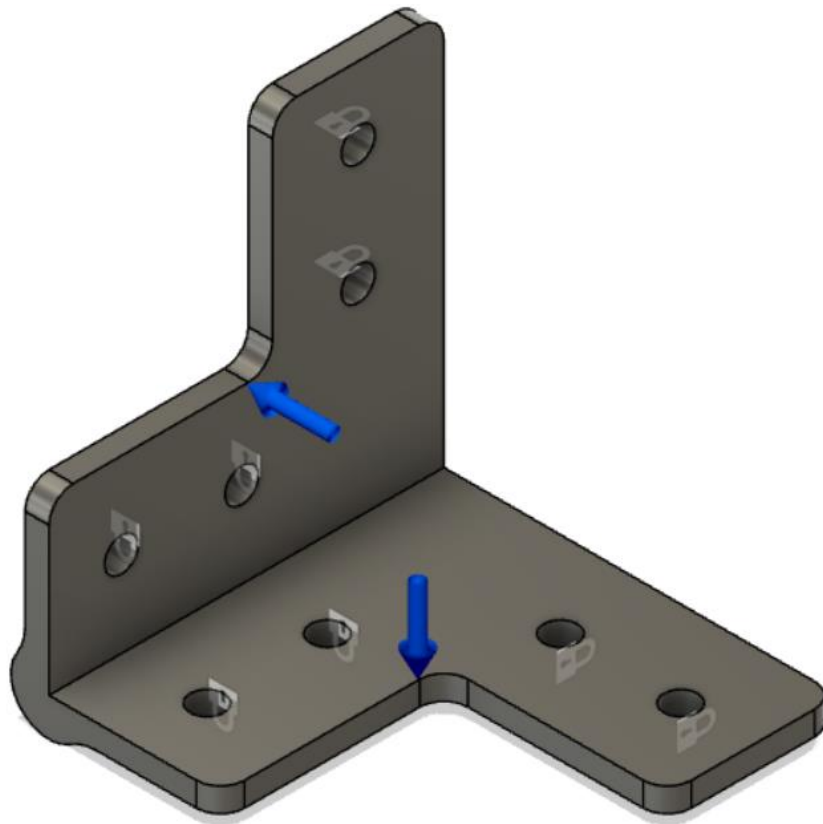


Figure G1. Constraints and loads on 3D printed bracket.

Each blue arrow in Figure G1 represented a force applied to the entirety of the inside faces of the bracket. This was to simulate the force applied from the vibrations induced by the motor. The force value was 3000 N, which was estimated from a Simulink model as a good testing range. The working force was expected to be around 500 N with the maximum output in a worst-case scenario at 6000 N. It was decided to throttle back the motor to keep it within a safe operating range. This provided an accurate estimation to the displacement of the material and the stresses it underwent. Lastly, the safety factor of the brackets was simulated. Since the brackets were the main failure points identified, they needed to be engineered to not only minimally support the forces of the device, but also to withstand greater forces than expected.

Failure Mode #2: Output Force

The next failure mode was simulated via Simulink in MATLAB, which modeled the resulting output force the weight could supply to the system given the motor specifications and gear ratios. The motor specifications were found on the manufacturer's site [8]. There were several assumptions and unknowns that were estimated for the model. For instance, exact inertias of the gears, shaft, etc. were assumed to be negligible due to the nature of the model, with the only source of inertia assumed to be from the slider-crank mechanism. The model also assumed an ideal voltage source and negligible friction effects on all moving parts. For other model inputs in the system, the slider stiffness and damping were also assumed to be negligible. The inertia of the slider-crank was estimated in the absence of angular acceleration at the instant of maximum torque. The system was observed as seen in Figure G2.

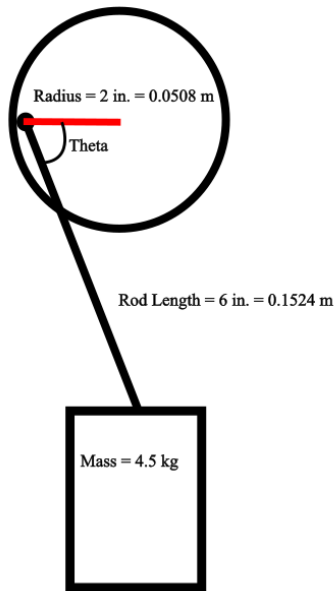


Figure G2: Free Body Diagram of weight effecting inertia on the system.

Under negligible angular acceleration, the general equations to solve for the inertia of the crank system, neglecting the disk's mass are shown below [9]. The variable definitions for equations 5-7 are given in table G3.

$$\tau = I\alpha; \alpha = 1 \quad \text{Eq - 5}$$

$$\tau = r \times F \quad \text{Eq - 6}$$

$$F = ma \quad \text{Eq - 7}$$

Table G3. Definition of Variables for Inertia Equations

Variable symbol	Variable name/description	Variable units
τ	Torque	N·m
I	Inertia	kg·m ²
α	Angular Acceleration	$\frac{rad}{sec}$
r	Disk Radius	m
m	Mass	kg
F	Force	N
a	Acceleration due to gravity	$9.81 \frac{m}{sec^2}$
θ	Angle in Figure 2	deg

Through this calculation, a rough estimate for the crank inertia, calculated to be 2.11 kg·m², was plugged into the Simulink model. The simulation was based on fundamental equations for gear and motor systems, shown below [10]. The variable definitions for equations 8-9 are given in table G4.

$$\frac{\omega_1}{\omega_2} = \frac{n_1}{n_2} = \frac{d_1}{d_2} = \frac{T_1}{T_2} = \frac{\tau_1}{\tau_2} \quad \text{Eq - 8}$$

$$a_t = \alpha \cdot r \quad \text{Eq - 9}$$

Variable symbol	Variable name/description	Variable units
ω	Angular velocity	$\frac{rad}{sec}$
n	Gear speed	RPM
d	Gear diameter	m
T	Number of gear teeth	-
τ	Torque	N·m
a _t	Tangential acceleration	$\frac{m}{sec^2}$
α	Angular acceleration	$\frac{rad}{sec^2}$
r	Radius of disk	m

[illegible]

The blue portion of figure G3 represented electrical supply of 230 V of AC voltage to the motor, and the motor itself was defined with specifications depicted on the motor and from the manufacturer's website [8]. The light green portion of figure G3 dealt with the rotational portion of the motor, including the gear reduction of 0.5, where the driver was twice the size of the driven gear, and a slider-crank which converted rotational motion to translational that was represented in

dark green. The translational motion segment had a defined mass of 4.5 kg and ideal translational sensors to track the position, velocity, and acceleration of the weight given a user defined time. This system assumed the AC motor starts at rest. The orange portion of figure G3 represented thermal effects which are not relevant to this failure mode analysis.

Failure Mode #3: Overheating of the Motor

To determine the temperature effects of the motor in the system, the Simulink model was used via thermal ports built into the Universal Motor interface. The system was open to its surroundings; therefore, the thermal mass of the surrounding air was assumed to be a very large quantity. For the sake of the model, 1,000,000 kg of air was used. The temperature was assumed to be on the more extreme end of weather conditions at 90°F , or 305.372 K, and the specific heat of air was input into the system as $1 \frac{J}{kg \cdot K}$. Finally, the main source of heat transfer in the system was convection to the surrounding air, and the governing equations which dictated this are shown below [11]. The variable definitions for equation 10 are given in table G5.

$$q = h \cdot A \cdot (T_s - T_{\infty})$$

Eq - 10

Table 5: Definition of Variables for Heat Transfer Equation

Variable symbol	Variable name/description	Variable units
q	Convection heat transfer	W
h	Heat transfer coefficient	W·m ² ·K
A	Surface area in contact with air	m ²
T _s	Surface temperature of motor	K
T _∞	Temperature of surrounding air	K

While most of these variables were quite easy to estimate, one which posed a particular challenge to obtain was the heat transfer coefficient, h . This was due to the fact that it was dependent on a multitude of factors, such as turbulent and laminar air flow conditions, thermal conductivity of the

material, etc. For this project, conditions vary in application, and the heat transfer coefficient was defined based on the flow of surrounding fluid being consistent, which in the real world it is not. For the worst-case scenario, the heat transfer coefficient was assumed to be $5 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}$, which, given the high thermal conductivity of the motor's metal body, was an appropriate approximation. The area of heat transfer was assumed to be 0.25 m^2 . The thermal effects can be seen below in Figure G4.

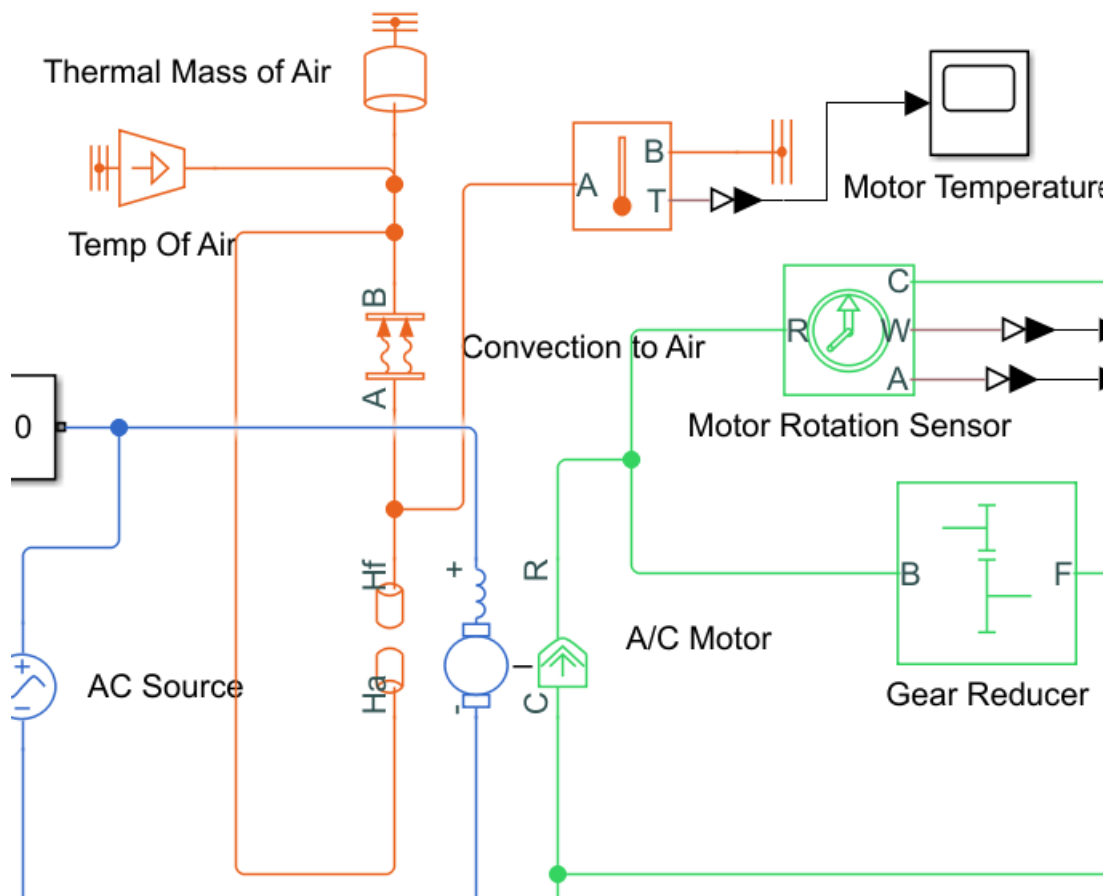


Figure G4: Thermal effects on the motor

This orange portion model showed the heat transfer of the motor, with it receiving and giving off heat to its surroundings. The temperature of the surface of the motor was monitored using an ideal temperature sensor.

G.3. Modeling/Analysis Results:

Failure Mode #1: Stress Max: 17.91 MPa, Displacement Max: 0.9643 mm, Safety Factor Min: 1.675

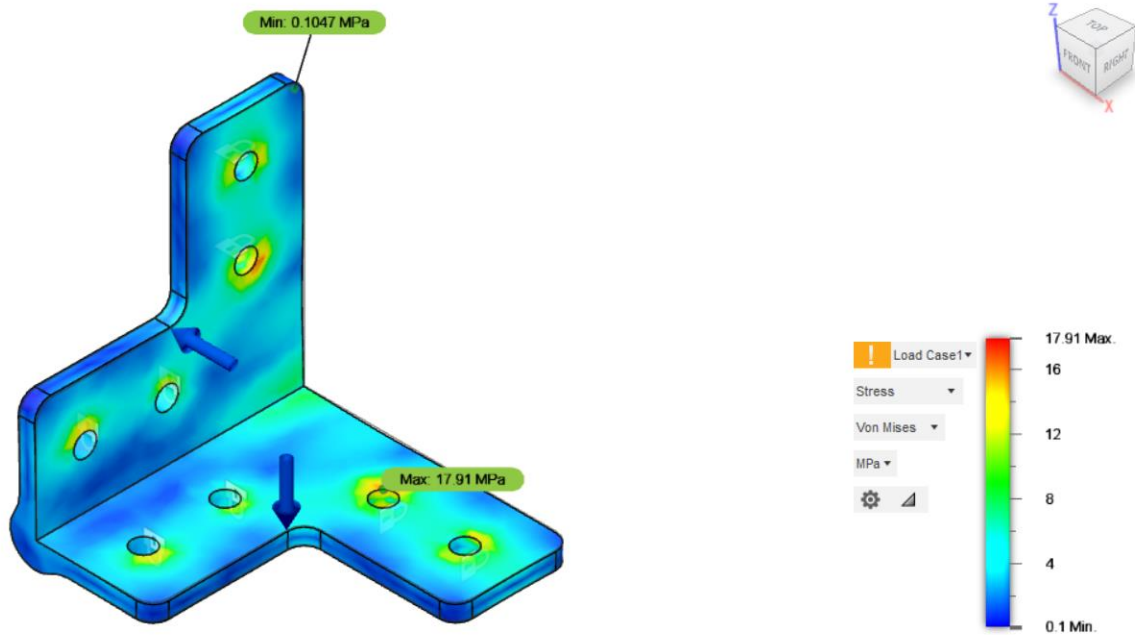


Figure G5: Stress simulation results.

The first modeling results analyzed were the stresses in the bracket. The results shown in figure G5 showed promising signs as the maximum stress induced on the part was approximately 17.91 MPa. The National Library of Medicine says that the yield strength for polylactic acid, 3D printing plastic, is 60 MPa [12]. The bracket was well within the safe zone of this material and is suitable for frame support. The stress maximums were located around the screw holes which was as expected.

The second model analyzed was the displacement model for the material, shown in figure G6. This model indicated that the material yielded 0.9643 mm for the 3000 N force that was applied. This minimal displacement took place at two locations. Both locations were on the top of the bracket furthest away from a locked constraint or another support, which was expected. After printing and attaching the bracket to the frame, it was decided for stability purposes that an additional L-bracket should be added to the inside of the frame as to resist the flexure of the unsecured sides of the extruded aluminum.

