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MEMS 411: St. Louis Science Center Vibration Station

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SP21 MEMS 411 Mechanical Engineering Design Project

Vibration Station

The St. Louis Science Center thrives on curiosity, where the science museum grants the ability for individuals of all ages to immerse themselves in a variety of science and technological topics ranging from dinosaurs to engineering. Every year, the St. Louis Science Center holds an expo for local engineers and scientists to exhibit properties of his or her studies to inspire young children and get them interested in science and technology.

This year, the Vibration Station was developed to show the physical properties of vibrations through that of how tension on a string affects the frequency, pitch, and musical note emitted when a string is plucked, such as the guitar. Taking inspiration from that very instrument, a design was formed that allowed a user to adjust tension in a string and pluck it, as well as change the physical volume of the interior of the vibration station, all while outputting both the tension force of the string and corresponding frequency.

The design itself is a box constructed almost entirely out of birch plywood that features two drawers to adjust the physical volume of the box. Additionally, on the top surface, a string is put into tension, where the tension force and frequency is continuously being measured and calculated, respectively, and outputted onto a screen to visualize what is happening when the Vibration Station is being manipulated. The initial redesign from the prototype in essence served as a way to fine tune the design, as no major changes occurred, though the final design will feature safety features such as a plexiglass shield that was not present on the original prototype.

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1 Introduction

The St. Louis Science Center in St. Louis, MO thrives on curiosity. The science museum grants people the ability to experience science and technology through imagination, innovation, and engagement. With discovery topics ranging from space science to dinosaurs to engineering, the center is filled with demonstrations and learning experiences for all [1]. Previously, the St. Louis Science Center has held a guitar exhibit where visitors were able to experience the science and history behind the guitar. This exhibit has since ended [2].

The strings on a guitar resonate on the wood creating a vibration which is transmitted through the hollow body of the guitar. The pitch the string produces depends on the mass, tension, and length of the string. If a string has a higher mass than another, the heavier string will vibrate slower. The frequency of the string is altered through the tension of the string. A string under tight tension will play a higher pitch. Beyond the string, the body of the instrument and the air inside is important in the science of the guitar [3][4].

Through the science of music, the goal is to design a demonstration based on vibration principles in engineering through a musical string instrument. The demonstration will provide users an opportunity to interact with the device while learning how an instrument provides sound through vibrations.

2 Problem Understanding

In the design process, researching existing devices as well as applicable codes and standards aid in understanding the problem. An interview with the customer develops an appreciation of the customer wants and needs are. With a clear understanding and the wants and needs of the customer taken into consideration, a more thorough design can be developed. The results are presented in this section.

2.1 Existing Devices

Three existing devices were researched to gain inspiration and knowledge for the design and are presented below. The demo will provide users an opportunity to learn more about sound through vibrations and physics. Musical instruments are great examples of already existing devices that produce sound. Thus, this section describes instruments and sound analyzing equipment to help inspire our design.

2.1.1 Existing Device #1: Acoustic Guitar

Figure 1 below depicts an acoustic guitar with an exploded view labeling each part to the left.

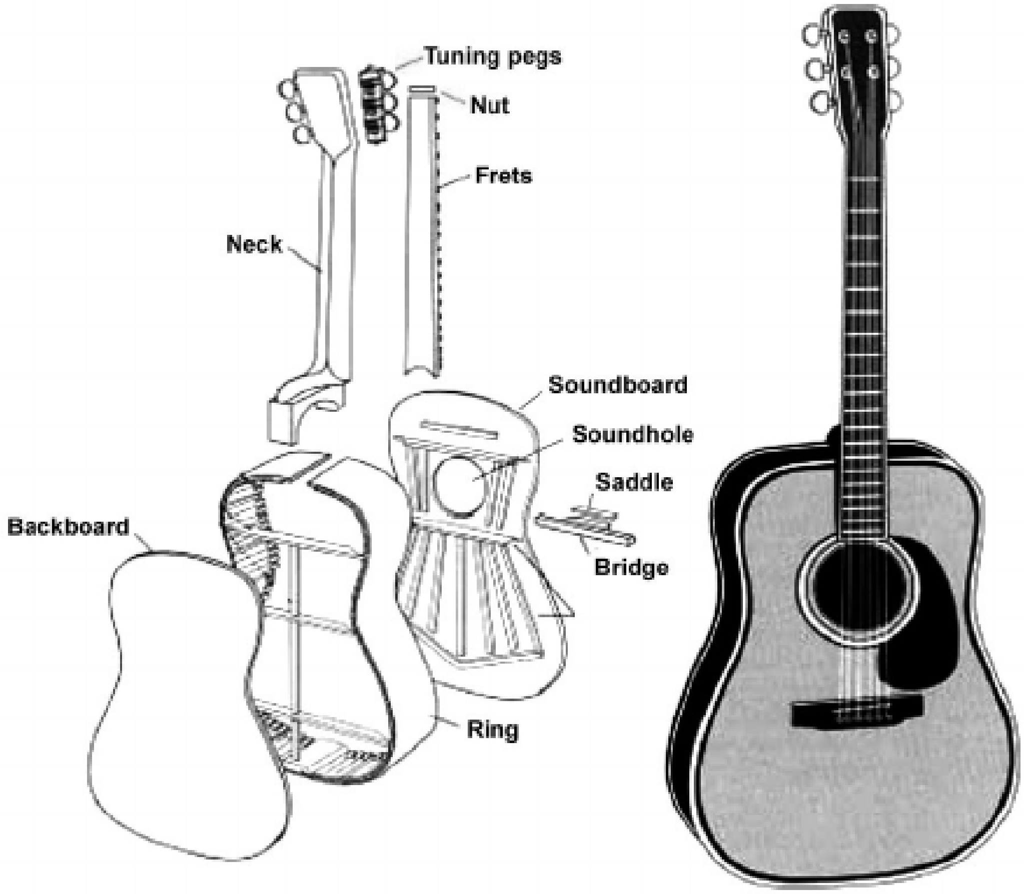


Figure 1: Acoustic Guitar [5]

Link: https://www.researchgate.net/figure/Parts-of-the-acoustic-guitar_fig2_266411382
Description: The acoustic guitar is an musical instrument with six strings and a hollow body made of wood. The top face of the body just below the strings is made of a flexible wood to resonate the sound of the notes [6]. The six strings are made of various masses and density's to produce different frequency's. The strings are attached to the body, extend over a small circular hole and up along the neck and are attached to tuning knobs. Clearly sectioned distances, called frets, along the neck indicate locations where the strings can be pressed to play multiples of the fundamental frequency that the string is originally tuned to [6]. Shortening the string increases the frequency. The frequency can also be changed by adjusting the tuning knobs and thus the tension of the string. The hole in the body located below the strings allows the pressure within the volume change, causing the air to oscillate and reverberate the sound. All aspects of the guitar including shape, tension of the strings and sound hole combined allow the instrument to produce sound.

2.1.2 Existing Device #2: Dan Bau

Figure 2 below depicts the ancient victimize instrument called a Dan Bau translated directly to "string guard" in English.

Figure 2: Dan Bau [7]

Link: https://ethnictune.com/shop/dan-bau-pro-with-mother-of-pearl-inlays/
Description: The Dan Bau is a single stringed Vietnamese musical instrument. The simple instrument has long hollow body made of wood and one string spanning the length. The string is attached to a flexible rod that can be pulled to slightly adjust the tension of the string, and the other end is tied to a tuning peg. The string is typically tuned to middle C but uses the tension of the string to play various overtones and harmony's. The sound resonates through the long body of the gourd allowing the sound to be amplified. When played, the flexible rod is pushed or pulled to adjust the frequency of the note. The notes are also shortened or dampened by pressing on the string at different distances along the body.

2.1.3 Existing Device #3: Digital Oscilloscope

Figure 3 below depicts a oscilloscope with a digital display of the frequency input signals.

Figure 3: Digital Oscilloscope [8]

Link: https://www.tequipment.net/Rohde-&-Schwarz/RTB2K-204/Digital-Oscilloscopes/
Description: A digital oscilloscope is a machine that can read and display frequency signals. Digital oscilloscopes display a frequency wave read from sensors and converted to analog voltage. They intake amplified data a set sampling rate that is passed through a microprocessor and displayed digitally in semi-real time [8]. Digital oscilloscopes can be used to measure vibrations from an acoustic devise such as a guitar or other instrument that resonates sound. Most oscilloscopes use the Fast Fourier Transform method to convert the input to a frequency wave.

2.2 Patents

Two patents are presented in this section that are relevant to our project. Patents were researched to determine designs that already exist and are protected under law. Alternatively, patents were researched for design purposes to gather ideas without infringing on the law. The Vibration Station will have a tuning head on the device where the user will be allowed to tune the string or strings. Thus, a patent pertaining to tuning was discovered and thoroughly researched. The additional patent in this section provides an idea of how to design the demo to change volume.

2.2.1 Guitar string tuning system (US5696341A)

Guitar strings often break or need to be tuned to the correct frequency. Patent US5696341A covers a specific tuning knob and system to tune a stringed instrument. The knob presented in the patent has a place for a crank to assist in turning the knob to tune. It is cylindrical in shape with knurls on the outside to provide grip if the user prefers to hand tune the guitar. Figure 4 The knob and crank are in an aftermarket kit that contains all of the pieces needed for attachment to a guitar and/or guitar tuning stem.