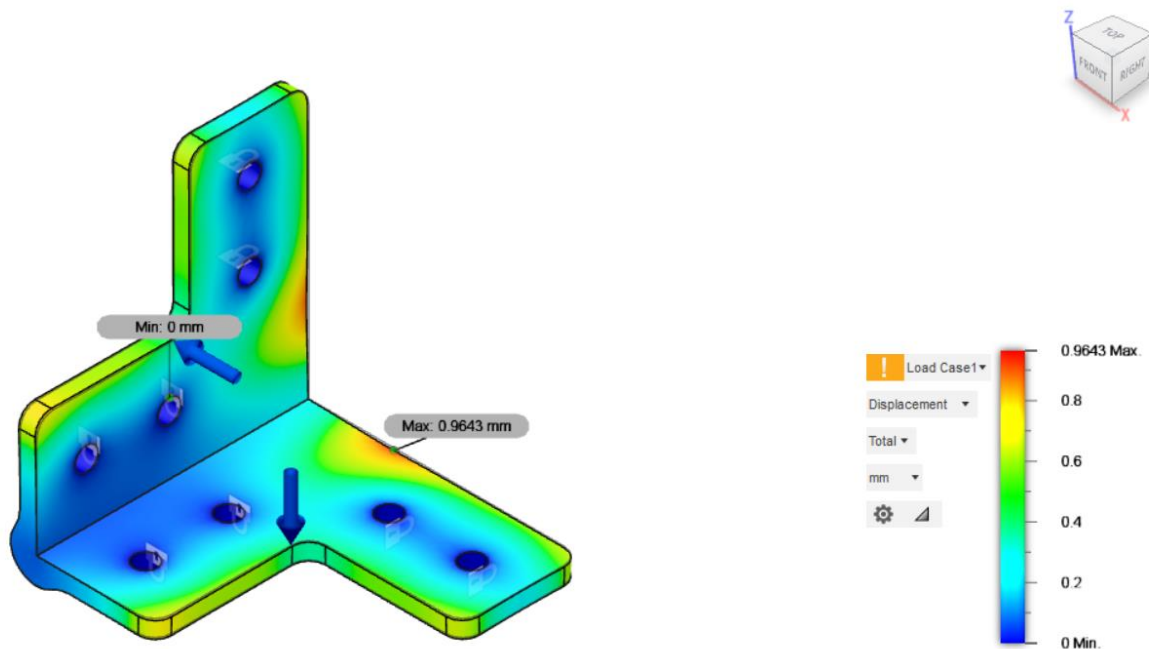


Figure G6. Displacement simulation results.

Lastly for this failure mode, shown in figure G7, the final area explored was the safety factor of the bracket. The lowest safety factor took place near the edge of the screw hole closest to where the maximum displacement took place and where the maximum stress was located. With a safety factor of 1.675, the design was considered mildly safe but requires more material added to help better protect against failure. For these reasons, this area was monitored closely during testing. The safety factor for this area increased with the latest adaptation to the design, which was to add rectangular guiding pieces along the same axis as the screw holes. This allowed the bracket to fit snugly in the extruded aluminum pieces and mechanically join the two pieces together more adequately. From the modeling performed on the brackets, the group determined that the brackets did not fail. They had a safety factor above 1 and were expected to increase further, experience stress well below the yield stress, and have a displacement of less than a millimeter. For these reasons, the group decided to move forward with 3D printing the brackets for the frame connections.

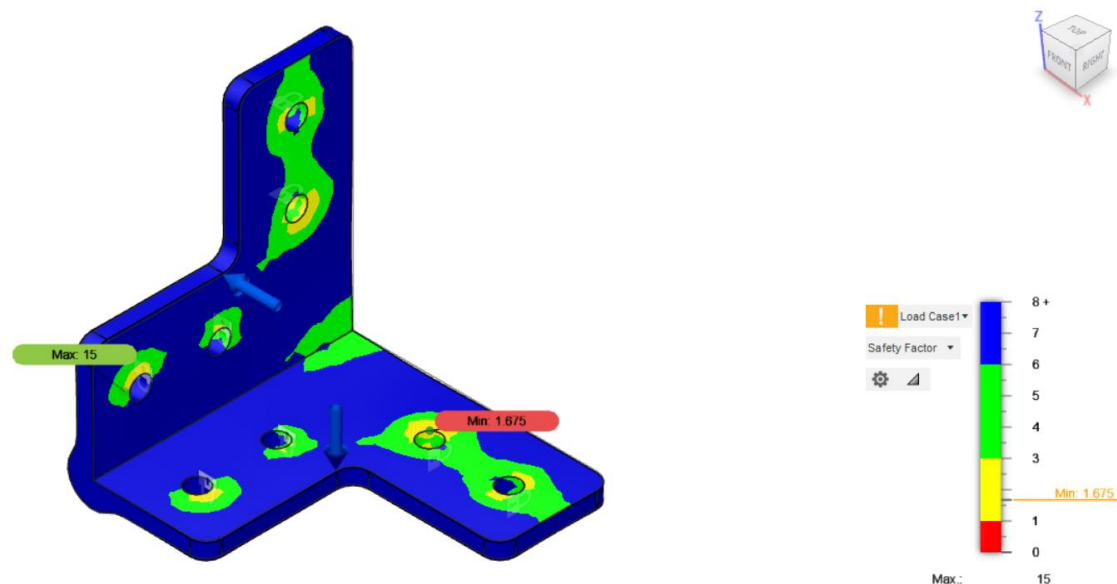


Figure G7: Safety Factor simulation results.

Failure Mode #2:

Input: 230 V; 100 seconds

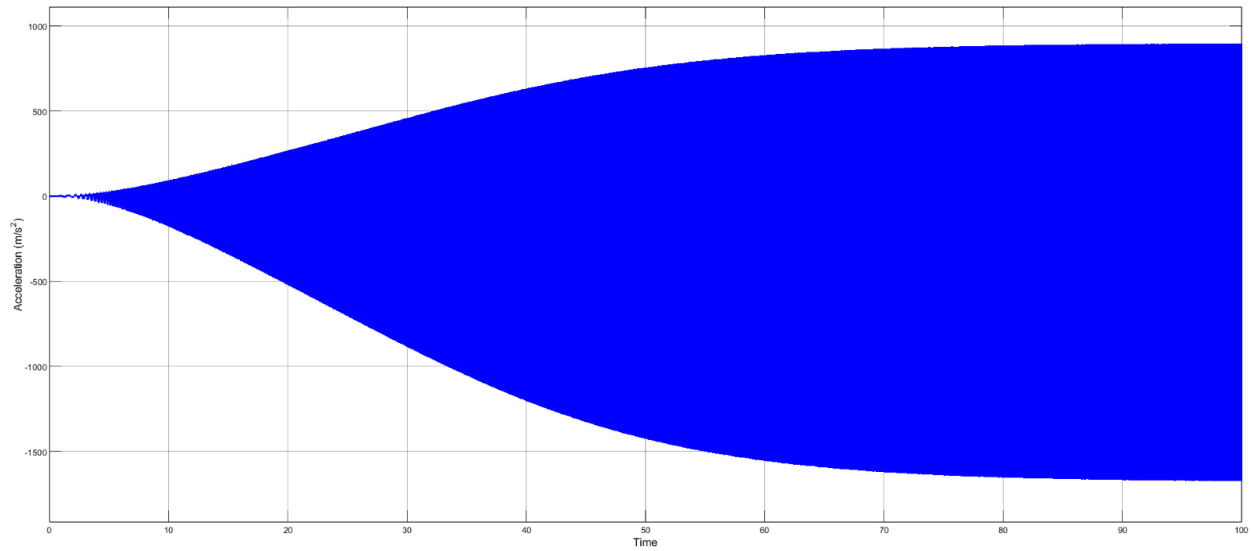


Figure G8. Acceleration of weight for 100 seconds.

Input: 230 V; 20 seconds

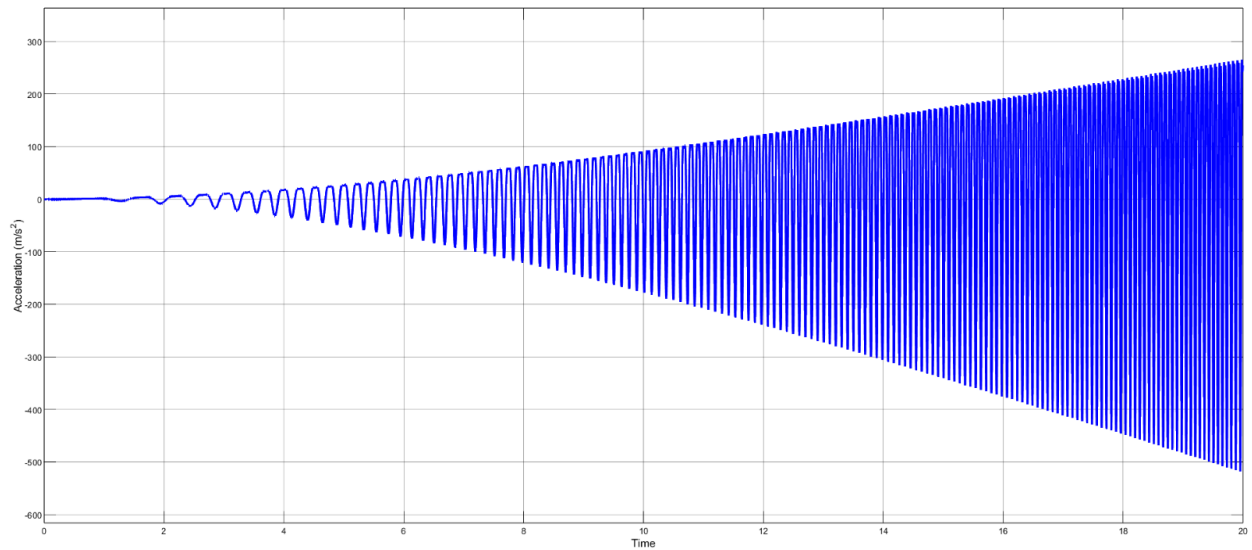


Figure G9. Acceleration results for 20 seconds.

As seen in the results above in figures G8 and G9, the acceleration at steady state reached well above $1500 \frac{m}{s^2}$, which generated a force over 6000 N, assuming a mass weight of 4.5 kg. The positive and negative values represented the acceleration of the weight moving upward and

downward. The downward acceleration was higher due to effects of gravity. Models are not perfect, and reaching this amount of acceleration could output forces well over the amount the frame could stand before failing. Therefore, in the final design the motor is throttled back to the design specifications to reach the amount of force necessary for observation in the vibration analysis. The assumptions and imperfections of the model made this level of acceleration highly optimistic to reach. However, the acceleration of the weight reaching such high values was useful for this project, as it was inferred that the shaker will at least be able to reach this project's target value of 500 N.

Failure Mode #3:

Input: 230 V; 1,000 seconds; 305.372 K Air Temperature

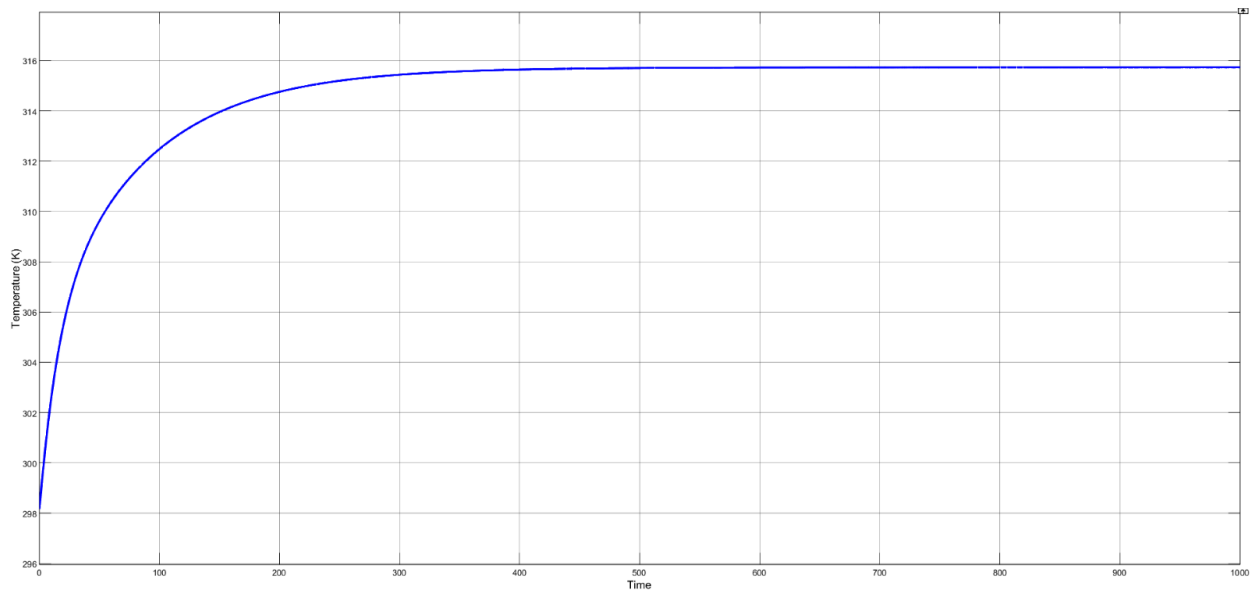


Figure G10: Temperature of the motor in operation for 1,000 seconds, exposed to 90 °F

As shown in Figure G10, the motor was subjected to 105.372 K or 90 °F heat during operation. The temperature of the motor rose and leveled off at steady state without reaching extreme temperatures, as the maximum temperature reached was less than 316 K, or 109.13 °F. This was well within safe operating temperatures for AC motors, and no active cooling was necessary to

provide additional heat transfer. This simulation also ran for 1,000 seconds, which was much higher than the expected time the shaker will be in use to collect data.

G.4. Conclusion and/or recommendations:

In this report, the first analysis performed was a simulation of the stress on the bracketing assemblies in Fusion 360 to test the strength of 3D printed brackets, which were requested by our project sponsor for their cost effectiveness. The main concern of these brackets was whether the plastic could handle the shear and bending stress, and the test was done using equations for the textbook “Machine Elements in Mechanical Design.” Based on the analysis done, the brackets should not fail, indicating that the brackets are adequate as is. The second analysis consisted of a SIMULINK model run through MATLAB to determine the output force of the motor. The results showed that the motor reached an acceleration above $1500 \frac{m}{s^2}$, which translates to a force of over 6000 N with a mass weight of 4.5 kg. The downward acceleration was higher because of gravity. The high level of acceleration resulted in forces beyond what the frame can handle, so the motor is adjusted to the design specifications for the vibration analysis. The acceleration of the weight demonstrated the shaker’s ability to reach the target value of 500 N for this project. Based on the model, the motor is adequate and will not need to be replaced. The third analysis was a SIMULINK model to determine the effects of the temperature of the motor during use. In the model, the motor reached a temperature of 105.372 K during operation. The temperature rose to 316 K, but it did not exceed it. The resultant temperatures were within the safe operating range for this motor, so no additional cooling is needed. The model indicates that the temperature of the motor will not cause it to need to be replaced.

H. Design for X

H.1. Introduction:

This DFX chapter entails this project's specific design goals, including the design for manufacturability and assembly, cost, safety, the customer requirements, ease of use, durability/reliability, and serviceability. The design refinements which are being processed consist primarily of the assembly and ease of use for the mass shaker. The assembly requires precise, accurate measurements along with the dimensions of the screw fasteners and brackets. Ease of use for the system comes down to programming the VFD, as it displays frequency data. Manufacturability is vital so the shaker is assembled and produced within a reasonable amount of time. The cost is also an important part of the design because the budget cannot be exceeded, therefore the group has been using many parts readily available in the ARTS Lab. Safety is arguably the most vital requirement, due to not only preventing injury to users of this project in the future, but also avoiding possible liability involved. The reliability/durability and serviceability of the bridge shaker go hand in hand. This project is planned to last without needing major servicing for several years (3-5), thus robustness with the sourcing of quality parts is key to this project's success within the ARTS Lab. The serviceability for the shaker is dependent on the methods of securing the parts together, and whether the parts remain available in the future.

H.2. Design for Manufacturability and Assembly

To optimize manufacturability, the team considered material selection and connector design. Off-the-shelf parts were chosen to ease sourcing, and parts were chosen considering both cost and replaceability. 8020 40-series extruded aluminum was chosen due to its ease of assembly. The 8020 series included support brackets, connectors, beams, and fasteners that were compatible with each other to facilitate the manual assembly process by reducing the number of specialized

parts and sourcing as many parts from one company as possible. The main trade off was that 8020 extruded aluminum was more expensive due to its specialized design, and all connectors had to be 8020 connectors to pair properly with the beams. The four corner connectors are 3D printed following an 8020 connector CAD model to reduce costs and weight; however, the team decided to perform poka yoke on the connectors since they were being printed. Guide channels are added to reduce the stress on the plastic from the screws and make assembly easier by keeping beams in place. In order to ensure the vertical beam is all the way down, the guiderail for the vertical beam is extended so that the two lateral beams are not be placed too far in and obstruct the vertical beam. Figure H1 illustrates the changes made to the brackets. A key tradeoff here is the time required to print the connectors, as well as the reduced strength of PLA versus aluminum.

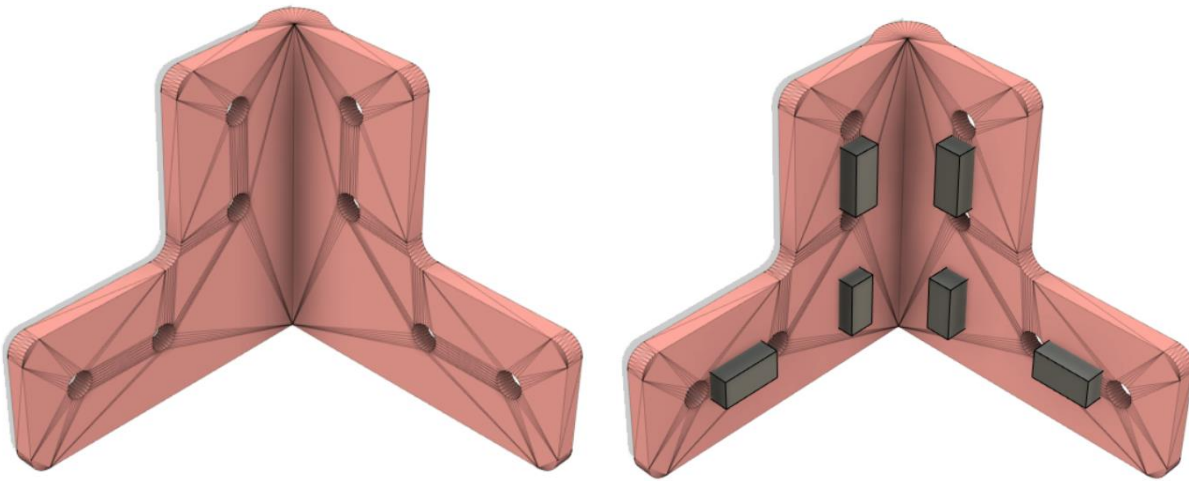


Figure H1. 3D printed bracket with only spine modification (left) and 3D printed bracket with poka yoke guiderail design.

H.3. Design for Cost

Cost was a limiting factor for the design team when inventing ways to produce the shaker for Dr. Austin Downey. Inflationary reasons made some parts of the build extremely expensive to buy and alternatives had to be sourced out. For example, a VFD was sourced from Amazon instead of a big-name company. This saved a few dollars throughout, but ultimately ended up reducing

the gross amount spent more than expected. Another way the team designed for cost was by using aluminum parts rather than steel parts. The ARTS Lab had an abundance of extruded aluminum for the team to use that reduced the frame production cost to \$0. A similar approach was taken to the motor and the brackets. The motor was recycled, with permission, from one of the older projects that are stored in the sub-basement of 300 Main St. This three-phase motor would have been \$400-700 (gathered from online stores while sourcing motors) off the shelf, instead it was sourced for free. Since the brackets for the frame have been designed and 3D printed, the cost for each bracket went from \$10-20 each, down to virtually \$0 thanks to the ARTS Lab's stockpile of PLA plastic. Lastly, an element of purchasing that saved a fair amount of money was sourcing parts through Grainger and placing a bulk order. Grainger offers free shipping and on larger orders such as the one placed, which saved money compared to other online parts store shipping costs.

H.4. Design for Safety

Operating a shaker that involves handling a weight through high voltage rotation poses significant safety concerns for any individuals within close proximity during usage. An identified concern was the potential for the vibrational mass shaker to become overly efficient and cause disintegration, thus projecting debris and the weight. To diminish this potential safety hazard, it was crucial to ensure that the shaker is securely mounted onto the bridge, withstanding any forces generated during operation without the risk of tipping over. The design team opted to stabilize the shaker with sandbags to guarantee operational safety. A further concern to consider was the possibility of encountering electrical issues. If the electrical components, namely the motor and VFD, are not correctly wired and grounded, the vibrational mass shaker poses a potential electrical shock hazard. To preclude these electrical risks, the design team conducted thorough research on wiring diagrams and component datasheets to ensure that all components were appropriately

grounded and correctly wired. To prevent any of these safety concerns from ever becoming a problem, regular maintenance and inspection of the shaker and its components is performed to ensure proper operation and determine any potential safety hazards.

H.5. Design for Customer Requirements

The goal of this project is to design a bridge shaker for the ARTS Lab that will be used to test vibration data by operating at different frequencies. It must be safe to operate and leave the bridge undamaged. The mass shaker induces vibrations via an oscillating weight which transfers that energy to the bridge. The Needs Metrics Matrix, shown in table H1, has remained stagnant throughout the design and assembly process, with the most important engineering characteristics still being adaptability, usability by others, and product details. The contact area and weight of the shaker were refined to have more emphasis on total product weight at the expense of the contact area, which is sufficient to transmit energy as the product will still be fully on the bridge, with the force increasing at the frame components in the base due to less material that would dissipate it.

Table H1. Needs Metrics Matrix.

Customer Requirements		Improvement Direction		Engineering Characteristics													
		↑	↑	↓	-	-	-	-	-	-	↑	↓	↑	-	↓	↓	
		Units	Hz	Hz	s	boolean	boolean	boolean	boolean	boolean	N	kg	m²	boolean	W	\$\$	
Importance Factor	Weight	System functionality	System output range	Measurement precision	Test run time	DAQ	User interface	Usability by others	Adaptability	Product details	Withstanding operation	Weight	Contact area	Minimally invasive	Power out / power in	Economically feasible	
Test vibration data	2	9	3	3	3	9		1			1			1			
Operate at different frequencies	3	9	9				3	1			1						
Resolution of at least 1 Hz	2	3	1	9			1	1									
Time control	1				9	3	3			3							
Record data	4	3	3	3	3	9									1		
Screen to monitor parameters	2						9	3	1	3					3		
Clear and safe operation instructions	5					1		9	9	9					1		
Usable after project	3				1	1	3	9	9	3	3	1			1		
Well documented	4				1	1	1	3	9	9							
Robust	4						1		3		9						
Portable	4					1		3	3			9		3			
Good contact to bridge	3										1		9	1			
Leave bridge undamaged	4	1									1		1	9			
Power efficient	1						1						1		9	3	
Cost-effective	2													1	1	9	
Raw Score (1028)		67	47	36	34	73	50	109	134	99	57	39	32	55	29	21	
Relative Weight (%)		7.60	5.33	4.08	3.85	8.28	5.67	12.36	15.19	11.22	6.46	4.42	3.63	6.24	3.29	2.38	
Ranking		5	9	11	12	4	8	2	1	3	6	10	13	7	14	15	

H.5.1. Design for Ease of Use

Ease of use was chosen because the Usability by Others EC was rated number 2 in the Needs Metrics Matrix. The VFD reads all user input to control the motor speed, but the data it displays is for the motor rather than for the weight. This requires the user to know the gear ratio to calculate the frequency of the motor, but yields a simpler and more accurate product. Additionally, the shaker is entirely open-source with an extensive GitHub (see Appendix) to promote user understanding and adaptability. The tradeoff of having the project open-source is that it is less profitable in a market as competitors can recreate the design, but that is not a concern for the sponsor.

H.5.2. Design for Durability/Reliability

To ensure the durability and reliability of the vibrational mass shaker, the design team prioritized the selection of high-quality materials and components. The frame of the shaker, constructed from high-strength 8020 series extruded aluminum, was chosen to withstand the significant forces exerted during operation and provide resistance to corrosion and wear. The metal components, including gears, links, and weight, were similarly selected for their durability and longevity, with either steel or aluminum materials used. The 3-phase AC motor chosen for the shaker was a high-quality component that is expected to function optimally for the entire operational lifespan of the shaker. Coupled with a reliable and functional VFD, these components provide a robust and dependable vibrational mass shaker, which is engineered for long-term use.

H.5.3. Design for Serviceability

The shaker is a relatively violent machine that attempts to vibrate itself into pieces. For this reason, the parts used were minimized and the shaker designed to be robust enough to remain strong even under the immense stress of the vibrations. This created concerns of part degradation or even

failure. Commercial products were sourced for the gears, shafts, frame, linkages, bearings, etc. so that anyone using the shaker in the future can easily source a part to repair the shaker. Additionally, everything purchased, changed, or installed is documented in a repository on GitHub that allows for a new user to understand the device and make simple repairs with ease. The only serviceability concerns are with the motor and the VFD. These two items cannot be worked on explicitly like the other parts of the shaker. The VFD will have to be sourced out and purchased again if it were to break, and the motor was recycled from an old project so it is likely that another motor would need to be sourced if the current one breaks.

H.6. Conclusions and Recommendations

Major refinements to this project mainly occurred in the layout and method of connecting parts to the frame, as well as refinement of the bracket design to increase robustness. Only minor changes were made to sourcing parts for the drive train, mainly the shaft and the sheave which will be secured to the frame. The dimensions for the sprockets have remained constant, as well as the method of meshing them together via chains. The chain method allows for flexibility of motor/sprocket replacement, especially if the dimensions of the motor or sprocket change. Further inspection of product safety deemed that the addition of surrounding walls for the shaker were necessary in case of an unexpected failure in one of the moving parts, and expanded steel was added to the final design in section L. Tradeoffs have occurred primarily in the mass shaker's base. While it needs sufficient contact to the bridge with a solid frame to place the components, too much weight on the bottom affected the ergonomics of the product. An entirely metal base increased the price of the project, while providing no benefits to the wasted space, so the base is comprised of 8020 beams that support the motor and weight guiderails. The method of stabilizing the shaker also changed from ratchet straps to sandbags on protruding extruded aluminum

connected to the frame. This gives the shaker more vertical stability than the original horizontal, which is completely logical considering the acting force is strictly vertical. This method also ensures the ratchet straps do not pull the shaker apart by slowly warping the frame, and users cannot accidentally over tighten them and break the shaker.

I. Build Instructions

I.1. Frame

This section focuses on constructing the outer frame of the bridge shaker. Table I1 lists the required parts for the build.

Table I1. Parts required for frame build.

Part Description	Quantity
80/20 40 Series Extruded Aluminum: 18 inches	4
80/20 40 Series Extruded Aluminum: 20 inches	11
80/20 40 Series Extruded Aluminum: 48 inches	2
M8 Screws	148
M8 Hammer Nut	148
3-way Bracket	4
Triangle Bracket	24
Flat Aluminum Bracket	10

Fabrication tools needed:

- 8 mm Allen key
- Ender 3D printer

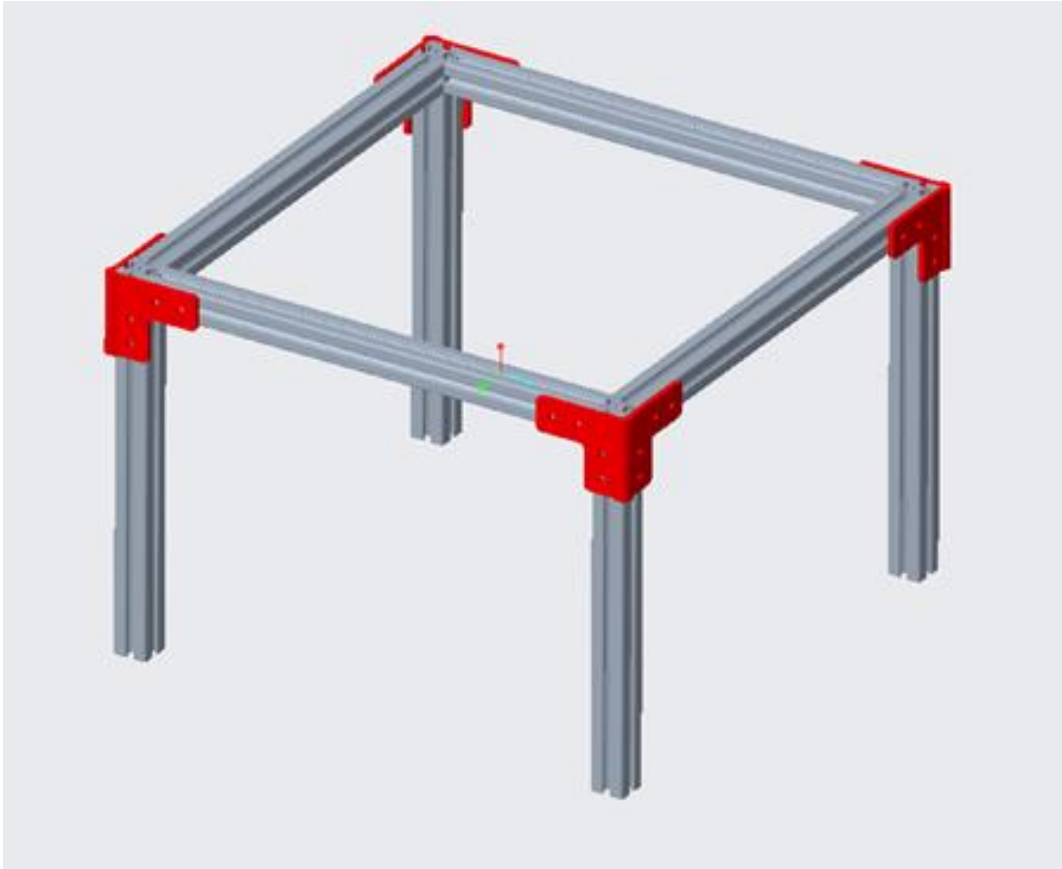
- 1.1. Begin by using a band saw to cut the extruded aluminum into the specified lengths in the table above (I.e., 20-, 18-, and 40-inch sections).
- 1.2. 3D-print the 3-way and 2-way brackets using the CAD files found in the GitHub repository.
- 1.3. Connect the 3-way bracket by first placing the 18-inch section in the ‘fold of the bracket’ ensuring that it is flush with the top of the bracket.
- 1.4. Insert four M8 Hammer Nut into the slots of the extruded aluminum aligning the Hammer Nut with the holes in the bracket.
- 1.5. Insert M8 Screws into the holes and tighten them down with an Allen wrench.