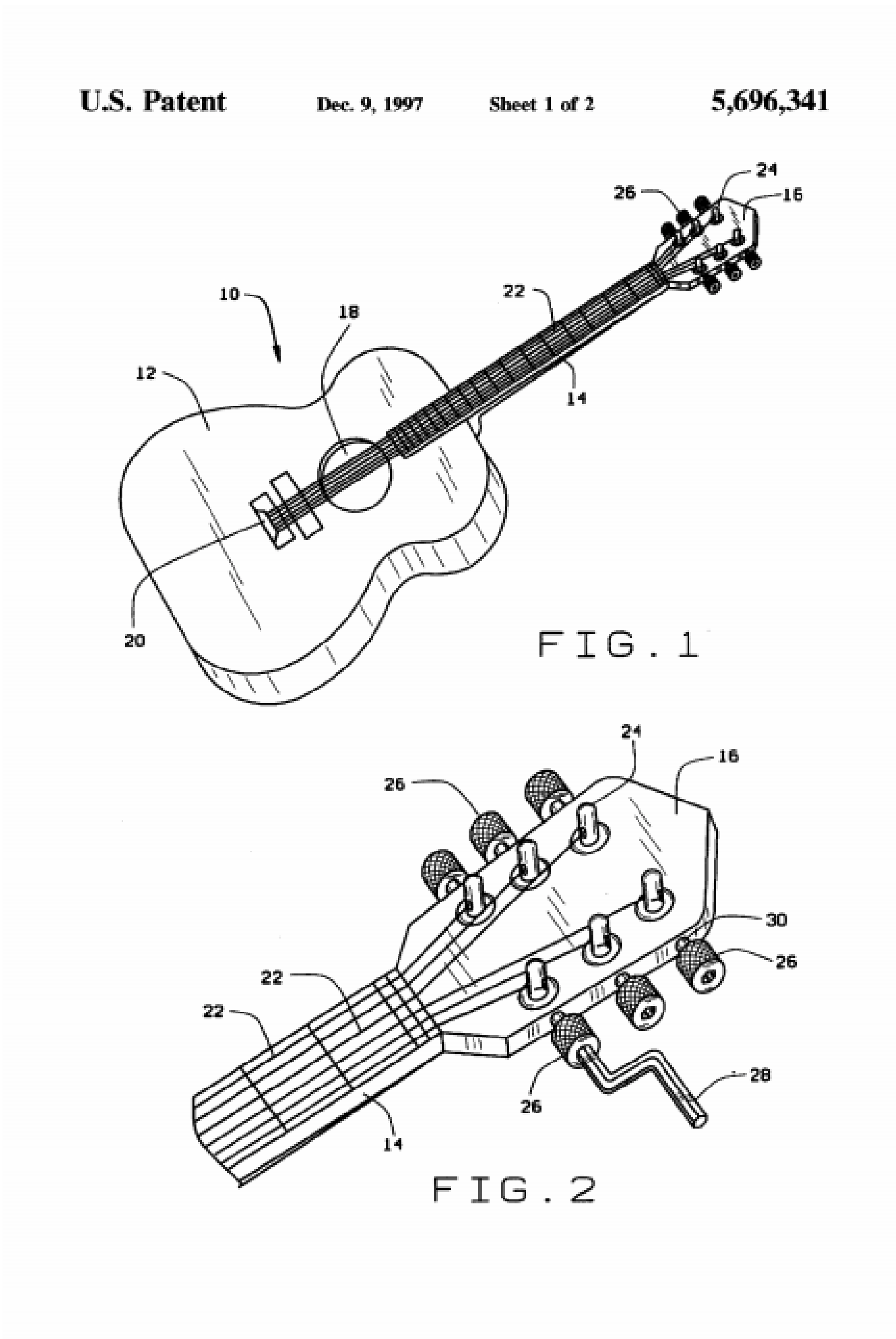


Figure 4: Patent Image for Guitar tuning system

2.2.2 Variable volume multi-species bird house (US6170437B1)

Patent US6170437B1 is a bird house that consists of panels to freely change the height, width, and breadth of the house as shown in Fig. 5 and 6. This allows for various species of birds to nest comfortably in the bird house without it being too small or large. This patent could come pertinent to our design as the volume of the device will be variable. The volume changing technology present in this patent is great design inspiration for our demo.