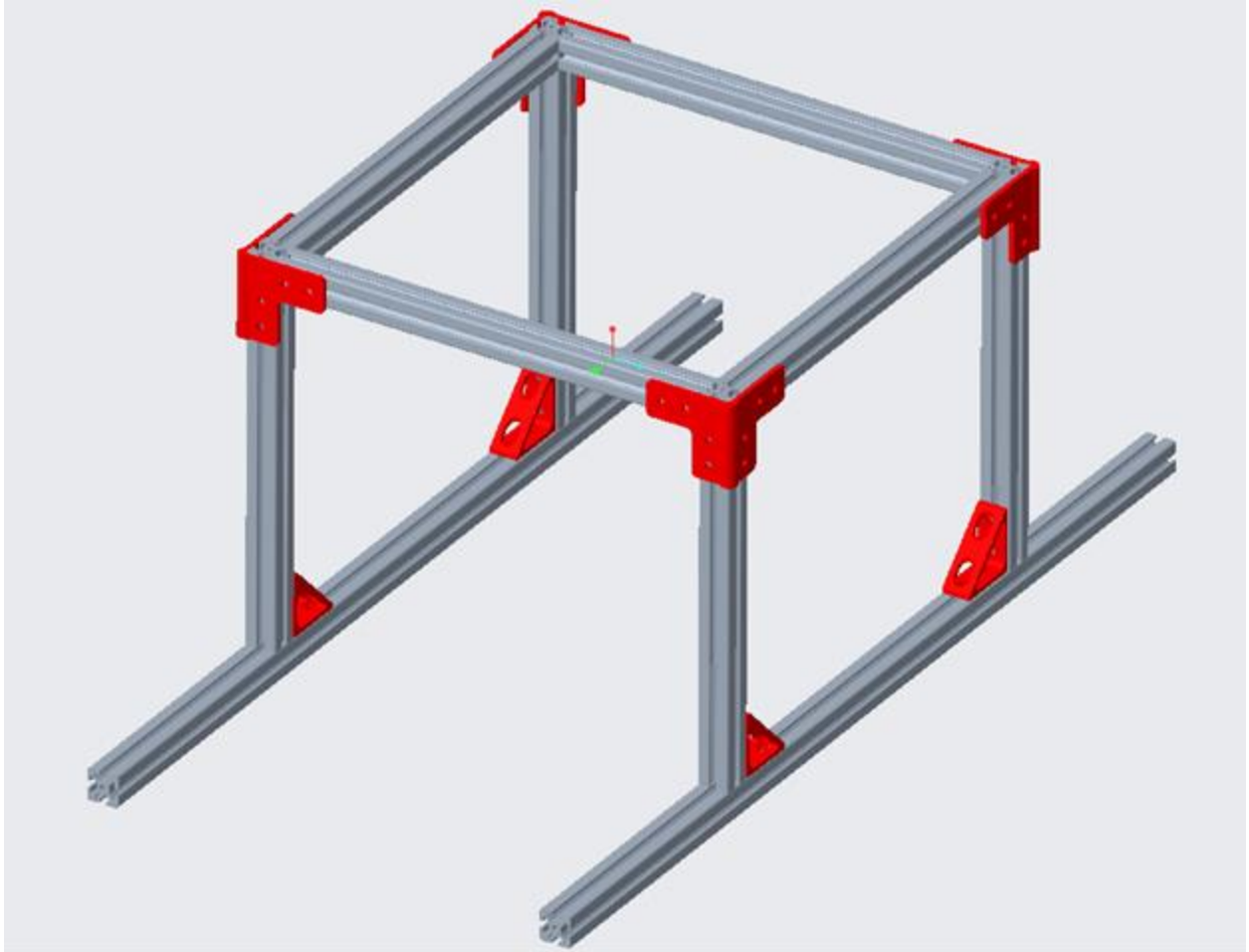
- 1.6. Repeat these steps with all four of the 3-way brackets and 18-inch sections of extruded aluminum.
- 1.7. Take two of the pairs created in the prior step and place a 20-inch section between them.
- 1.8. Mount one side of the 20-inch section of extruded aluminum to the left or right side of the 3-way bracket.
- 1.9. Connect the section by using two M8 Screws and two M8 Hammer Nut.



- 1.10. Continue this pattern for the three remaining 3-way bracket and 18-inch aluminum assembly. The result should be 4 identical assemblies that consist of a 20-inch extruded aluminum piece, 18-inch extruded aluminum piece, and a 3-way bracket.
- 1.11. Connect the respective empty ends up the 20-inch section to the open space in the bracket.
- This should create what is shown below.

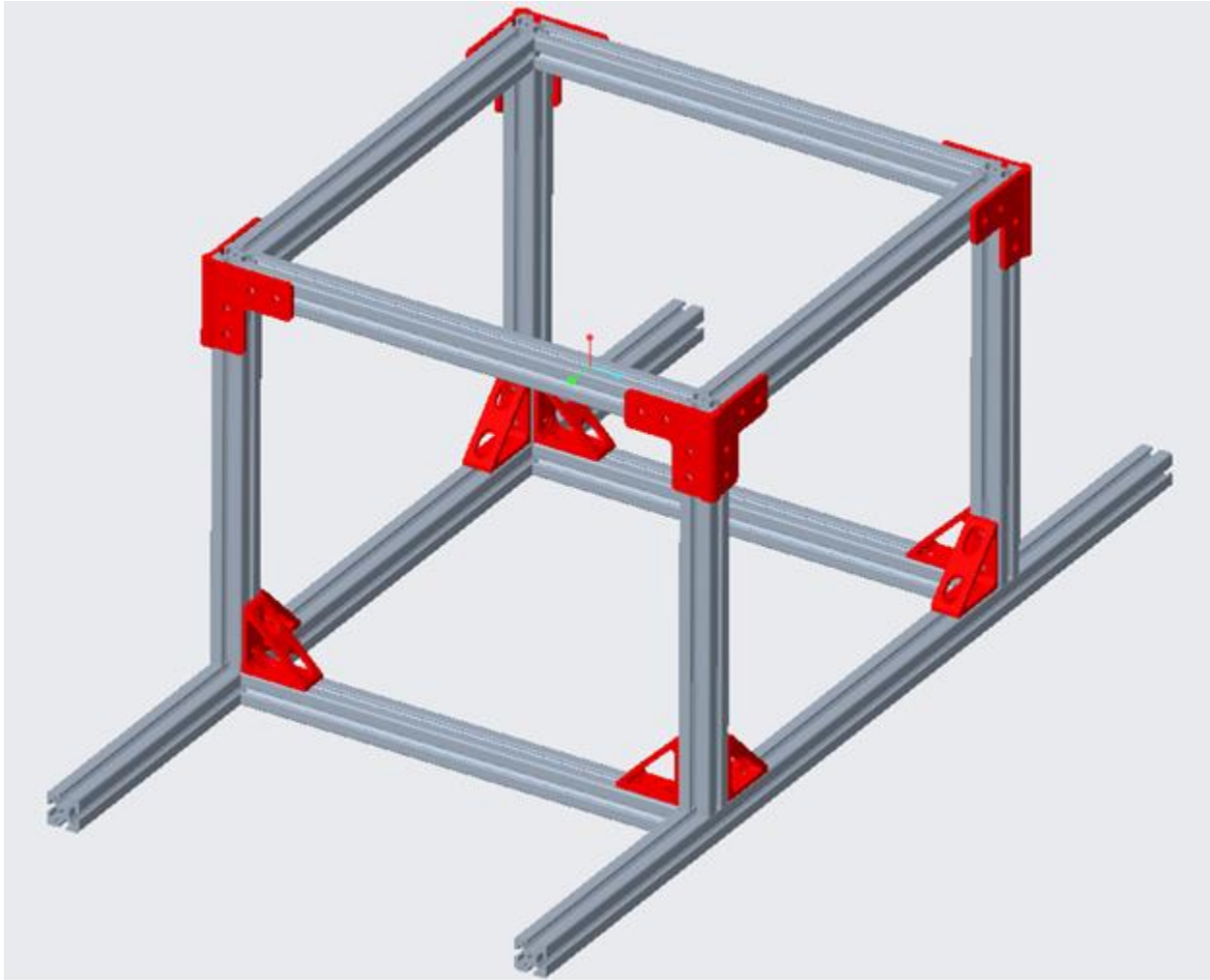


- 1.12. Next, place 2 48-inch pieces of extruded aluminum on the ground parallel to one another and set the assembly on top of the pieces.
- 1.13. Connect a triangle bracket to each of the four legs to connect the main assembly to the 48-inch pieces.



1.14. To strengthen the frame, place 2, 20-inch sections between the legs of the frame to create an assembly as shown below.

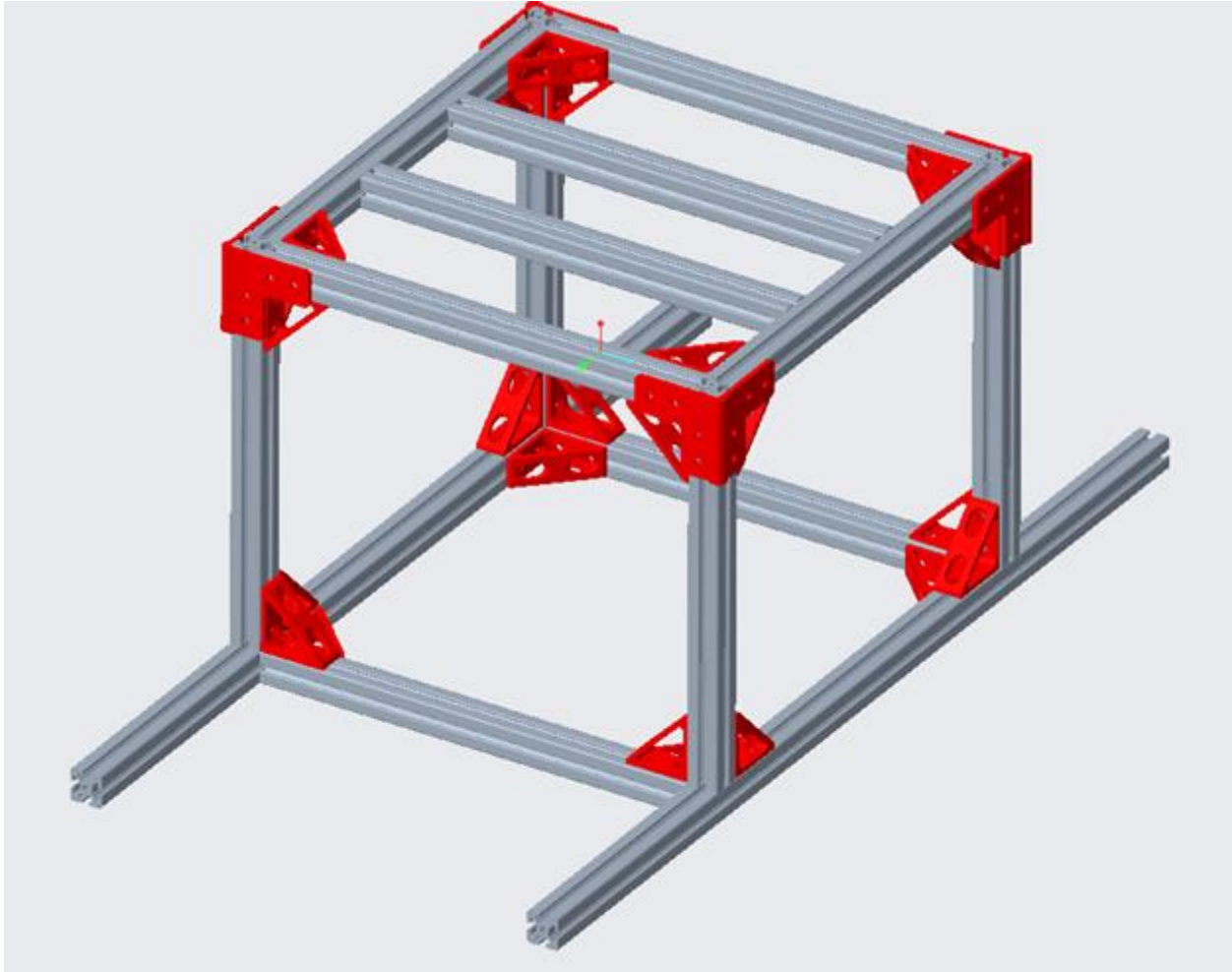
1.15. Secure these with triangle brackets and M8 screws and hammer nuts.



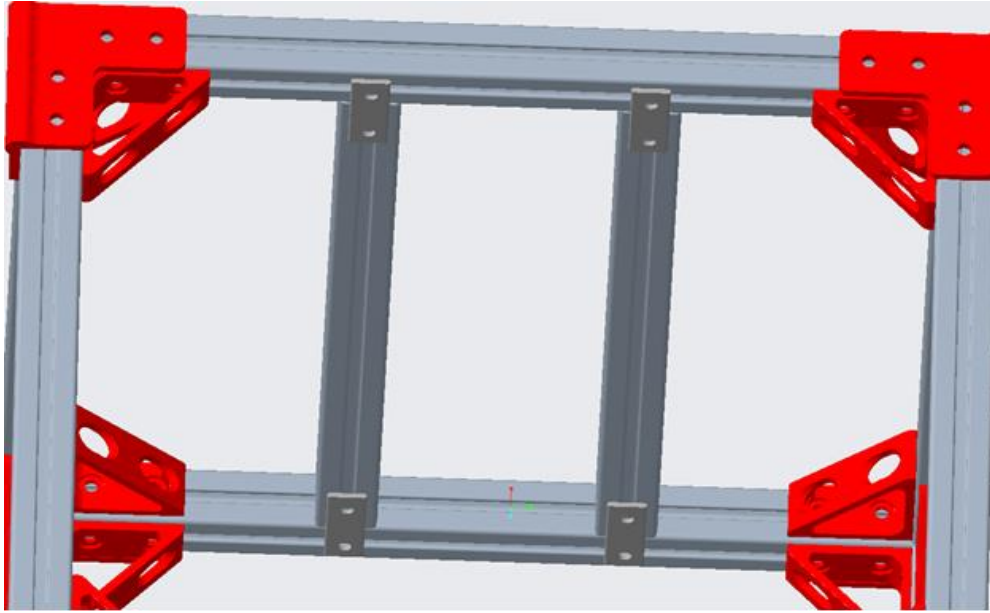
1.16. This creates the main frame that all other components will be mounted in. 5 other 20-inch extruded aluminum pieces were cut to mount the motor, mounting rod, and shaft bearings on.

The placement will vary based on the desired setup for the shaker.

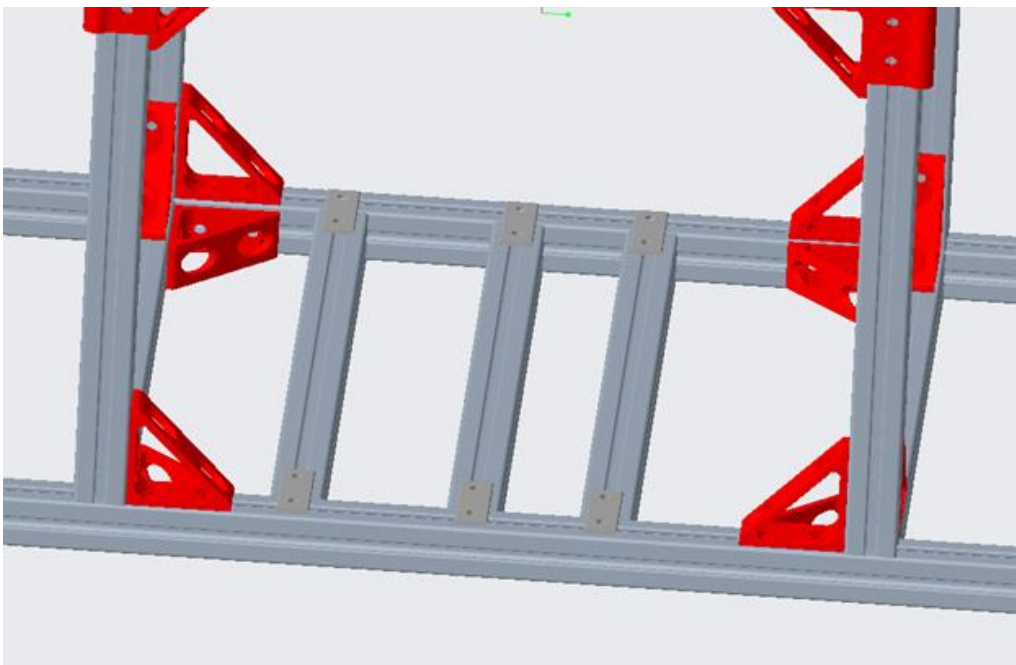
1.17. Add triangle brackets to all corners of the frame to resemble the image below.