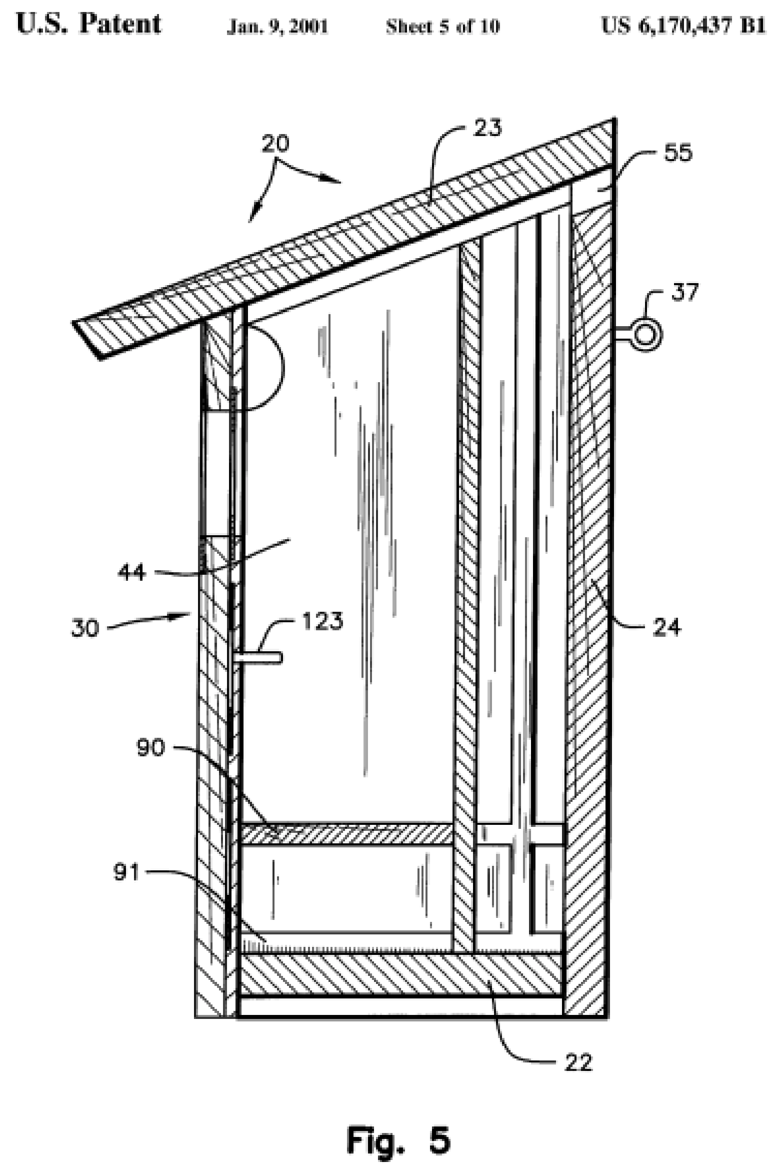


Figure 5: Patent Images for Variable volume multi-species bird house

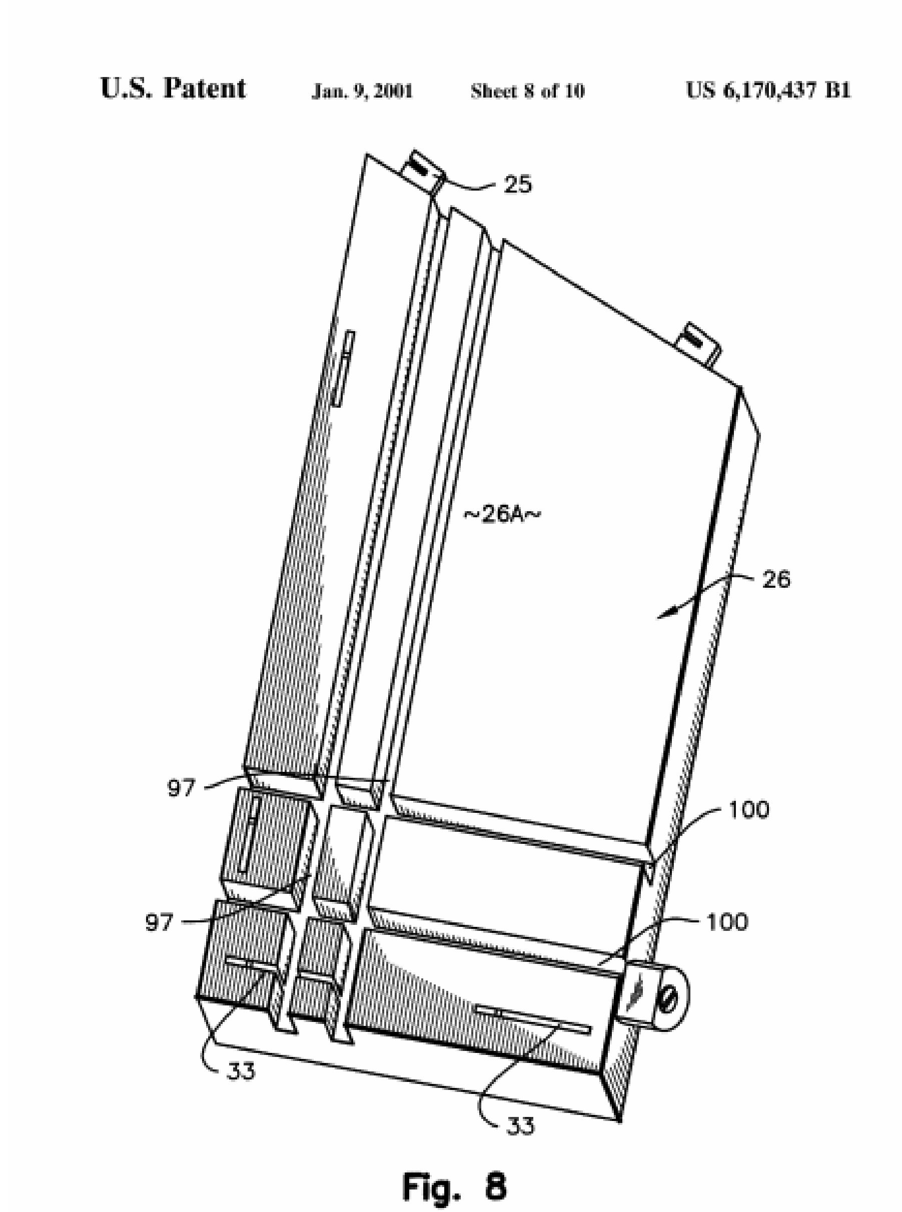


Figure 6: Patent Images for Variable volume multi-species bird house

2.3 Codes & Standards

In this section, standards applicable to the breadth of this project are presented. Codes and standards provide guidelines, constraints, and specifications to ensure proper development, testing, and safety of goods and services. This design will be interactive and displayed at the St. Louis Science Center where people of all ages will be able to interact with the demo. Thus, safety is of extreme importance. In addition, the design will include musical instrument parts, including the strings. It is critical to understand any specifications or guidelines for these parts.

2.3.1 Steel Wire, Music Spring Quality (ASTM A228)

ASTM International has a standard pertaining to the manufacturing of music spring quality wire (ASTM A228). This standard contains several sections detailing the specifications in which high quality, round, cold-drawn steel music spring quality wire undergo with regards to high stresses and good fatigue properties. By using the sections in this thread, an appropriate wire can be selected to perform vibrational analysis on, while still maintaining the longevity of the wire, as well as the safety of the users around.

2.3.2 Safety of Toys (ISO 8214)

The International Standard Organization has a standard pertaining to the safety of toys (ISO 8214). This standard contains several sections which provide specifications regarding the safety of mechanical toys as well as guidelines governing the appropriate age range for the toy. The demonstration will be in the St. Louis Science Center where children will be able to interact with the demonstration. By using the sections in this standard, a proper age range can be determined and applicable warning labels and hazards can be displayed. While designing the demo, this safety standard will need to be closely adhered to to ensure a safe demo for children is developed.

2.4 User Needs

A remote interview was conducted with a representative of the St. Louis Science Center. The demo is designed to introduce simple concepts of vibrations and physics to a variety of individuals, mainly tailored to children above the age of six. The design required that is was safe for all ages, in addition to being engaging and interactive with those children six years or older. Emphasis was placed on the string used to conduct vibrational analysis to be well protected, as to limit the possibility of breaking under tension. Additionally, the 'Vibration Station' should mimic the appearance of a guitar to promote interaction with the design. The goal of the design is to make it engaging, while limiting the chance of injury due to a string breaking under tension.

2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Remote
Date: February 4^{th}, 2021
Setting: We engaged in a detailed interview, inquiring mainly on the parameters of the actual demo itself, as well as solidify what the Demo would focus on. The whole interview was conducted remotely via Zoom, and took ~50 min.

Interview Notes:
Would the product be nailed to a wall or sitting on a table?

- Sitting on a table is okay for now, always easier to nail something to a wall after.

What are the ages of the children interacting with the Demos at the Science Center?

- Kids of all ages will be at the Science Center, though children age 7-8 and parents/guardians will be the likely demographic. Ensure that the Demo itself is not too tall for the children

What is your biggest safety concern regarding the Vibration Station?

– Pinch Hazards mainly for your Demo. Other notable hazards such as sharp edges, sharp points, high temperatures, and strings breaking.

How many adjustable parts should the children have access to?

– Two, with focus on an actual plucking of the guitar, as well as adjustments for the tension in the string. Make sure to limit exposure to the rest of the body of the vibration station, and just direct attention to your two variables being adjusted.

How long should the Demo explanation take prior to use?

– Assume that the children will not read the instructions. In most cases, the user will watch another user manipulate the controls, and be inspired to interact with the controls themselves. The action of the thing itself should be more interesting in an effort to promote supplementary reading.

How long should the Demo last with respect to maintaining the design (How Durable)?

– No need to worry about durability at this point. Additionally, do not prioritize portability.

How long should the demo last with respect to the children interacting with the design?

– This varies so much with who is playing with the it. I would assume most are 10 to 30 seconds.

What size constraints are there, if any?

– None, there is lots of space. Don't make the design too big or too small. The size of an acoustic guitar is probably ideal.

How many strings should be on the design?

– Though a guitar has 6 strings, I would find the analysis on one string much more interesting.

How easy should the Demo be to transport?

– Not a high priority, but portable enough so that it can work in a variety of locations. Think of that from a manufactures perspective.

What features would you liked to see?

– Emphasize the "guitarness" so that people will want to interact with it based soley on the fact that it looks like a guitar.

What specification would you not compromise on?

– Make sure that string is mostly covered up by something for safety. Minimize the risk of the string breaking itself. Also make sure that there is a shield between the user and the string.

2.4.2 Interpreted User Needs

Through the interview with Dr. Jackson Potter, a table of interpreted customer needs was generated. The importance of these needs were rated on a scale from 1 to 5 with 5 being the highest need. Table 1 below describes the needs and their respective rankings.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The VS is intuitive and easy to use with little instruction/guidance.	4
2	The VS is safe for all ages	5
3	The VS is engaging for ages 6+ and keeps an attention span for at least 10 to 30 seconds	3
4	The VS tuning mechanism contains a stop to ensure string safety.	4
5	The VS contains an attractive digital display output of the sound and it's vibrational characteristics	4
6	The VS has at least one string that is tunable.	3
7	The VS features at least 2 interactive aspects	4
8	The VS is at least the size of an acoustic guitar	3

2.5 Design Metrics

Based on the interpreted customer needs in Table 1, specific design metrics generated to address each of the needs presented. The metrics are presented below in Table 2 along with ideal and minimum acceptable specifications for each.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	9	Total weight	kg	1.5	3
2	1	Maximum Tension of String	N	75	70
3	6	Number of strings	integer	1	2
4	4	Strings can be tuned to variable frequencies	Hz	110	440
5	7	Interactive Components	integer	2	3
6	7,3	Sharp edges and points meet acceptable crieteria according to Section 1 of ISO 8124 (Safey Aspects Related To Mechanical and Physical Properties	binary	Pass	Pass
7	7,3	Switch cycles before energy depleted	m^3	0.3	1.2

2.6 Project Management

The Gantt chart in Figure 7 gives an overview of the project schedule.