- 1.18. Rotate the assembly upside down, this will allow for the installation of the top supports to be easier.
- 1.19. Place 2 20-inch pieces of extruded aluminum perpendicular to the 48-inch sections (these will hold the shaft bearings and should be adjusted in the frame as needed).
- 1.20. Secure these pieces with a flat aluminum bracket on both sides, M8 screws and hammer nuts.

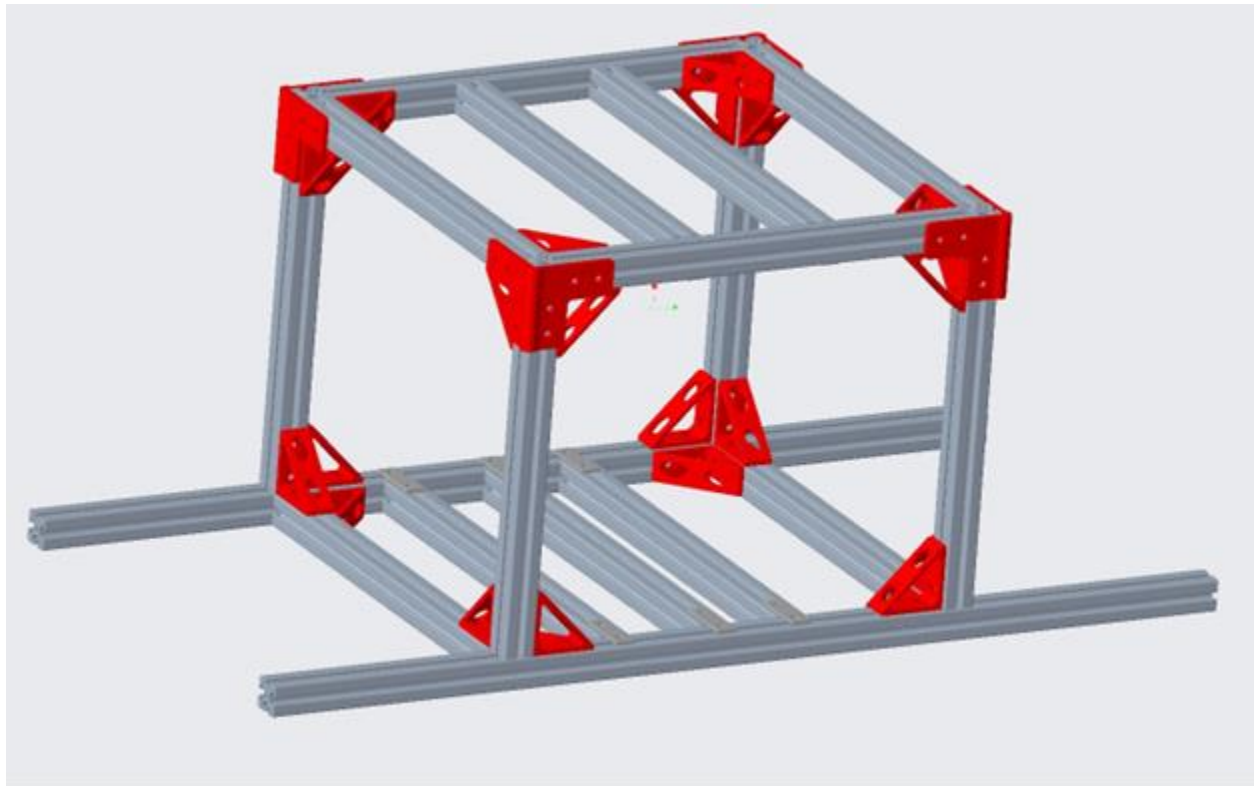


- 1.21. Rotate the assembly back to where the 48-inch sections are on the ground.
- 1.22. Place 3 20-inch sections in the bottom, perpendicular to the 48-inch sections (these will be used to fix the motor and mounting rod to the frame. They should be adjusted as needed based on the base plate of the motor and location of the weight assembly).



1.23. Secure these pieces with a flat aluminum bracket on both sides, M8 screws and hammer nuts.

1.24. Secure the motor and VFD to the 20-inch sections of extruded aluminum using M8 screws and hammer nuts.



1.25. Place 4 20-inch sections of extruded aluminum using triangle brackets and M8 screws under the top section.

1.26. Place one more 20-inch section of extruded aluminum across perpendicular to the orientation of the motor.

I.2. Motor/VFD

This section focuses on the wiring of the motor to the VFD. Required parts are listed in table I2.

Table I2. Parts required for motor build.

Part Description	Quantity
3 Phase AC Motor	1
Variable Frequency Drive	1
12 Gauge Wire	3
Nuts	3

- 2.1. Make sure no power is turned on to the VFD or the motor before making any connections.
- 2.2. Connect the three motor wires to the U, V, and W terminals on the VFD as shown in figure I1.
- I1. Make sure the connections are tightly screwed in and secure.

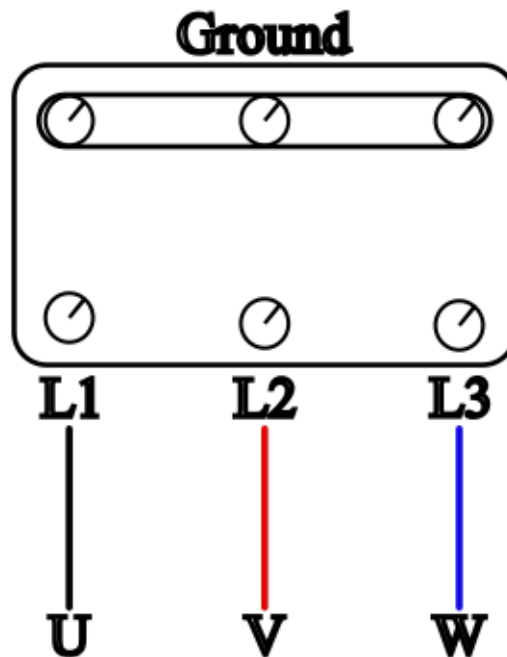


Figure I1. VFD to motor wiring.

- 2.3. Connect the VFD to a wall outlet power supply by wiring to the VFD's power input terminals.

2.4. Ground the VFD and motor to the ground pin on the motor and ensure that all connections are tight and secure.

I.3. Chain Sprockets and Shaft

This section focuses on the assembly of the chain sprockets and shaft. Table I3 lists the required parts.

Table I3. Parts required for chain sprockets and shaft build.

Part Description	Quantity
4" Sprockets	2
2"x2ft Shaft	1
M8 Screws	8
M8 Hammer Nut	8
Bearings	2

Fabrication tools needed:

- Hex key set
- Phillips head screwdriver

3.1. Use a Phillips head screwdriver, 4x M8 screws and 4x M8 Hammer Nuts to secure the two bearings to the two top aluminum supports, with the holes on both being directly in line.

3.2. Insert the 2"x2' shaft through both bearing holes.

3.3. Attach the two sprockets to the shaft, with one being in line with the motor gear, and the other being in line with the weight.

3.4. Ensure the weight-bearing sprocket is set flush with the shaft, so no protruding parts will interfere with the linkage, and tighten it with a hex key.

3.5. Move the motor-end sprocket to its desired location where it will sit in line with the motor gear and tighten fasten it to the extruded aluminum frame with the M8 screws and hammer nuts.

I.4. Weight

This section focuses on fabrication of the linearly oscillating weight. Required parts are listed in table I4.

Table I4. Parts required for weight build.

Part Description	Quantity
Weight	1
Slider	1
Ball bearing	2
Rail	1
Linkage	1

Fabrication tools needed:

- Band saw
- Drill
- Tap and die set

4.1. Cut the weight to a desirable size.

4.2. Drill holes into the weight in identical areas to the holes on the slider.

4.3. Thread the holes in the weight to be able to fit 5 mm screws.

4.4. Drill the rail into a piece of extruded 40 series aluminum to later connect to the frame.

4.5. Securely mount the rail onto the frame and ensure that the rail is level.

4.6. Screw the weight to the slider and attach the weight/slider to the rail.

4.7. Attach the ball bearing and linkage to the weight.

4.8. Connect the other end of the link to the sprocket from the end of the shaft using a ball bearing.

4.9. Ensure that all connections made are tight and secure.

J. Economic Analysis

J.1. Introduction

Ensuring that the product will have a net positive gain and not be a ‘money pit’ was done by evaluating the current assembly costs and operating costs coupled with the yearly expected expenses tied to maintenance and operation. The shaker was designed for research purposes and has no specific industry value as this is a ‘one-of-a-kind’ product that was designed specifically for the students who are testing the structural integrity of bridges and walking paths. The monetary value for this product was estimated through the possibility of grants being offered to the students for research in this field. Given this fact, the break-even analysis, variable cost of labor, “year zero” cost, and the cost reduction analysis were estimated using reasonable values. This analysis covered the expenses incurred and compared them to the expected future value of the parts most often replaced.

J.2. Costs, Savings, and Revenues

The bridge shaker is intended to be an academic tool rather than a commercial product; however, the value of this shaker lies in the grant money that stands to be awarded by using the shaker for long-term vibration testing on large structures, something the ARTS Lab does not currently have equipment for. The costs are primarily from materials, as the labor required to build the shaker can be delegated to lab researchers. The cost for a single prototype was broken into fixed (materials, manufacturing/assembly) and variable costs below, and were modeled assuming the product would be commercially sold. Technician labor was estimated rather than researcher labor, and all parts are sourced from professional suppliers. Table J1 shows the fixed costs for a single bridge shaker based on the previous prototype.

Table J1. Fixed costs per unit of current prototype.

Materials			
Description	Cost (USD)	Quantity	Source
3 Phase AC Motor	705.18	1	Grainger
Industrial Chain	29.55	1	Grainger
Shaft pinion, 4"	40.00	2	Grainger
Motor gear, 8"	64.58	1	Grainger
Keyed Shaft: 1 in Dia, Aluminum	52.63	1	Grainger
Aluminum 80/20 40 series, 1 ft	15.44	18	Grainger
Elegoo Uno R3	17.99	1	Amazon
LCD	5.99	1	Amazon
3pin IR Infrared Module	1.89	2	Amazon
OSH Park custom PCB for sensor input to Arduino UNO (shield form factor)	23.55	1	OSH Park
Shaft bearings	26.79	2	Grainger
Extension cord	25.98	1	Amazon
Weight, aluminum 4 kg	9.89	1	Grainger
80/20 40 series fasteners	1.54	100	McMaster Carr
VFD, 230 Volts, 1 to 3 Phase	118.84	1	Amazon
PLA 3-way bracket	2.52	6	Cura 3D printer slicing estimate (101 g PLA per unit)
PLA Triangle Bracket	1.42	20	Cura 3D printer slicing estimate (57g PLA per unit)
Total:	1666.98		
Manufacture/Assembly			
Description	Cost	Quantity	Source
Machining labor (2D cutting)	20.00	2 hours	Wade 2022
Assembly labor	18.81	5 hours	Indeed 2023
Total:	134.05		
Total fixed cost:	1801.03		

The total fixed cost per one bridge shaker was \$1,801.03. It is important to note that for the final shaker presented in this work, many parts were able to be sourced for free, including the AC motor and aluminum. In the case of commercial production, this is a reasonable fixed cost considering the size and scale compared to other modal shakers. Table J2 displays the variable costs per year of the shaker.

Table J2. Variable costs per unit per year of current prototype.

Description	Cost	Quantity	Source
Maintenance	18.81	20 hours	Indeed 2023
Operational electricity	14.54/hr	0.15 hours per test, assume 50 tests	Dominion Energy 2021 (0.021086 per kWh, at 690W)
Total variable cost:	485.25		

The total variable cost per year was approximated at \$485.25. This estimate assumed 50 ten-minute tests per year and 20 hours of maintenance over the year by the same technicians responsible for the assembly of the shaker in the fixed costs. The predicted lifespan of the bridge shaker was three years, assuming proper pre-test maintenance (tightening fasteners, lubrication).

Table J3 shows the up-front cost of the shaker.

Table J3. Up front (“Year Zero”) costs.

Description	Cost	Quantity
Research and development	50.00/hr	90 hours
Creality 3D printer	236.00	1
Total Year Zero cost:	4736.00	

The up-front project costs totaled to \$4,736.00 and were primarily the cost of design consulting with the team. The cost of the printer was included as an equipment cost, but the cost of the machine that manages 2D cutting of the aluminum was not included because the task is outsourced to machinists.

Table J4. Reduced cost of the materials for a version of the shaker.

Reduced Cost Version of Materials			
Description	Cost (USD)	Quantity	Source
3 Phase AC Motor	705.18	1	Grainger (Dayton)
Industrial Chain	15.32	1	McMaster Carr
Shaft pinion, 4"	40.00	2	Grainger
Motor gear, 8"	64.58	1	Grainger
Keyed Shaft: 1 in Dia, Aluminum	45.15	1	McMaster Carr
Aluminum 80/20 40 series, 1 ft	15.44	18	Grainger
Elegoo Uno R3	8.96	1	eBay
LCD	5.99	1	Bill of materials
3pin IR Infrared Module	1.89	2	Bill of materials
OSH Park custom PCB for sensor input to Arduino UNO (shield form factor)	23.55	1	Bill of materials
Shaft bearings	26.79	2	Bill of materials
Extension cord	25.98	1	Bill of materials
Weight, aluminum 4 kg	9.62	1	McMaster Carr
80/20 40 series fasteners	1.54	100	McMaster Carr
VFD, 230 Volts, 1 to 3 Phase	118.84	1	Bill of materials
PLA 3-way bracket	2.52	6	Cura 3D printer slicing estimate (101 g PLA per unit)
PLA triangle bracket	1.42	20	Cura 3D printer slicing estimate (57g PLA per unit)
Total:	1635.97		

Table J4 includes material cost reductions in terms of money on parts. It is important to note that the reduction was not substantial as the team optimized costs for the current prototype already. However, there were some significant optimizations when sourcing some materials, such as the keyed shaft, from McMaster Carr rather than Grainger. There were cheaper options for building a frame such as welding materials together, but that was found to be unnecessary as the sponsor wanted the option to take the shaker apart. As sourcing cheaper materials did not change the cost of labor for assembly, the cost of assembly stayed the same at \$134.05. This brought the reduced total fixed cost to \$1770.02, around a 2% reduction in cost. An option for increasing longevity and reducing the need for maintenance was to source aluminum brackets to replace the PLA. This increased the cost of the triangle brackets from \$1.42/bracket to \$21.99/bracket and the 3-way bracket from \$2.52/bracket to \$10.99/bracket when sourcing from Amazon.

J.3. Analysis

Break-Even Analysis

The bridge shaker is intended to be a viable tool in engineering work for 10 years. This period was chosen because at that point the research performed with the shaker is completed and the project breaks even according to the break-even analysis, which was performed to determine when the revenue would surpass the cost along with initial startup. The following values were considered in Table J5.

Table J5. Break even analysis conditions.

Break Even Analysis	
Startup Costs	\$4,736.00
Flat Interest Rate	10%
Total Capital Cost	\$5,209.60
Sale Per Unit	\$1,900.00
Cost Per Unit	\$1,801.03
Maintenance Cost Per Unit	\$376.20
Units/Year	10
Profit Per Unit	\$ 98.97
Profit Margin	5%
Years to Break Even	7.7
Profit Per Year	\$ 989.70

These values assumed the shaker had low demand, only producing 10 units a year and requiring yearly maintenance for upkeep. The shaker's price was set at \$1,900, which made about a 5% profit per sale. With these variables the break-even point was determined.

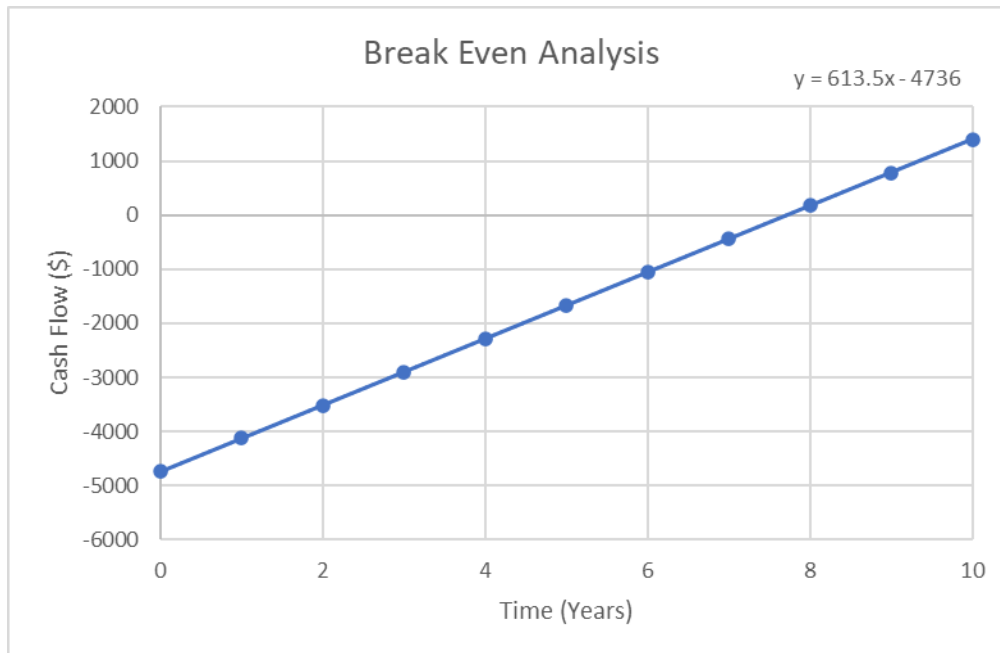


Figure J1. Break-Even Analysis

As shown above in Figure J1, the equation of the trendline was used to estimate the year this project broke even at 7.7 years. This is unfavorable as the use for this project was for short term research applications. The cash flow diagram of this project is shown below in Figure J2, with the initial cost of startup at year 0, and every year, having costs to produce 10 shakers a year. The profits each year come from the sales of 10 shakers each year.

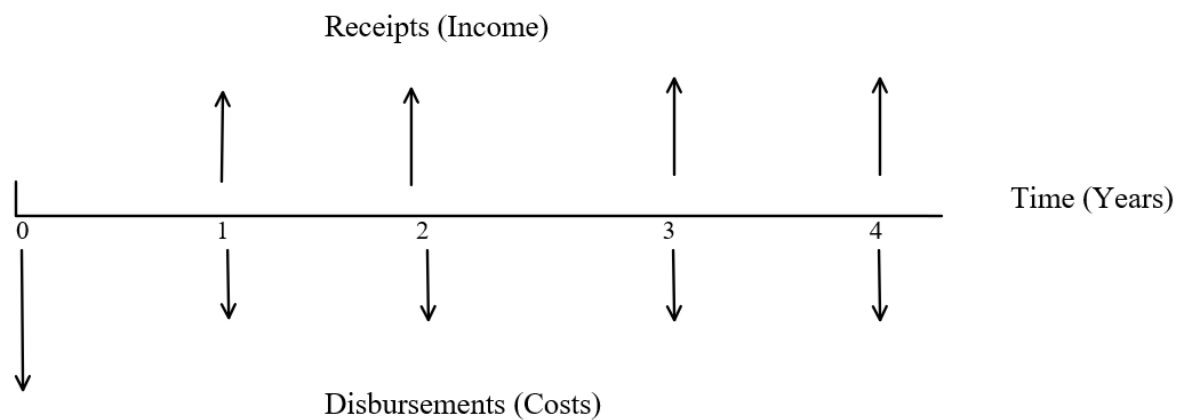


Figure J2. Cash flow diagram

Net Present Value

The Net Present Value represents the difference between the present value of cash inflows and outflows over a specified period. It was used to analyze the profitability of the project over its life cycle/useful lifetime [16]. The equation used to determine the present value for each year is shown below as Equation 11.

$$NPV = \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0$$

Eq - 11

In this equation, NPV is the net present value, t is the period, starting at 0 and stretching over its life cycle until year 10, C_t is the net cash inflow of the period, r is the discount rate, and C_0 is total initial investment cost. To find the discount rate, the NPV equation was set to 0, and the other values were known besides r as shown below in Table J6.

Table J6. Values for the NPV Equation

Variable	Value
t	10
C_t	98.97×10
C_0	4,736
NPV	0

With these variables all known and r unknown, the discount rate was calculated to be 14.5%.

Finally, the NPV was calculated as shown in Table J7 below.

Table J7. NPV Calculation

Net Present Value		
	Project Time (Years)	10
	Discount Rate	14.5%
Year	Present Value	
0	-\$4,736.00	
1	\$5,600.37	
2	\$5,490.91	
3	\$5,395.31	
4	\$5,311.81	
5	\$5,238.89	
6	\$5,294.66	
7	\$5,119.59	
8	\$5,071.01	
9	\$5,028.59	
10	\$4,991.53	
Total Net Present Worth	\$47,806.67	

As shown above, the net present worth of the project was estimated to be \$47,806.67. This was a favorable outcome and held opportunity to be profitable. However, this project is not meant for something to be in mass production. While the sourcing of the parts was relatively easy, the fact of the matter is there is no way of knowing the demand for the product, which has means only to serve the ARTS Lab in conducting experiments dealing with constant impulse-induced vibrations. While there could be universities that would like to fund this and may want to purchase a shaker for these reasons, there is no guarantee that the market would be there. Additionally, the shaker was designed to last for at least 10 years with relatively minimal maintenance besides replacements for parts which are under the greatest stress. Therefore, it is advised to keep this as a small scope project for the purposes of the University and research grants that come in for which this shaker can be used to aid in its development.

J.4. Conclusions and Recommendations

The bridge shaker is expected to be useful for three years until research is completed. A break-even analysis was conducted to determine when revenue would exceed costs by assuming low demand, a production rate of 10 units per year, and yearly maintenance. The shaker was priced at \$1900, resulting in a 5% profit per sale. The break-even point is estimated to be 7.7 years based on the trendline equation.

K. Product Testing

K.1. Introduction

Engineering tests were conducted on the bridge shaker to evaluate its performance with respect to the target and fallback specifications, listed in Table K1. The team consulted the list of priority needs to decide the target and fallback specifications on which to perform engineering testing. It was decided that the vibration data accuracy, system output range, instrument resolution, robustness, weight, and displacement should be assessed. These were chosen because they align with the top seven needs and have specific ranges that are key to the project application. The team decided not to test any of the Boolean specifications as they could not be verified through empirical engineering testing. The tests and their results are outlined in this document.

Table K1. Target and fallback specifications

Metric	Units	Target	Fall Back
Vibration data accuracy	mean % error	2%	6%
System output range	Hz	0-20 Hz	0-15 Hz
Measurement precision	Hz	1 Hz	2 Hz
DAQ	boolean	Yes	Yes
User interface	boolean	Yes	Yes
Usability by others	boolean	Yes	Yes
Adaptability	boolean	Yes	Yes
Product details	boolean	Yes	Yes
Robustness	# failed brackets	0	0
Weight	kg	73 kg	80 kg
Displacement	cm	2 cm	5 cm
Minimally invasive	boolean	Yes	Yes
Economically feasible	\$	< \$1000	< \$2000

K.2. Test Methods

As previously mentioned, the parameters that were examined in this report were vibration data accuracy, system output range, instrument resolution, robustness, weight, and displacement.

There were six simple tests that needed to be performed to ensure that the shaker is in good

working order. The first three tests were concerned with the functional performance of the shaker as a tool for structural excitation. The first of these was to ensure that the shaker was producing accurate vibrations to excite the modal frequencies of whatever bridge or structure it was placed on. The methodology for this test has been laid out below.

I. Test vibration data

- a. Parameter: Mean percent error
- b. Target value, Fallback value: 2%, 6%
- c. Testing Procedure: To verify that the shaker is functioning correctly to test vibration data, one PCB Piezotronics ceramic shear accelerometer and the shaker will be placed onto a pedestrian bridge, and another PCB Piezotronics ceramic shear accelerometer will be placed on the shaker. The accelerometers will report data through an NI DAQ system with an IEPE accelerometer module to LabVIEW. The shaker will be turned on, and the corresponding vibration data will be collected by the accelerometers as time domain amplitude data and will be put into the frequency domain using a Fast Fourier Transform (FFT). This test will only be performed once. The verification test will be considered successful if the accelerometers detect peaks in vibration within 2% of the specified frequency of the shaker.

The second test conducted was to ensure that the shaker operates at a range of frequencies to find the resonance frequencies of the structure. Testing this range from 0-20 Hz was done prior to product handoff. The procedure and explanation follow.

II. Operate at different frequencies

- a. Parameter: Frequency (Hz)
- b. Target value, Fallback value: 0-20 Hz, 0-15 Hz
- c. Testing Procedure: The shaker's output range should conform to the specifications table, which requires it to operate between 0-20 Hz. This range was chosen to ensure that the shaker has the capacity to stimulate lower frequencies that are inherent to a pedestrian bridge, particularly one that is comprised of concrete. The shaker and a PCB Piezotronics ceramic shears accelerometer will be placed onto a pedestrian bridge. A second PCB Piezotronics ceramic shears accelerometer will be placed directly onto the shaker. Once the shaker is activated, data will be read into LabVIEW from both the accelerometer on the bridge as well as the accelerometer on the shaker through a DAQ system equipped with an IEPE accelerometer module. The team will assess the functionality of the shaker once at different frequencies of 5 Hz, 10 Hz, 15 Hz, and 20 Hz, and the accelerometers will be utilized to process the resulting time

domain data with an FFT. The test will be considered successful if the accelerometers read the specified peaks that are output by the shaker.

Thirdly, the shaker's resolution was explored. The shaker was designed so that it could operate closely to the desired frequency. The target specification was 1 Hz, but the group experienced better control than 1 Hz. For this test, the procedure for validating high resolution is explained.

III. Resolution of at least 1 Hz

- a. Parameter: Frequency (Hz)
- b. Target value, Fallback value: ± 1 Hz, ± 2 Hz
- c. Testing Procedure: To test the resolution, the shaker and a PCB Piezotronics ceramic shear accelerometer will be placed on a pedestrian bridge as well as a second accelerometer of the same type on the shaker. As with previous tests, LabVIEW and a DAQ system including an IEPE module will be used to read the data from the accelerometers. The shaker will be set to 10 Hz output and allowed to stabilize at this frequency. The accelerometers will be used to verify that the shaker is at 10 Hz using an FFT on the time domain data. Then, the shaker will be set to 11 Hz and the accelerometer will be used again to verify the frequency. The test will only need to be run once as the shaker's functionality is relatively static. If the measured frequencies match the set frequencies with a difference of 1 Hz, then the test will be deemed successful.

The next three tests focused on the physical structure of the shaker. The first of these centered around the overall weight of the shaker. This test was very simple and required only a scale. The shaker was designed to be easily carried by two people and then have additional weight in the form of sandbags added after the shaker was in place on the bridge. This test was conducted once the shaker was assembled.

IV. Portable

- a. Parameter: Weight (kg)
- b. Target value, Fallback value: 73 kg, 80 kg
- c. Testing procedure: The weight of the shaker must be between 73 and 80 kg, according to the target and fallback specifications table. These specifications are to allow two people to comfortably transport the shaker. The weight of the shaker will be tested using an industrial scale located in the materials test lab. The shaker will be

set on the scale while turned off and the data recorded manually by reading the value, no data processing needed. The shaker will be weighed while turned off because that reflects the state in which it will be transported.

The next test was done before, during, and after any test was performed. The shaker inherently creates forces that strain or loosen the connections holding it together. For this reason, it is vital to the safety of the operators and the device itself that the procedures are followed well. Failures in joints result in negative consequences to the people, shaker, or structure in the surrounding area. The procedures for checking the joints are as follows.

V. Robust

- a. Parameter: # of failed brackets
- b. Target value, Fallback value: 0 brackets, 0 brackets
- c. Testing Procedure: During testing, each of the joints will be inspected to ensure system stability. The frame is what holds everything together, and without it, the entire system could be a potential hazard. The first test will be conducted when the motor is at low speed at 5 Hz, medium speed at 10 Hz, and high speed at 15 Hz. After each test, all joints of the shaker frame and moving parts from the drive train will be inspected, as well as all fasteners to ensure they do not come loose during operation. The target and fallback specification are the same, as there is no number of failed brackets that are acceptable.

Lastly, to ensure that the shaker is transferring as much energy as possible to the bridge or structure, a test was performed after the experimental testing was complete. If the shaker ‘walks’ (as described below), the shaker is less efficient and makes the data collected far less useful. This was another very simple but very important test to the success of the shaker.

VI. Good contact to bridge

- a. Parameter: Displacement in cm
- b. Target value, Fallback value: 2 cm, 5 cm
- c. Testing Procedure: The initial and final position of the shaker after operation must have a difference no greater than 2 cm. The movement of the shaker is considered “walking. “Walking” in this sense is the movement of the shaker in the ‘X,’ ‘Y,’ or ‘Z’ direction. To assess the ‘X’ and ‘Y’ directions, the team will mark the initial position of the shaker on the bridge and then run a test. After the test is completed, the

team can observe the total movement of the shaker over the test with a ruler or calipers. If there is significant ‘walking’ then more weight will be added to the extended legs. To observe the movement in the ‘Z’ direction (vertical in this case), the team will physically observe the shaker and ensure that it is staying down on the bridge. This test does not require data processing.

K.3. Analysis

After completing tests I-III, an FFT was performed on the raw acceleration data read from the accelerometers. For each test, the sampling frequency of 2460 samples/second over a 3 second test yielded 7380 raw data points. Because of this, raw data is not supplied in tabular form, but rather visually displayed in graphical form as time-domain data, shown in figure K1. In the context of vibration testing, FFTs were used to analyze and transform time-domain data, as seen in figure K1, into frequency-domain components, as seen in figures K2-6. This transformation allowed the identification and visualization of the different frequencies of the structure the accelerometers are placed on. The equation for the FFT is:

$$F(k) = \sum_{n=0}^{N-1} f(n) \cdot e^{-2\pi i \cdot k \left(\frac{n}{N}\right)}$$

Eq - 12

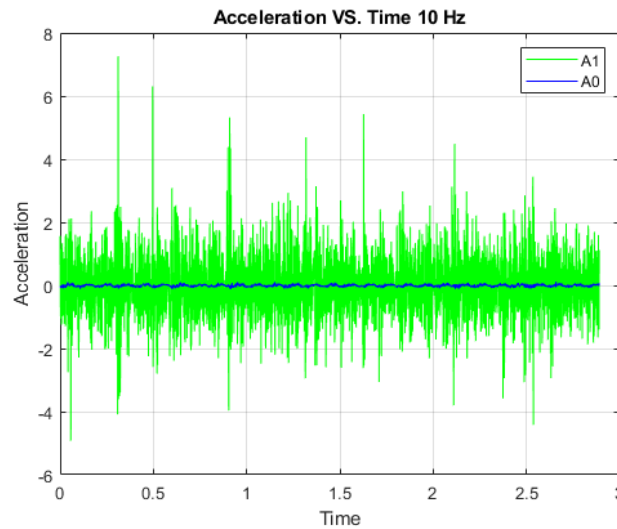


Figure K1. Time-domain data from 10 Hz frequency test.