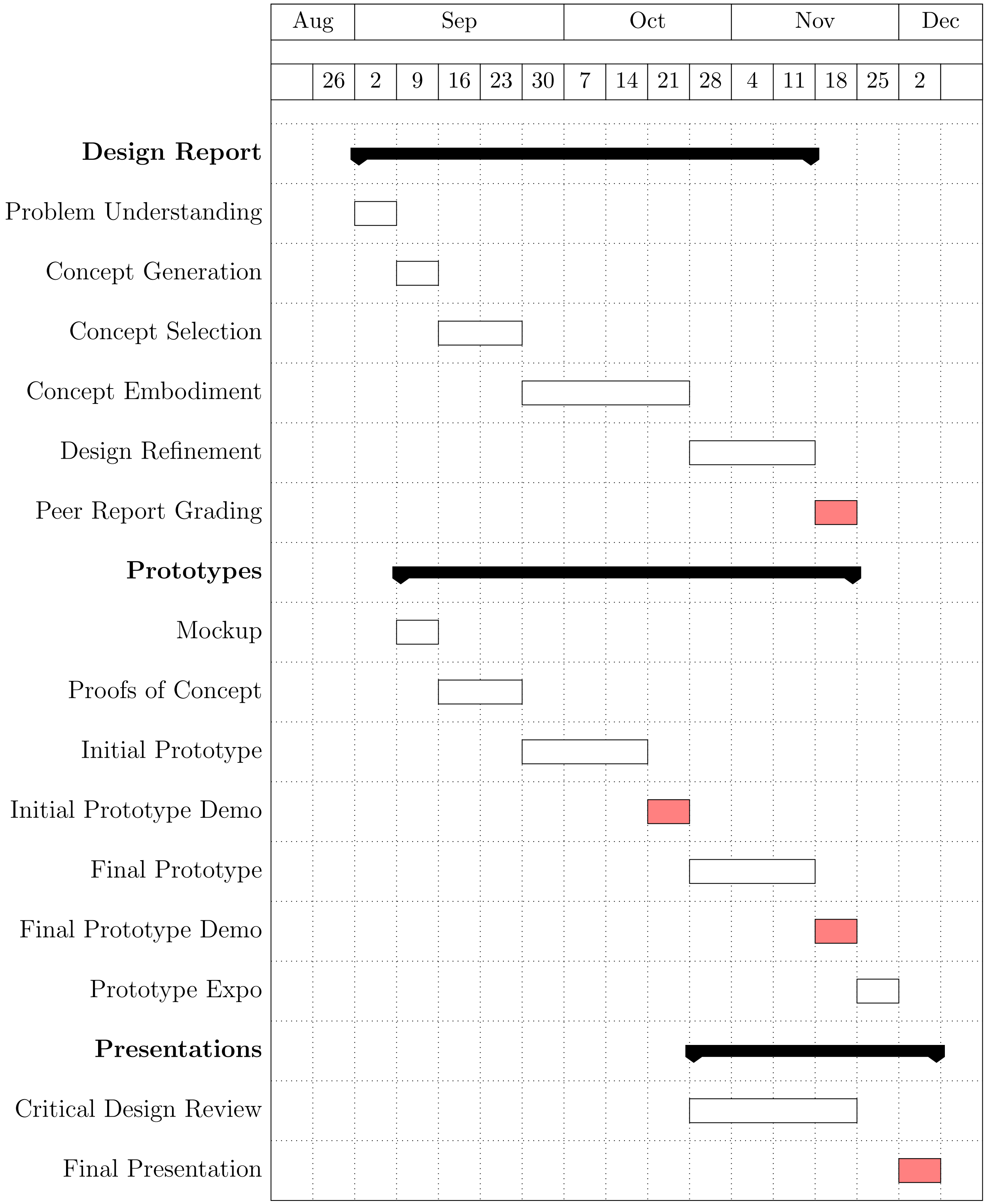


Figure 7: Gantt chart for design project

3 Concept Generation

3.1 Mock-up Prototype

A mock-up prototype of the demonstration was created to further understand and test design ideas. This prototype was created using a cereal box and rubber bands as the primary components, supplemented by smaller cardboard components. The point of this mock-up was to illustrate the different sounds created with various "string" sizes and tensions. Three various size rubber bands were place over a cereal box: one thin, loose band; one slightly thicker and tighter band; and one thick, tight band. The cereal box had a hole cut out to demonstrate the sound hole of the Vibration Station. Figure 8 displays the mock-up prototype created.

Figure 8: Mock-up prototype with the thinnest string in the middle.

The prototype performed as expected. The three rubber bands produced three different sounds when strummed. For our initial design, we will know how various masses and tensions will affect the sound. From this, we will consider including more than one string to display the difference on our output display.

Additionally, a note card was place underneath the rubber bands to cover the sound hole. This was tested to determine the effect of the sound hole on the demonstration. Figure 9 illustrates the covering of the sound hole.

Figure 9: Mock-up Prototype: Covering of the sound hole to determine the effect

In this configuration, the produced sound was not as loud for any of the rubber bands. The volume change was not a large difference, but significant enough to notice the difference. This will be important for our future designs as our initial design could incorporate a piece to slide over the sound hole. The difference would be displayed on a laptop.

The volume of the prototype was also examined. A slit was cut in the top and bottom of the prototype to where a piece of cardboard could slide in and out. Both ends were cut to allow the cardboard piece to rest on the opposite end without falling into the box. Figures 10 11, and 12 illustrate the slot with the cardboard inside from different angles to show the volume change.

Figure 10: Mock-up Prototype: Volume effect - View 1

Figure 11: Mock-up Prototype: Volume effect - View 2

Figure 12: Mock-up Prototype: Volume effect - View 3

The volume difference produced deeper sounds as expected. With this understanding our initial design could include multiple slots to experience different sounds for the various volumes. The mock-up prototype was a significant help in understanding how the vibrational characteristics through the sounds are affected when various elements are altered. The prototype will be beneficial in our initial design.

3.2 Functional Decomposition

To generate concepts, a function tree, as shown in Figure 13, for a interactive station to illustrate mechanical behaviors of sounds was created. The entire design revolves around the the plucking of a string in tension. From there, adjustable components are created to alter the sound created from the pluck of the string. Alterations to the sound emitted from the string are adjustable physical volume of the box, as well as tension adjustment knobs located on the top of the Vibration Station. Here, the subsections illustrate how the the sound is created and visualized, as well as safeguard against any destructive aspects of the Vibration Station, namely the breaking of a string in tension.

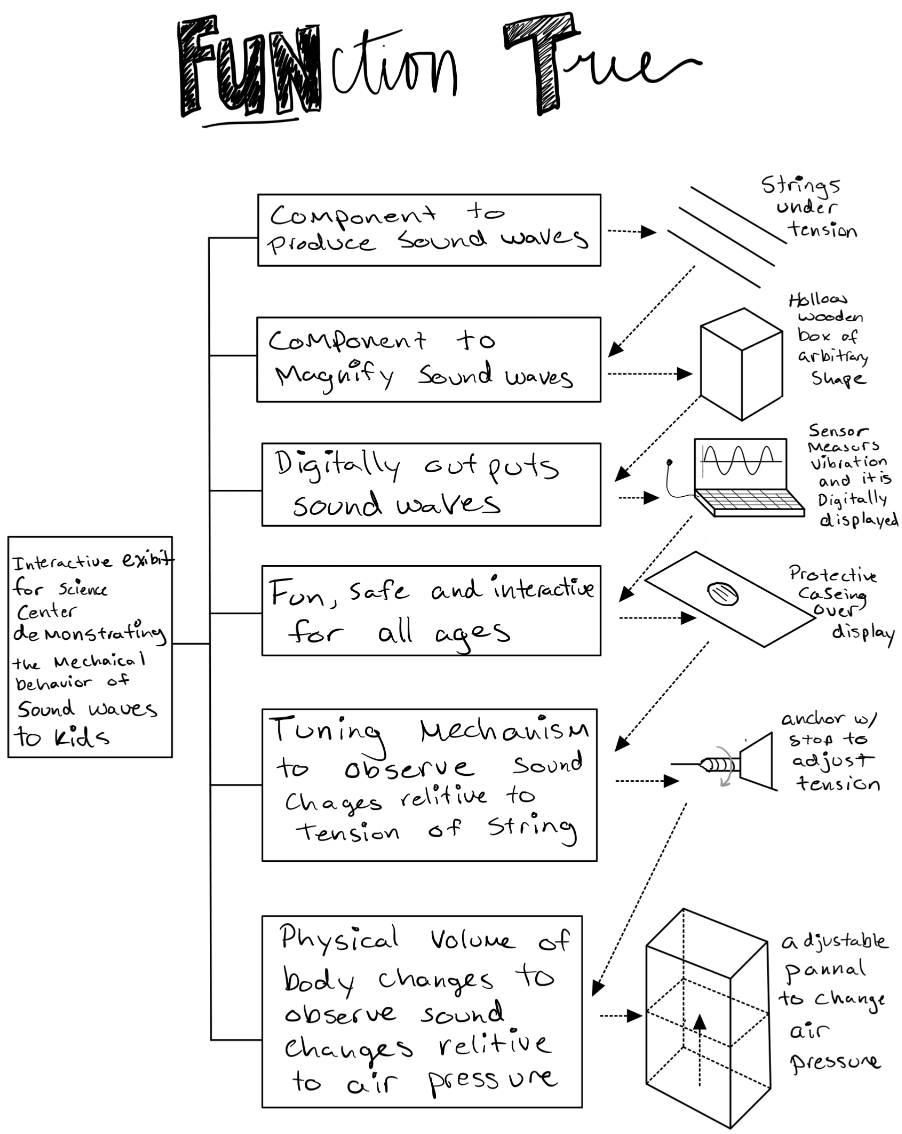


Figure 13: Function tree for Useless Box, hand-drawn and scanned

3.3 Morphological Chart

A morphological chart was created based on the subsections determined in the function tree. As show in Figure 14 below, graphics were created to represent solutions to each of the aforementioned subsections. Each subsection features three to four ideas that could theoretically perform the required task. After selection processes are made, the ideas are then used to produce sketchs and preliminary drawings.

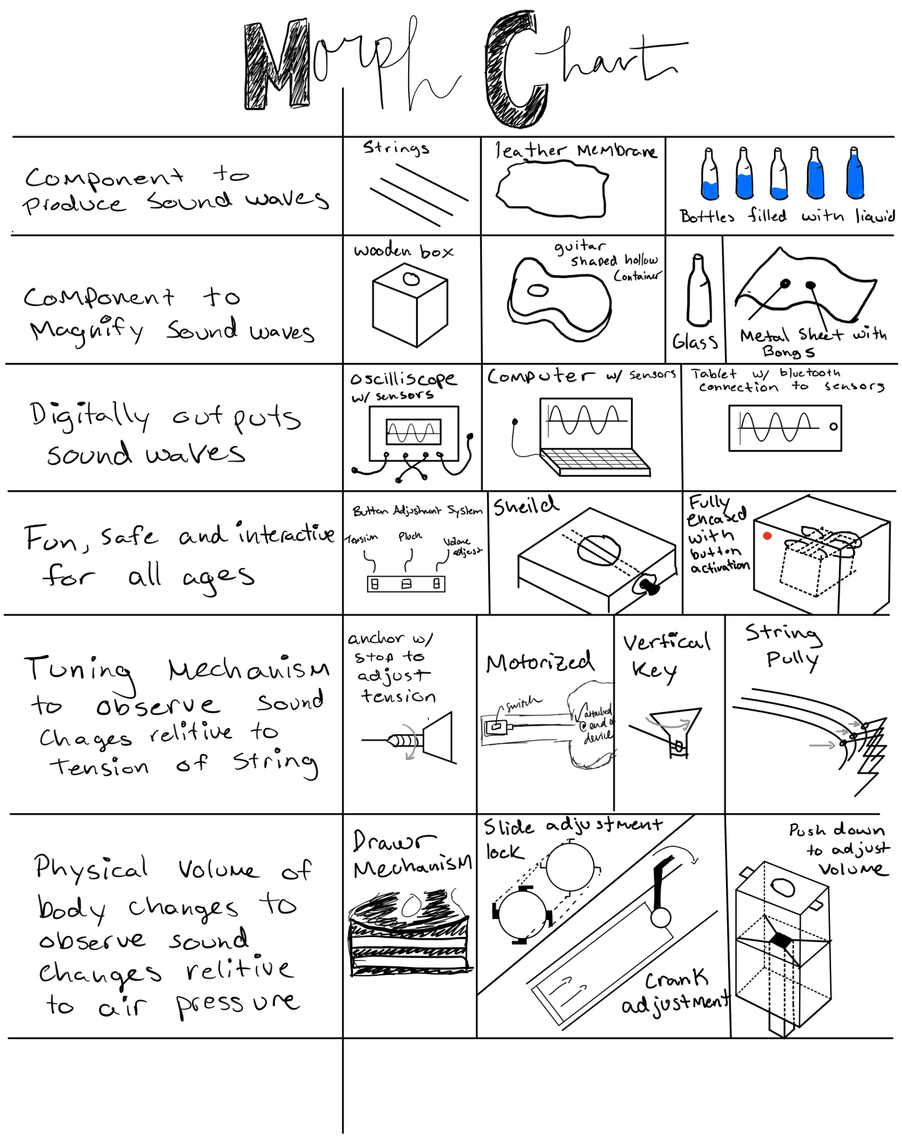


Figure 14: Morphological Chart for Useless Box

3.4 Alternative Design Concepts

Each team member created a design concept for the Vibration Station demonstration. The concepts are detailed below.

3.4.1 Vibration Tinker Machine

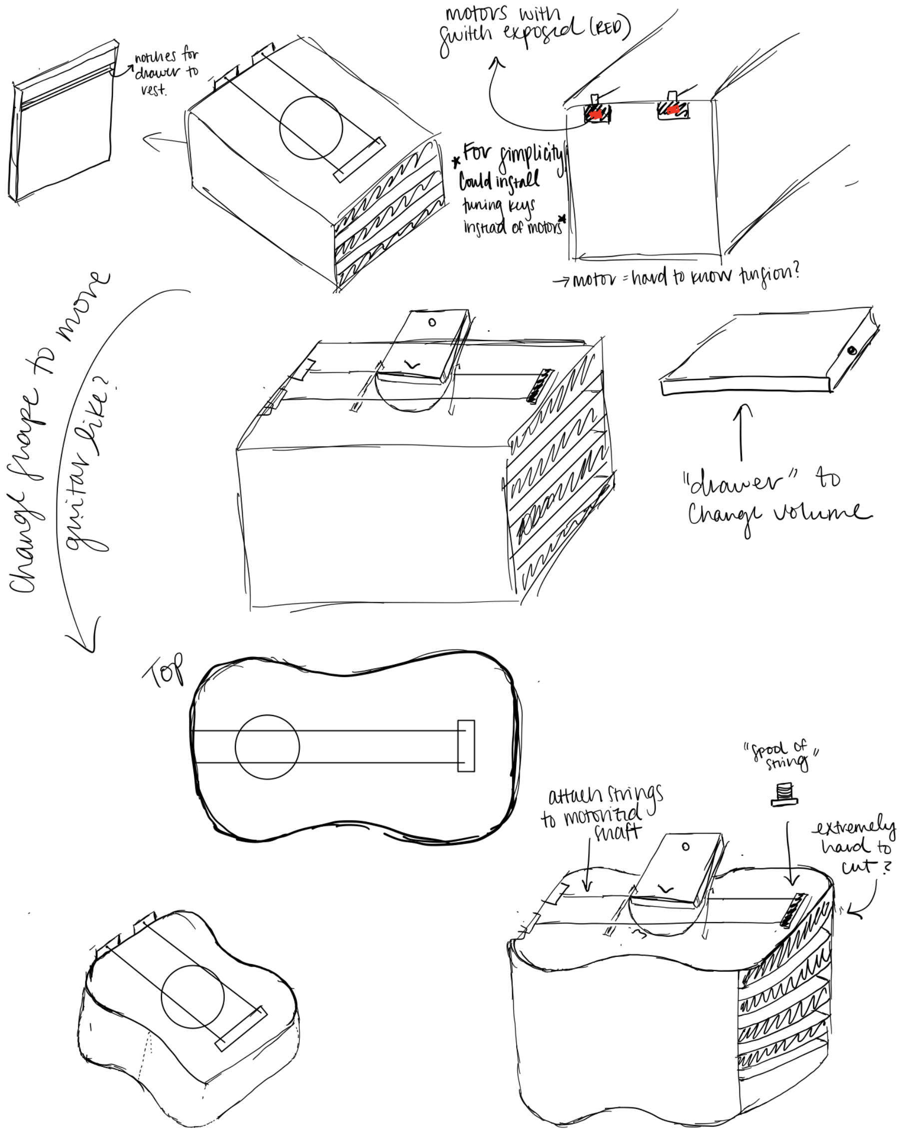


Figure 15: Preliminary sketches of Vibration Tinker Machine

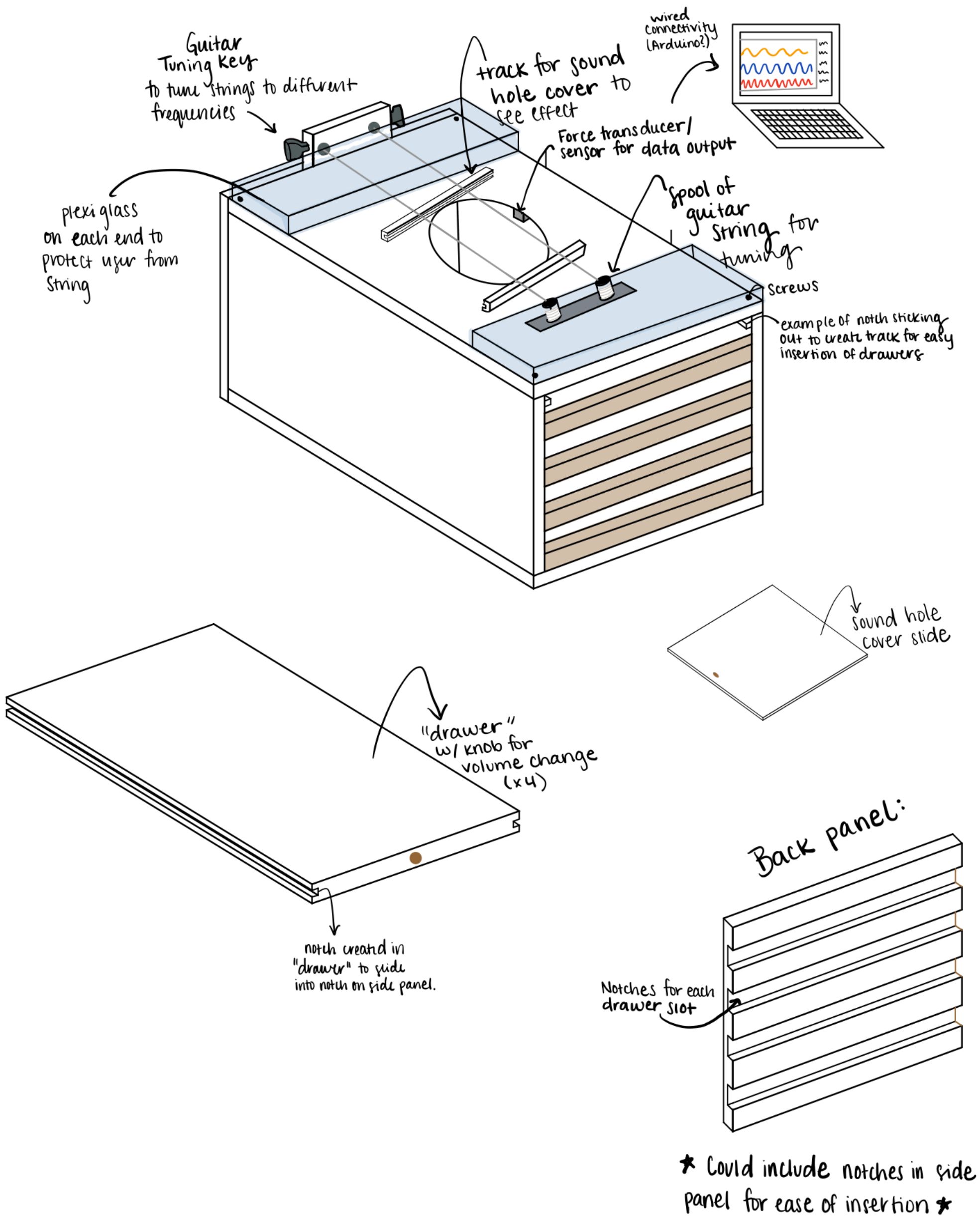


Figure 16: Final sketches of Vibration Tinker Machine concept

Solutions from morph chart:

1. Plexi glass to shield the string
2. Strings to produce soundwaves
3. Drawer mechanism to change volume
4. Tuning keys (pegs) to tune strings
5. Computer with sensors to display output of sound
6. Hollow wooden box to magnify soundwaves

Description: This design features a hollow wooden box with a sound hole located on the top panel of the box. Two strings are attached and can be tuned using guitar tuning pegs. To produce different sounds, the demonstration features a ”drawer” mechanism. There will be four drawers created to allow for different variations in the volume. An additional track is located under the strings on the top to cover the sound hole. Plexiglass shields are installed on the top of the box at either ends to protect the user if a string is to snap. A sensor will be placed inside the sound hole and wired to a computer to display the vibrational characteristics when the strings are strummed.