The time-domain data presented above revealed a large contrast in the levels of excitation measured by the green and blue accelerometers. This was attributed to the positioning of the accelerometers, with the green one placed directly on the shaker and the blue one placed on the bridge. Owing to its proximity to the vibration source, the green accelerometer registered a higher level of acceleration. In contrast, the blue accelerometer measured a lower acceleration as it accounts for the response of the bridge to the induced vibration.

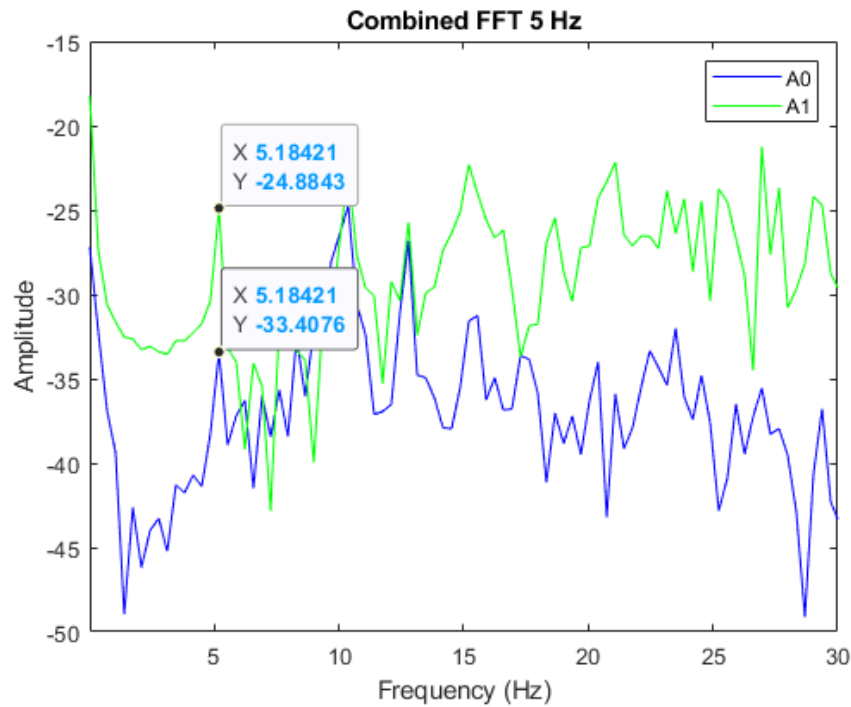


Figure K2. Frequency-domain data from 5 Hz test.

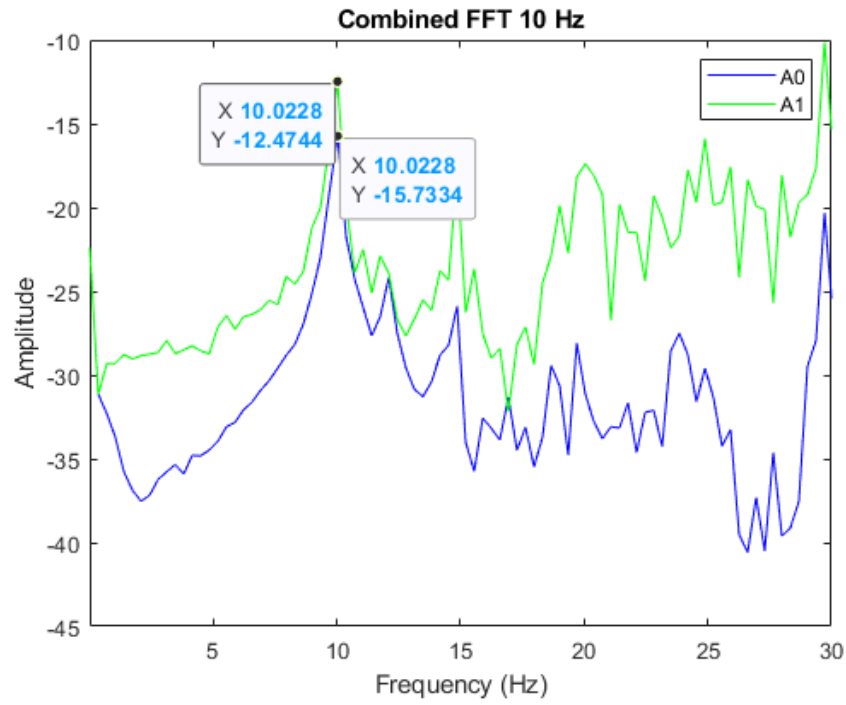


Figure K3. Frequency-domain data from 10 Hz test.

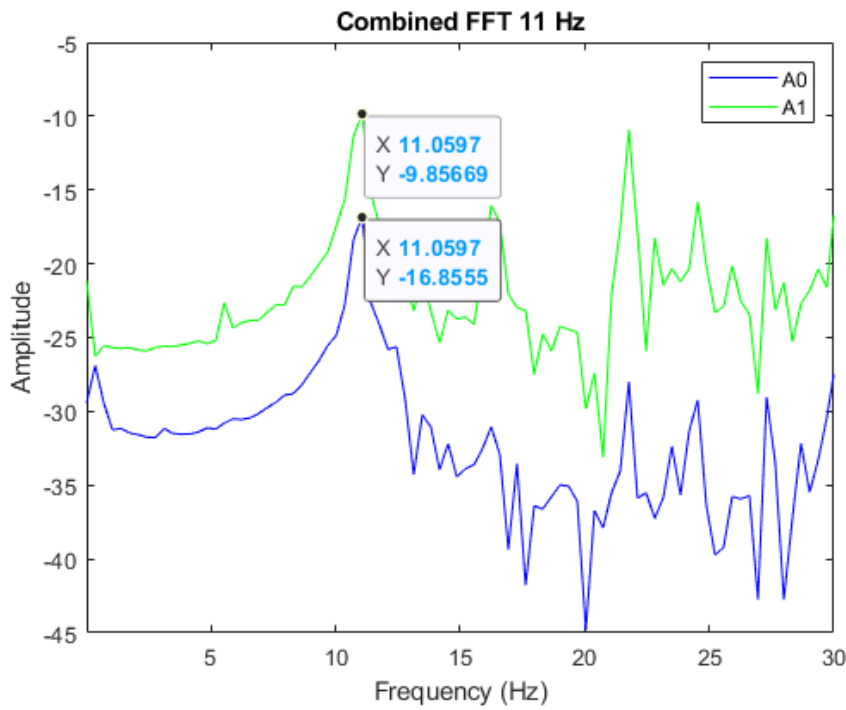


Figure K4. Frequency-domain data from 11 Hz test.

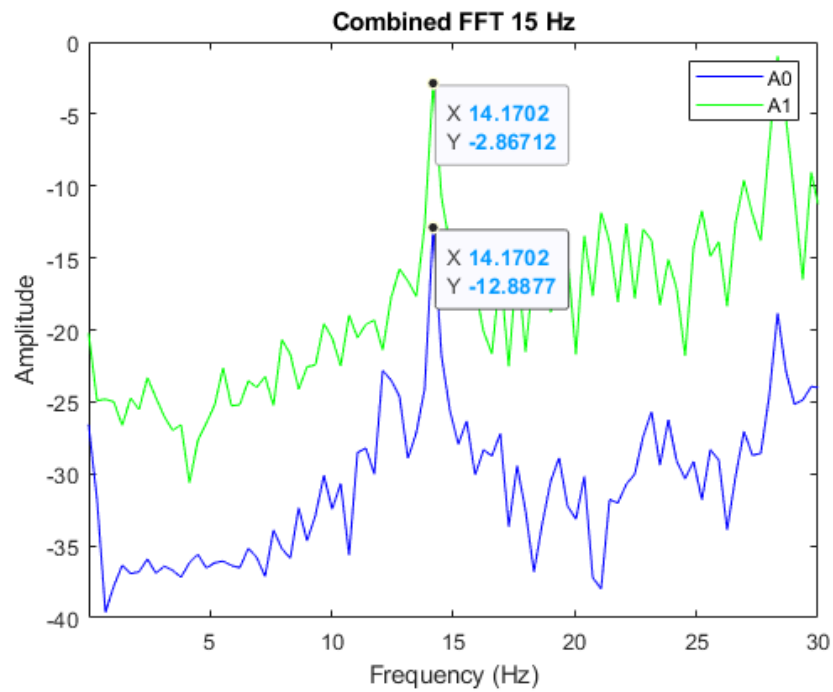


Figure K5. Frequency-domain data from 15 Hz test.

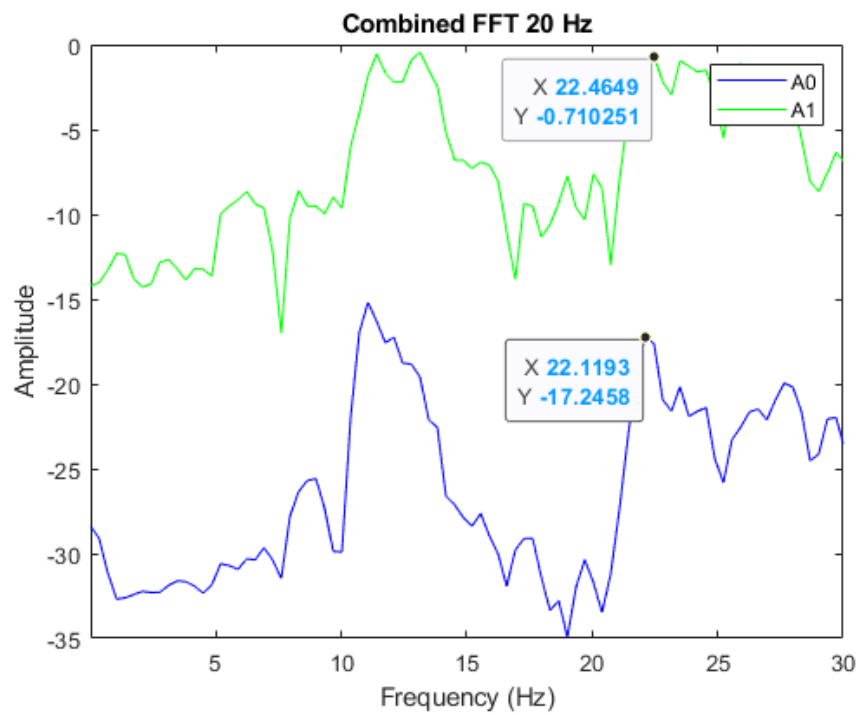


Figure K6. Frequency-domain data from 20 Hz test.

The results presented above demonstrated highly promising outcomes for vibration testing. The tests revealed a remarkably low mean percent error of 5.1923% for the 5, 10, 15, and 20 Hz tests. Particularly impressive were the test results at 10 and 11 Hz, exhibiting percentage errors of 0.228% and 0.543%, respectively. These outcomes were especially encouraging since the predicted first modal frequency of the bridge structure was estimated to occur around 10-11 Hz. As such, these frequencies were anticipated to produce more pronounced vibrations, leading to reduced error in the accelerometer data. With this information, the tests ran were considered acceptable for the final product.

Tests IV-VI were recorded as individual values and are addressed individually in this report. In Test IV for portability, the recorded weight of the shaker was 50 kg, which fell far below the target value. During testing, the shaker was also transported easily with two people, satisfying the portability specification.

Test V for robustness showed that after testing in the higher frequencies, specifically at 20 Hz, multiple brackets were broken by the force of operation. After inspection, it was found that the shaft bearing had deformed from the force of operation, which resulted in the shaft oscillating vertically and inducing unexpected stress on the frame. It was theorized that this stress was what caused the brackets to fail, and the shaft bearings were changed to sturdier zinc die-cast bearings. These bearings did not deform during subsequent testing and the shaft oscillation has not been an issue, reducing the broken bracket count to zero even at high frequencies and satisfying the robustness specification.

Test VI for displacement resulted in a 19 cm displacement in the Y direction when the shaker was operated at 20 Hz, far above the 5 cm fallback value. This issue was due to too little weight holding the shaker down during operation, resulting in poor contact to the bridge. It has

been addressed by adding additional sandbags on the shaker periphery, which has eliminated the displacement issue and satisfied the testing requirements. In the final design, supports were added to place sandbags on top of the shaker directly above the linear weight to optimize energy transfer and reduce required supplemental weight.

K.4. Conclusions/Recommendations

Table K2. Engineering test results compared to target and fallback specifications.

Parameter	Target value	Fallback value	Measured performance	Satisfactory? (Y/N)
Vibration Data Accuracy	2%	6%	0.228%	Y
System Output Range	0-20 Hz	0-15 Hz	0-15 Hz	Y
Measurement Precision	1 Hz	2 Hz	1.037 Hz	Y
Portability	73 kg	80 kg	50 kg	Y
Robust	0 Failed Brackets	0 Failed Brackets	1+ Failed Brackets	N
Displacement	2 cm	5 cm	19 cm	N

As shown in Table K2, the tests for vibration data accuracy, system output range, instrument resolution, robustness, weight, and displacement were performed and mostly satisfied the target/fallback specifications. The Boolean parameters were not tested because they corresponded to lower priority needs and were not suited for engineering performance tests. The vibration data accuracy tests ensured that the data collected lacked significant error, with a measured performance of 0.288% that satisfies the target value. The system output range test displayed the viable frequency range, which was shown to be 0-15 Hz and within the fallback specification. The measurement precision test was performed to ensure the frequency of the shaker had a resolution of 1-2 Hz, which satisfied the fallback value at 1.037 Hz. The portability of the shaker was tested based on the shaker's weight, which was easy to carry for two people. The total

weight of the shaker was measured to be 50 kg, very far below the target specification. The robustness of the shaker was also quantified by the number of brackets broken during operation. During testing, the shaker broke several 3D printed brackets at high frequencies. Optimally, the shaker breaks no brackets, and this problem was solved by switching out the shaft bearings and opting for metal brackets. The displacement of the shaker was measured to assess unwanted movement while shaking. During testing, it moved 19 cm, and additional weight was added to address the issue and satisfy the displacement specification. At this point, the product is not yet satisfactory. While the 3D printed brackets have been replaced with much sturdier metal brackets that have not failed, the distance of the shaker traveling during operation is being solved by adding a design that allows sandbags to sit on top of the frame, better securing it to the bridge. Moving forward, the team will continue to experiment with supplemental weight to decrease the shaker's displacement. Additionally, the team is increasing the product safety by adding expanded steel on the top to prevent injury.

L. Final Design

L.1. Introduction

The final design is based on the selected concept in section E.4. and is the product of many iterations based on results from engineering testing in section K, manufacturability in section H, and most importantly sponsor feedback throughout the design process. It seeks to satisfy all needs and specifications outlined in sections B and C. The design process and development process merge to create a bridge shaker that tests vibration data, operates at different frequencies, is safe to operate, and leaves the bridge undamaged.