3.4.2 Vibration Station 1 Concept

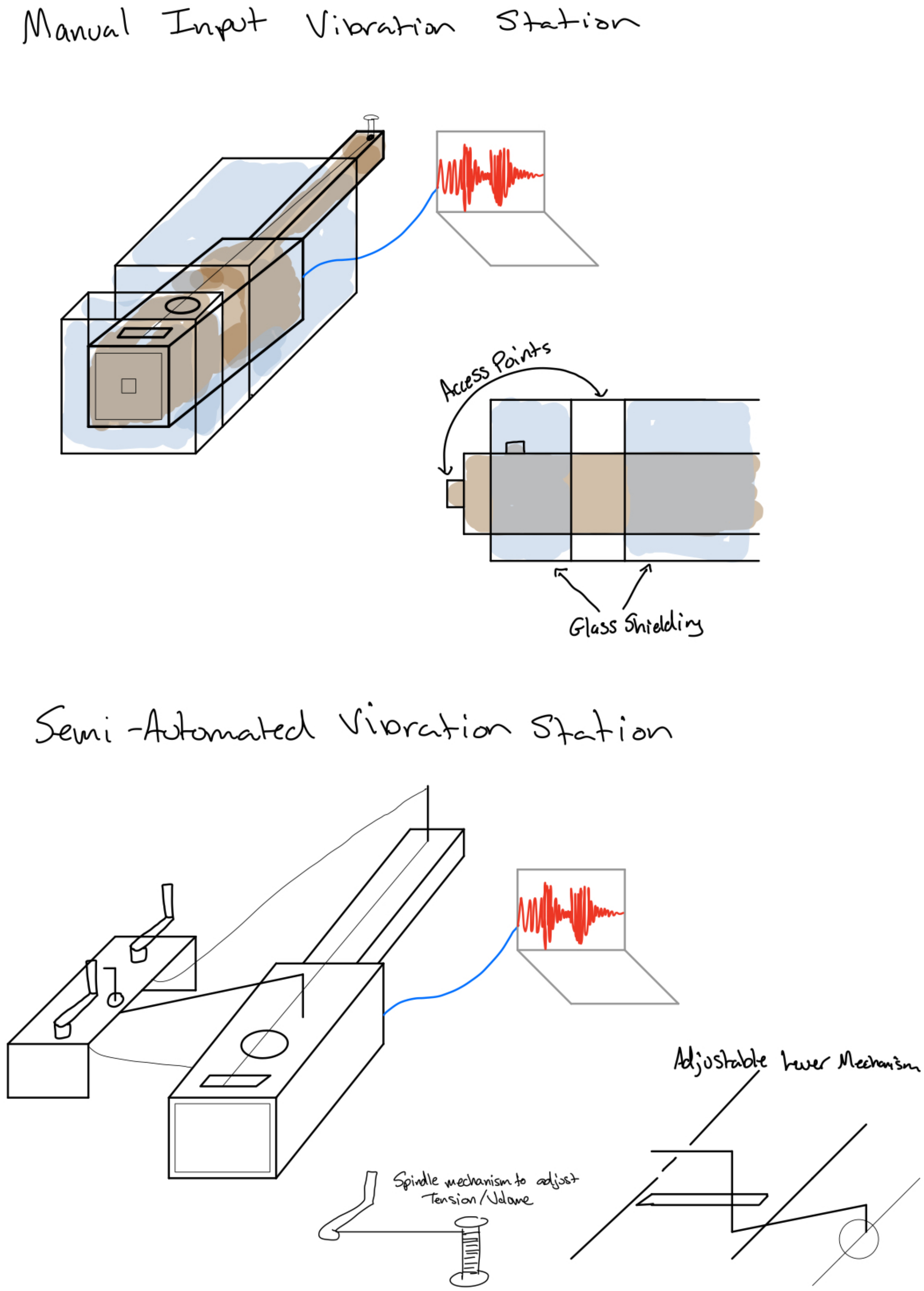


Figure 17: Preliminary sketches of Vibration Station 1 concept

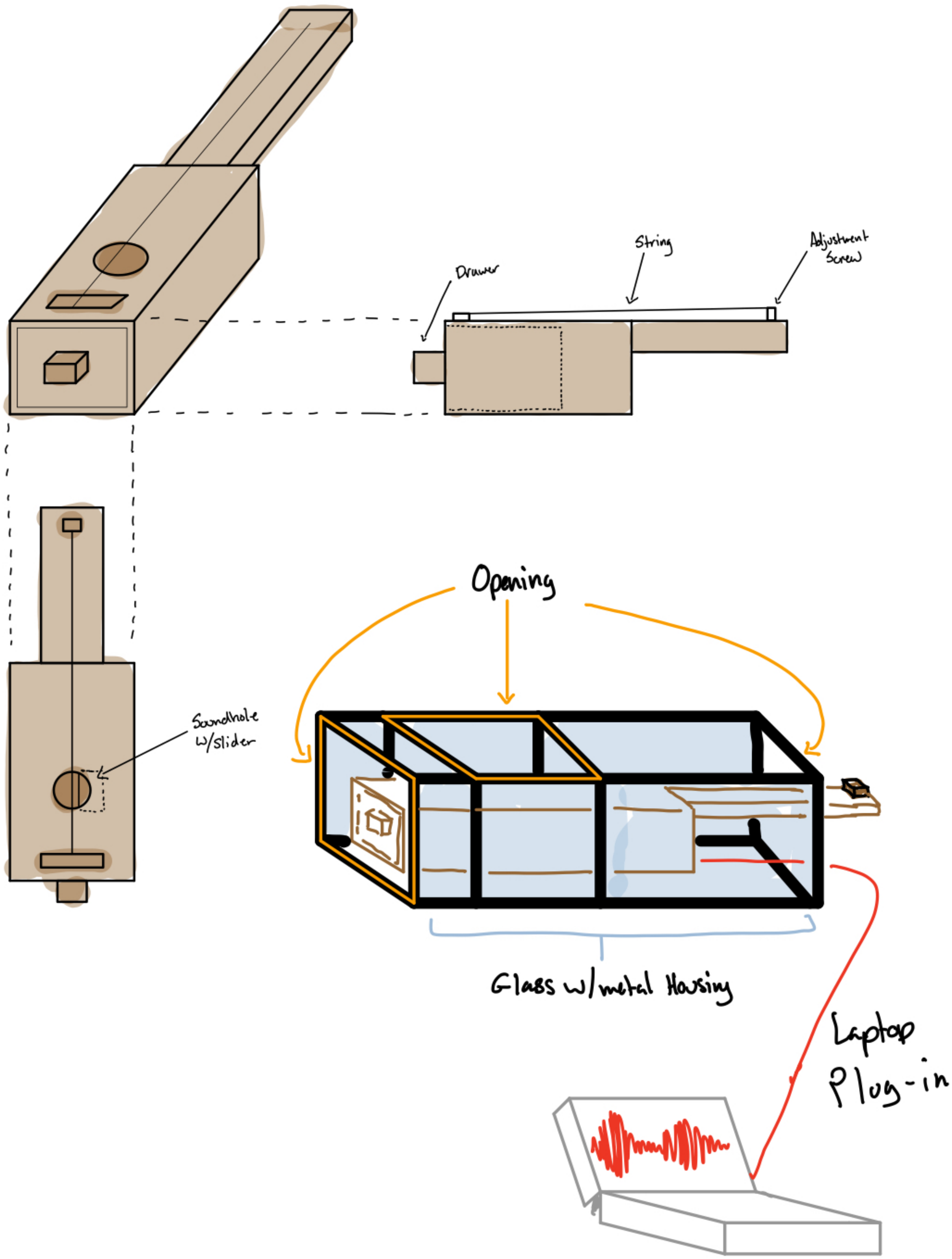


Figure 18: Final sketches of Vibration Station 1 concept

Solutions from morph chart:

1. Strings
2. Wooden Box
3. Computer with Sensors
4. Shield
5. Vertical Key
6. Drawer Mechanism

Description: Manual adjustment parts are located at both ends of the Vibration Station. The large end features a drawer adjustment knob to change the physical volume, which as a built in stop. On the opposite end, a knob adjustment is featured to tighten or loosen the string. In the middle, features a area to actually pluck the string. The entire design is encapsulated by a glass, metal container, which openings featured only on the interactive parts to limit liabilities. The design has a plug-in to a computer to generate a visual representation of the sound.

3.4.3 Vibration Station 2 Concept

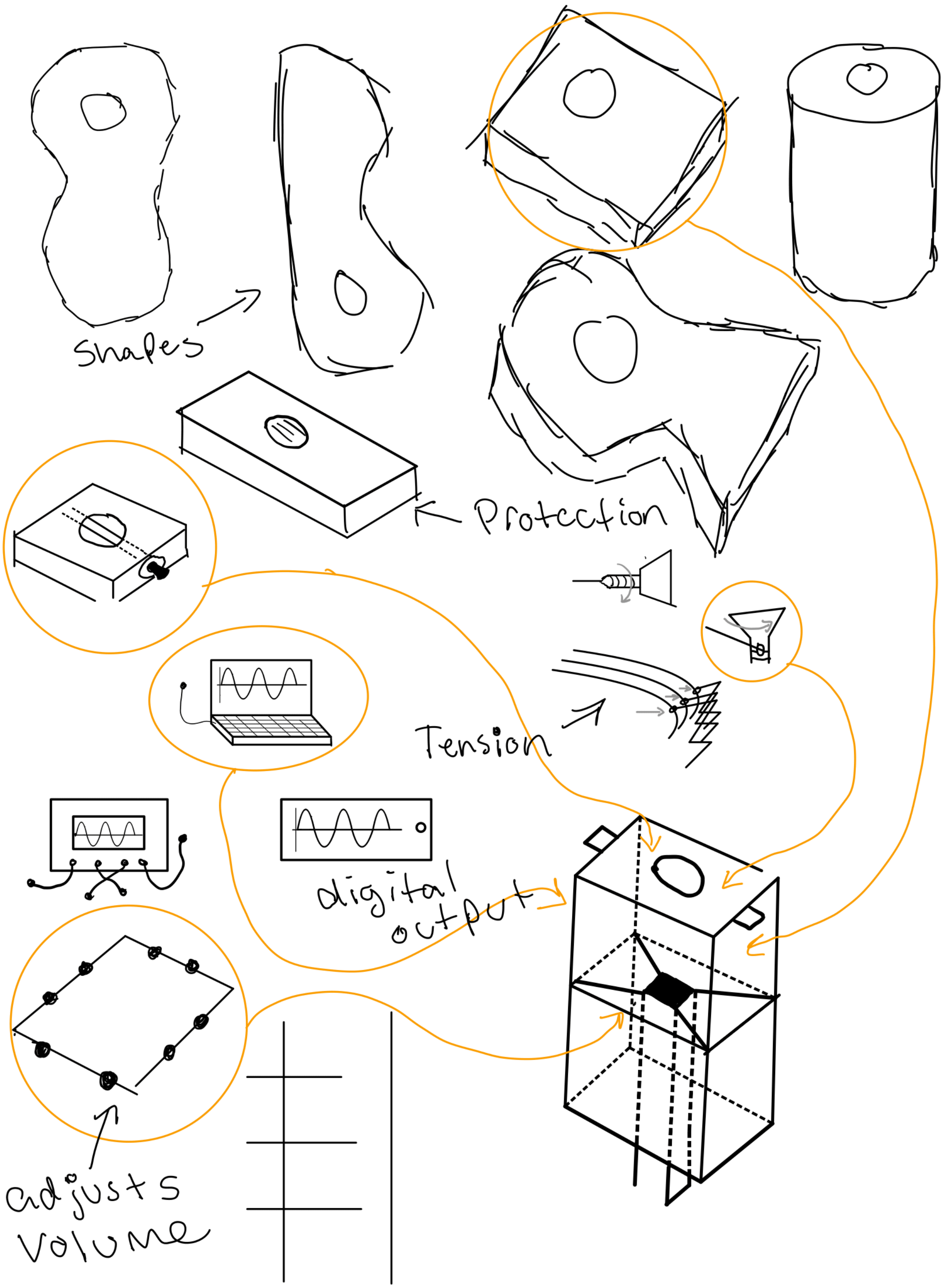


Figure 19: Preliminary sketches of Vibration Station 2 Concept

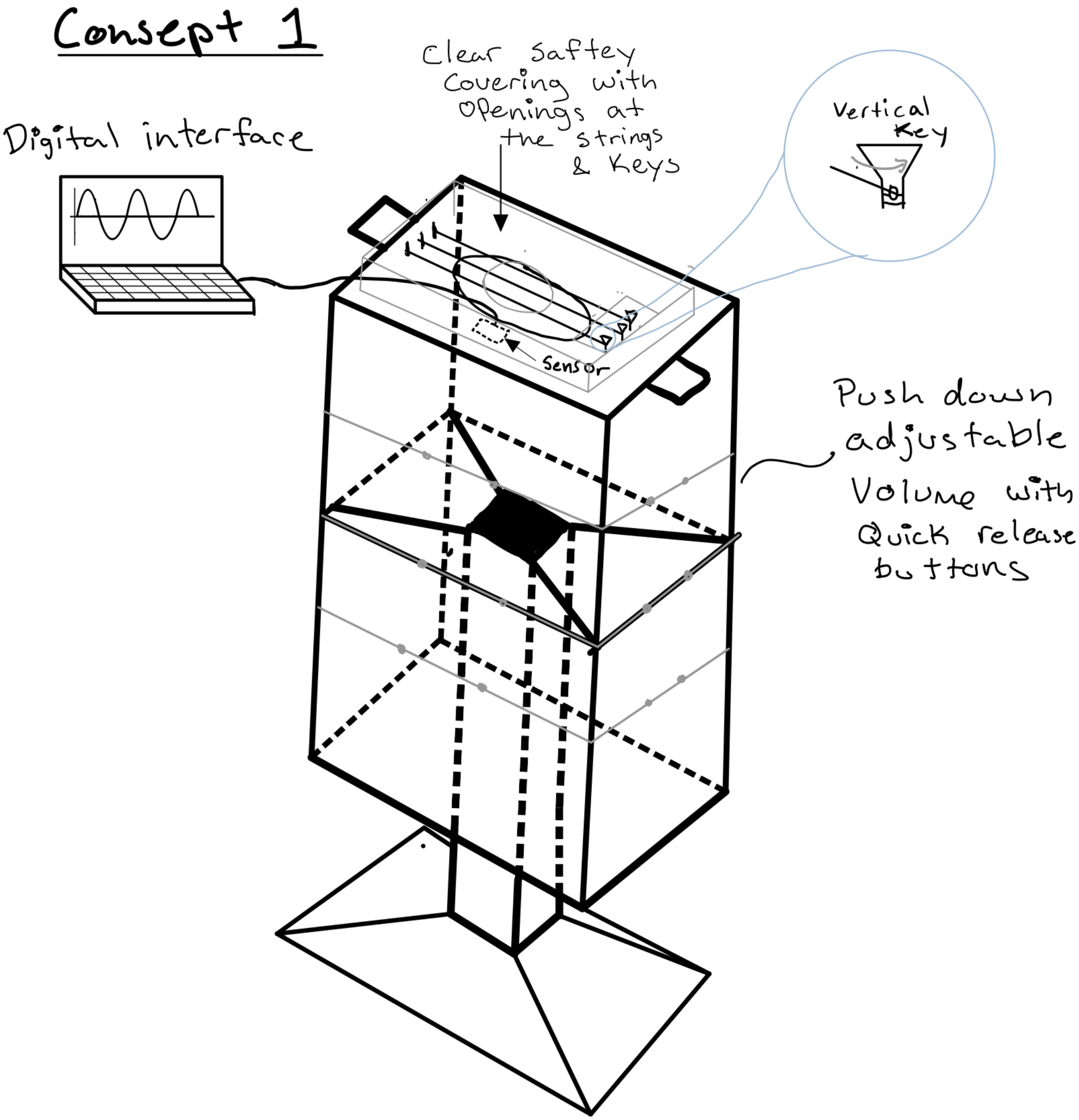


Figure 20: Final sketches of Vibration Station 2 Concept

Solutions from morph chart:

1. Unit sits on floor
2. Strings with vertical key tension adjustment
3. Computer with digital display
4. Sensors to read sound vibration
5. Protective shield
6. Push down physical volume adjustment
7. Wooden body to magnify sound

Description: A sensor on the inside of the wooden body close to the hole opening measures the vibration induced by the strings. The sensor is feed through a digital converter connected to a computer which outputs the frequency as a wave. The strings are tight across the opening and attached to vertical keys which can be turned to adjust the tension. A protective cover is placed over the strings with small openings for access to the middle of the strings and tension keys. The bottom panel of the box can move freely allowing for the physical volume of the body to change. Handles on either side of the wooden box allow the user to move the body to various levels. Pins at each level hold the body in place and allow for easy adjustment. The whole contraption is supported by a foot attached to the bottom panel.

4 Concept Selection

4.1 Selection Criteria

Figure 21 below depicts the analytic hierarchy process used in determining the concept that best represented the user needs and selection criteria. The safety rating is the baseline at 1.00 and the rest of the criteria are rated relative to safety following the numerical ratings key shown below the matrix.

	Safety (string, electrical, etc.)	Intuitive and entertaining for age 6 and older	Ease of assembly	Interactive (tunable string, volume changing, etc.)	Aesthetic appeal (instrument shaped/digital display)	Row Total	Weight Value	Weight (%)
Safety (string, electrical, etc.)	**1.00**	3.03	9.09	5.00	7.14	25.26	0.42	42.49
Intuitive and entertaining for age 6 and older	0.33	**1.00**	0.33	0.33	0.20	2.20	0.04	3.69
Ease of assembly	0.11	3.00	**1.00**	7.00	0.20	11.31	0.19	19.02
Interactive (tunable string, volume changing, etc.)	0.20	3.00	0.14	**1.00**	5.00	9.34	0.16	15.71
Aesthetic appeal (instrument shaped/digital display)	0.14	5.00	5.00	0.20	**1.00**	11.34	0.19	19.07
					Column Total:	**59.45**	**1.00**	**100.00**

Row criterion is ________ than/as column criterion

Numerical ratings:
9 -- Extremely more important
7 -- Very strongly more important
5 -- Strongly more important
3 -- Moderately more important
1 -- Equally important
1/3 -- Moderately less important
1/5 -- Strongly less important
1/7 -- Very strongly less important
1/9 -- Extremely less important

Figure 21: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

Figure 22 below shows the matrix of alternative design concepts with the weighted criteria from the analytical hierarchy process applied. Each concept is given a rating on a one to five scale based on how well it meets the criteria. The higher the rating the better the concept fits the criteria.