L.2. Final Design

The final design is housed in a frame composed of 8020 40 series aluminum held together with metal triangle brackets and mending plates. The system is powered by 110V single phase AC, which can be supplied from a wall outlet, to the variable frequency drive (VFD) that steps up the voltage to 220V three phase AC. The VFD is encased in a grounded electronics closure with shielded 3 and 4 conductor wires fed through strain relief conduit fittings. A 20 tooth pinion drives a 40 tooth gear connected to a steel shaft through a chain, which quarters the input frequency from the VFD. Pillow block bearings support the shaft at two points from below. The gear is on the same shaft as a 4 in gear that is part of a crank slide mechanism connected to a rectangular 7 kg weight that oscillates linearly. Two SBR16 guide rails and ball bearing sliders attach to the weight to constrain its motion and reduce friction during vertical movement.

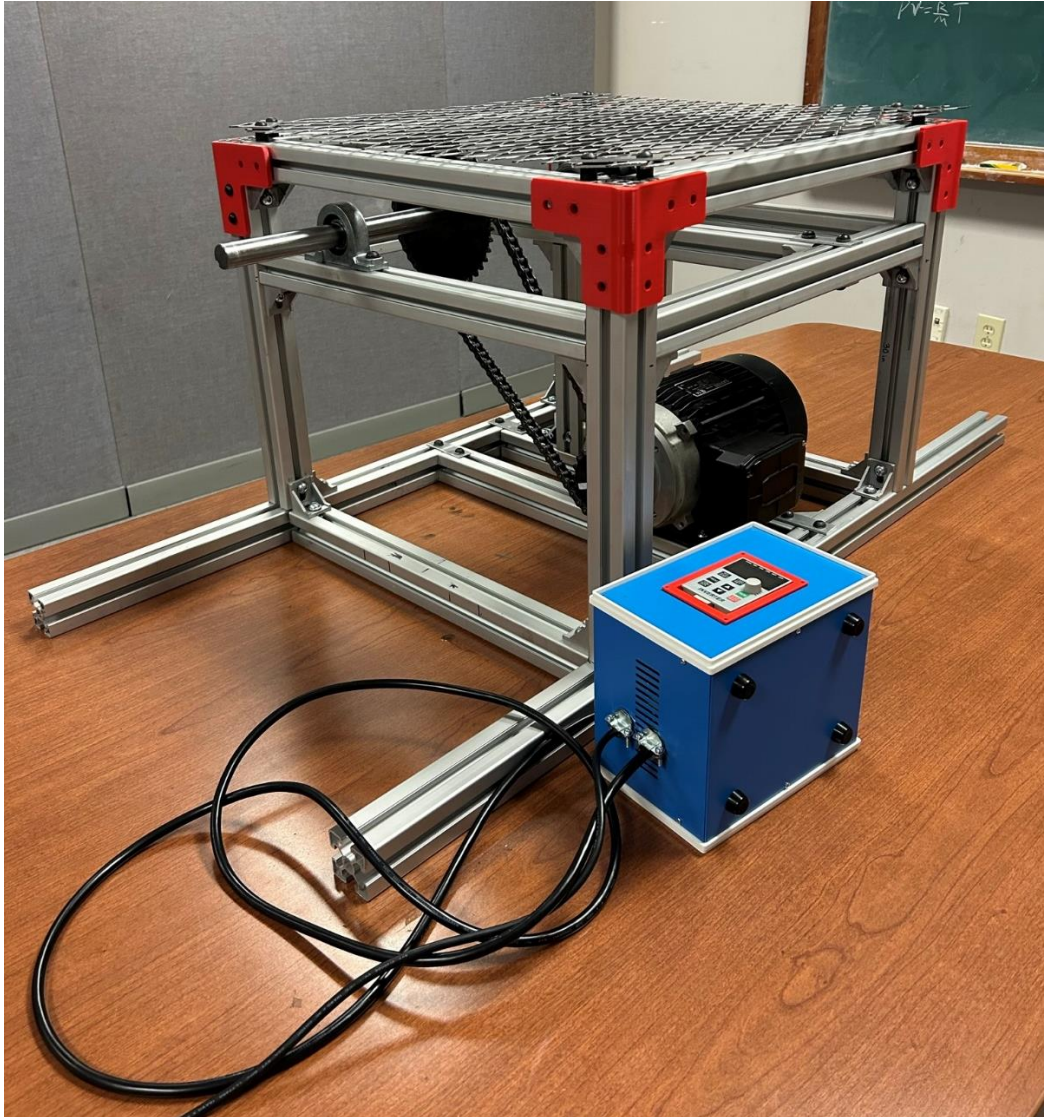


Figure L1. Final design of the bridge shaker.

Figure L1 shows the final design of the bridge shaker. The final design excites structures by converting rotational motion into linear motion via the gear train. The AC motor is controlled by the user through the VFD, which rotates the gear train, whose gear ratio can be varied depending on the structural application. The gear train rotates the shaft to power the crank slide mechanism and linearly actuates the weight along the vertical guide rails. The frequency of the linear weight, rather than the pinion or gear, is the frequency at which the structure is excited.

L.3. Final Bill of Materials

The bill of materials for the final design can be found in table L1.

Table L1. Final bill of materials.

Materials			
Description	Cost (USD)	Quantity	Supplier
3 Phase AC Motor	705.18	1	Grainger
Industrial Chain	29.55	1	Grainger
Shaft pinion, 4"	40.00	2	Grainger
Motor gear, 8"	64.58	1	Grainger
Keyed Shaft: 1 in Dia, Aluminum	52.63	1	Grainger
Aluminum 80/20 40 series, 1 ft	15.44	18	Grainger
Metal brackets	1.10	28	Amazon
SBR16 guide rail and bearing	22.50	2	eBay
Weight linkage rod end	11.71	2	Grainger
Expanded steel, 2' x 2'	41.54	1	Grainger
Zinc die-cast shaft bearing	60.91	2	Grainger
Extension cord	25.98	1	Bill of materials
Weight, aluminum 7 kg	9.89	1	Grainger
80/20 40 series fasteners	1.54	100	McMaster Carr
VFD, 230 Volts, 1 to 3 Phase	118.84	1	Amazon
Electronics enclosure 12.6" x 10.6" x 4.7"	32.99	1	Amazon
Wiring, 10'	20.99	1	Amazon
Conduit fittings	7.99	1 4-pack	Amazon
Total:	1842.12		

M. Conclusions

M.1. Summary

The aim of this project is to provide a bridge shaker that tests vibration data, operates at different frequencies, is safe to operate, and leaves the bridge undamaged. The shaker was designed with a list of needs and specifications from the sponsor, outlined in sections B and C. These metrics were used to generate five concepts, of which one was selected to become the project design. This selected concept has become the final design of the product, which underwent engineering analysis, design evaluation, economic assessment, and engineering testing. These examinations were designed and conducted with respect to the sponsor's needs and specifications in order to evaluate the efficacy of the product for the sponsor's goal. Table M1 organizes the specifications and their complementary needs and the outcomes of the various product evaluations.

Based on the data collected throughout the project design and testing phases, the current product satisfies all but two target specifications and five needs. These two target specifications, robustness and displacement, have been discussed in depth in section K.4., and their corresponding needs are needs to be robust (4), needs to be easily repairable (22), needs to withstand the stress of operation (24), needs to have high efficiency (14), and needs to have good contact to the bridge (15). Each of these target specifications and needs have been addressed as discussed in section K.4. Once implemented, the product will be satisfactory for the sponsor as all other product specifications and needs have been met.

Table M1. Product performance ratings for each product specification and need.

Product specification	Customer need # (reference section B)	Target value	Fallback value	Measured performance	Satisfactory? (Y/N)
Vibration Data Accuracy	1, 13, 30, 31	2%	6%	0.228%	Y
System Output Range	2, 3, 27	0-20 Hz	0-15 Hz	0-15 Hz	Y
Measurement Precision	19, 28	1 Hz	2 Hz	1.037 Hz	Y
DAQ	25	Present	Present	Present	Y
User interface	8, 10, 12, 20, 36	Present	Present	Present	Y
Usability by others	5, 8, 21, 33, 34, 35	Present	Present	Present	Y
Adaptability	6, 11	Present	Present	Present	Y
Product details	32, 33	Present	Present	Present (GitHub repository)	Y
Robust	4, 22, 24	0 Failed Brackets	0 Failed Brackets	1+ Failed Brackets	N
Weight	7, 18	73 kg	80 kg	50 kg	Y
Displacement	14, 15	2 cm	5 cm	19 cm	N
Minimally invasive	9, 16, 17, 26	Present	Present	Present	Y
Economically feasible	23, 29	<\$1000	<\$2000	1842.12	Y

M.2. Standards

Tables M2a and M2b summarize the relevant and applicable industry standards that the bridge shaker must satisfy. The standards are primarily compliant with OSHA guidelines, and the features addressed are the mechanical and temperature standards, addressed in Table M2a, and electrical standards, addressed in Table M2b.

Table M2a. Relevant mechanical and temperature standards.

Organization	Applicable standard	Product feature satisfying this standard
OSHA	1917.151(h)(2) Belt, rope, and chain drives shall be guarded to prevent employees from coming into contact with moving parts.	Expanded steel protecting from hands being inserted through the top of the shaker
OSHA	1910.212(b) requires machines designed for a fixed location to be securely anchored to prevent walking or moving.	The shaker weight is increased with sand bags to prevent the machine from “walking” or moving during operation, especially under high frequency outputs.
OSHA	1926.403(b)(1)(ii) Mechanical strength and durability, including, for parts designed to enclose and protect other equipment, the adequacy of the protection thus provided.	The shaker frame holds all moving parts together firmly to prevent excess noise in gathering data during testing. It also is held together with metal brackets and m8 hammer nuts and screws which are fastened to hold everything firmly together under maximum output from the motor. Further support beams are also used to prevent shearing of brackets and warping of the extruded aluminum and bearings under stress during operation.
OSHA	1926.403(b)(1)(iv) Heating effects under conditions of use.	The motor has been tested under ~85 deg F heat and did not show any signs of overheating. It is an open system and the natural convection from surrounding air does a sufficient job at cooling the motor. The VFD also produces heat, and in its housing is encased a fan which provides adequate air flow to the internals of the circuitry.
OSHA	926.403(d)(2) Cooling. Electrical equipment which depends upon the natural circulation of air and convection principles for cooling of exposed surfaces shall be installed so that room air flow over such surfaces is not prevented by walls or by adjacent installed equipment. For equipment designed for floor mounting, clearance between top surfaces and adjacent surfaces shall be provided to dissipate rising warm air. Electrical equipment provided with ventilating openings shall be installed so that walls or other obstructions do not prevent the free circulation of air through the equipment.	The motor has been tested under ~85 deg F heat and did not show any signs of overheating. It is an open system and the natural convection from surrounding air does a sufficient job at cooling the motor.

Table M2b. Relevant electrical safety standards.

Organization	Applicable Standard	Product feature satisfying this standard
OSHA	1910.304(a)(1)(ii) A conductor used as an equipment grounding conductor shall be identifiable and distinguishable from all other conductors.	A distinguishable ground screw in the 3-phase motor is used as a grounding conductor
OSHA	1910.303(b)(1) Examination. Electric equipment shall be free from recognized hazards that are likely to cause death or serious physical harm to employees. Safety of equipment shall be determined using the following considerations:	The shaker will not be used in wet conditions, and has heat shrink insulation on all connections to VFD. Motor electrical box is shielded with a screw-fastened plate to prevent risk of high voltage shock.
OSHA	An electrical conductor splice connection point must be guarded by approved cabinets or other forms of approved enclosures or by any of the means required under paragraph 1910.303(g)(2)	The shaker has a junction box encapsulating the VFD and motor wiring connections.
OSHA	1926.403(g) Marking. Electrical equipment shall not be used unless the manufacturer's name, trademark, or other descriptive marking by which the organization responsible for the product may be identified is placed on the equipment and unless other markings are provided giving voltage, current, wattage, or other ratings, as necessary. The marking shall be of sufficient durability to withstand the environment involved.	The motor and VFD are both marked and labeled, with the motor having an electrical diagram and ratings engraved on the side, and the VFD having labeled connections which can be deciphered with its manual.
OSHA	1926.403(b)(1)(vi) Classification by type, size, voltage, current capacity, specific use.	All wires and components are designed to withstand the current and voltage which are to be applied to the system.
OSHA	1926.403(b)(1)(iii) Electrical insulation.	All wires which are exposed to the environment are covered with a double layer of insulation. One which wraps each individual wire, and one which wraps all insulated wires together, preventing avenues of failure and risk of electric shock. Wires which are not double insulated are protected inside junction boxes on the motor and the VFD.

M.3. Future Work

The product currently satisfies most of the needs and specifications outlined in sections B and C. Modifications have been performed to address the issues of printed brackets and deformed shaft bearings, as well as insufficient shaker weight during operation. It is recommended that these modifications undergo formal engineering testing before the product is considered satisfactory and ready for commercialization.

To further address these issues, it is posited that replacing the current 8020 40 series and metal brackets with a welded frame will enhance the robustness of the shaker. If the shaker were to be

manufactured and sold for a profit, welding would yield a product that is more shelf-ready and able to increase the frequency range to excited higher modes. Additionally, to increase the safety of the structure, the expanded steel on top of the frame may be added on the sides of the frame as well.

The presented concept for the bridge shaker is novel, as many mass shakers use a rotating offset weight rather than a linear weight driven by a gear train to excite structures. The use of a gear train allows for customization on the user's end to reach different frequencies. For example, the shaker in this work originally had a gear ratio of 1:2, which doubled the input frequency on the VFD and allowed for a maximum theoretical frequency of 130 Hz, but was only able to output ~5Hz on the lower bound. The gear ratio presented in the current configuration in section L has a gear ratio of 4:1, which quarters the input frequency on the VFD and allows for a maximum theoretical frequency of 16 Hz and a minimum frequency of ~0.5 Hz. This ability to modify the gear ratio allows the design to be used for a wide range of structures and at several different modes.

M.4. Lessons Learned

Throughout the design process, it was discovered that 3D printed brackets did not provide the support needed for a vibration generator. All triangle brackets on the shaker were once 3D printed triangle brackets, which would easily fail along the layer lines of the print. The energy requirements of the shaker necessitated the use of robust metal brackets, though 3D printed brackets may be possible if the shaker is intended solely for low frequency applications.

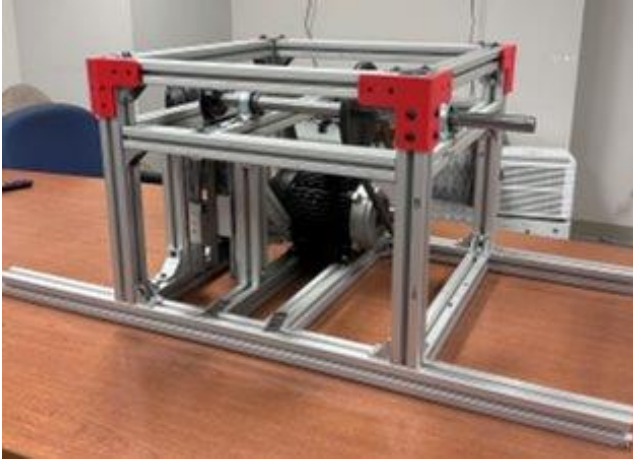
The influence of weight on energy transfer was also emphasized during the project. The failures experienced during the displacement testing illuminated the importance of weight distribution in providing good contact to the bridge. After learning this, the addition of the expanded steel and support beam allows stabilizing weight to be placed directly above the linear weight, optimizing energy transfer.

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O. Appendix



GitHub Link: <https://github.com/ARTS-Laboratory/Bridge-Shaker>