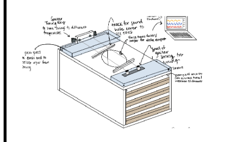
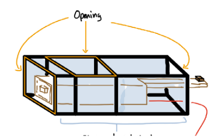
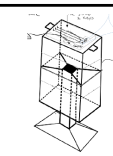
Alternative Deisgn Concepts		Concept #1		Concept #2		Concept #3	
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Safety (string, electrical, etc.)	18.52	4	0.74	3	0.56	2	0.37
Intuitive and entertaining for age 6 and older	13.34	4	0.53	3	0.40	3	0.40
Ease of assembly	22.15	5	1.11	3	0.66	2	0.44
Interactive (tunable string, volume changing, etc.)	18.41	5	0.92	5	0.92	5	0.92
Aesthetic appeal (instrument shaped/digital display)	27.59	4	1.10	4	1.10	3	0.83
	Total score	**4.406**		**3.644**		**2.962**	
	Rank	**1**		**2**		**3**	

Figure 22: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

Scoring the alternative design concepts with the weights shown in Fig. 22, Concept #1 scored the highest. The key difference that set Concept #1 apart from the other concepts was its score in *Ease of Assembly*, where it earned a perfect rating. This selection criterion accounts for over 20% of the entire design concept, second only to the *Aesthetic Appeal*, which accounts for over 25% of the entire design concept.

The main goal of the design was to attract users, while simplifying the assembly process. However; design factors such as safety, intuitiveness, and interactivity, were also taken into account. Since the primary demographic of users would be that of children between the ages of 6 to 10 years old, ensuring that the movable parts on the design would not harm the children was an important factor. Concept #1 was the clear best option in this, as it featured clear shielding to direct attention to the parts of the design that could be altered, such as adjusting the string tension, plucking the string, and adjusting the physical volume of the box. Concept #2 and Concept #3, both fell short on this as the designs itself created more safety issues than the ones that were already generated. Intuitiveness was also a factor, as the ability for the user to interact with the design with little to no experience was important. Concept #1 featured only three adjustable parts, easily distinguishable due to their location on the design. Concept #2 and Concept #3 both scored below Concept #1 due to size and complexity of each design without some introduction. As for the assembly of the design, Concept #1 dominated this criterion, as its design was simplified down to a box, where the complicated aspects of the design came in the form of constructing removable drawers. Concept #2 and Concept #3 had shortcomings due to the bulky safety shielding put into place and the complicated drawer respectively. In terms of interactivity, all concepts excelled due to their ability to adjust tension, allow for their strings to be plucked, and adjust the physical volume; all vital components of the design. Lastly, the aesthetic appeal was the most important factor, where Concept #1 and Concept #2 tied. Concept #1 was simpler, boasting a cleaner design, but did not appear to be representative of any known instrument. As for Concept #2, it was model after the widely known acoustic guitar, but its bulky safety shielding limited the appeal for this design.

All in all, Concept #1 led in all selection criterion, with exception of *Interactive* and *Aesthetic*

Appeal, where it tied other concepts in those particular criterion. The simplistic design did not score below a 4 in any of the criterion, setting well apart from the other concepts.

4.4 Engineering Models/Relationships

The design itself is structured to educate the vibrational properties of a string. Though these vibrational properties can manifest itself in the form of acoustics and sound, those concepts can be reduced down into three distinct concepts of the natural frequency, the frequency relationship with change in length of string, and the yield stress of the string. Each of these properties are crucial to the educational experience of the design, as well as can be altered as part of the design.

Natural Frequency

Given a string in tension, show in Fig. 23, produces some frequency that when plucked, vibrates. This frequency that it vibrates at is known to be the natural frequency, an integral part of instrumentation. When a guitarist plucks his or her guitar string, the goal is to find a vibration with a natural frequency that is musically sounding.

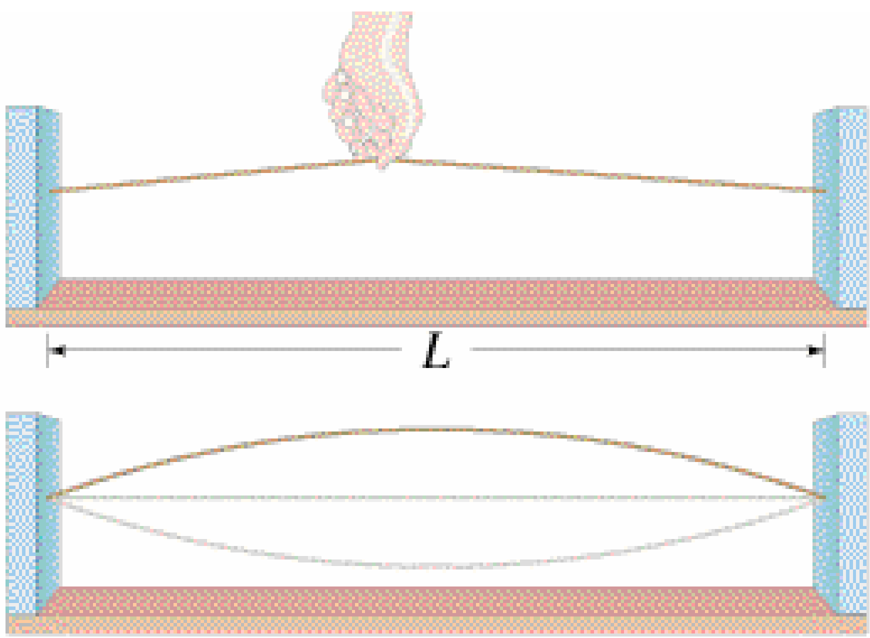


Figure 23: Plucked String in Tension with Length [L] [9]

The oscillation of the string can be modeled by a differential equation with appropriate boundary conditions as seen below:

$$\ddot{y} - c^2 y" = 0 \tag{1}$$

where $\ddot{y}$ is the second derivative of y with respect to time, y" is the second derivative of y, and c is a constant, calculated using the Eq. 2 below"

$$c = \sqrt{\frac{T}{\rho}} \tag{2}$$

where T is tension of the string in units of $[N]$ and ρ is the density of the string in units of $[kg/m^3]$. It can then be assumed that the solution to the differential equation in Eq. 1 is of the form below:

$$Y(x) = Acos(\beta x) + Bsin(\beta x) \tag{3}$$

with boundary conditions of:

$$Y(0) = 0, \rightarrow A = 0 \tag{4}$$

$$Y(L) = 0, \rightarrow Bsin(\beta L) = 0 \tag{5}$$

where A and B are constants. Solving for β and ignoring the trivial solution, results in the following equations for β:

$$\beta = \sqrt{\frac{n^2\pi^2}{L^2}} \tag{6}$$

$$\beta = \sqrt{\frac{\omega^2}{c^2}} \tag{7}$$

where combining the Eq. 6 and 7 and solving for ω results in the natural frequency of the system, show below:

$$\omega_n = \frac{n\pi}{L}\sqrt{\frac{T}{\rho}} \tag{8}$$

where ω_n is the natural frequency of the system in units of $[Hz]$, n is the node of the string, where n is equal to 1,2,3,4 ..., and L is the length of the string in units of $[m]$. Knowing Eq. 8, it can be determined the natural frequency of the system at a given tension [10].

Frequency Relationship with Change in Length of String

Since the design is focused on the sound emitted from plucking a string under various conditions, namely that of tension on the string, it is important to understand the change in frequency with respect to the change in length. The below equation relates tension force on the string to the change in guitar length, where the string length can be altered by a tuning, similar to that found on guitar:

$$F_T = \frac{EA\triangle L}{L_0} \tag{9}$$

where F_T is the tension force on the string in units of $[N]$, E is Young's Modulus, A is the cross-section area of the string in units of $[m^2]$, $\triangle L$ is the change in string length in units of $[m]$, and L_0 is the initial length of the string in units of $[m]$. From here, it can be assumed that the tension force is constant throughout the string and is not affected by being wrapped around the tuning peg. Thus, when the string is plucked, the waves travel at the speed V, where:

$$V = f\lambda = \sqrt{\frac{F_T}{\mu}} \tag{10}$$

where V is the velocity of the wave in units of $[m/s]$, f is the frequency in units of $[Hz]$, λ is the wavelength in units of $[m]$, and μ is the mass per unit length of the string. Equation 9 and 10 can now be combined such that:

$$f^2 = \frac{E \triangle L}{\rho \lambda^2 L_0} \tag{11}$$

where ρ is the density, derived from combining μ and A. Equation 11 can now relate the how change in the length of the string adjusts the frequency [11].

Yield Stress of String

Using existing models of stress analysis, it can be determined the maximum allowable tension the string used can undergo. This property is represented by the Young's Modulus. Figure 24 below shows the stress-strain curve of a typical steel string.

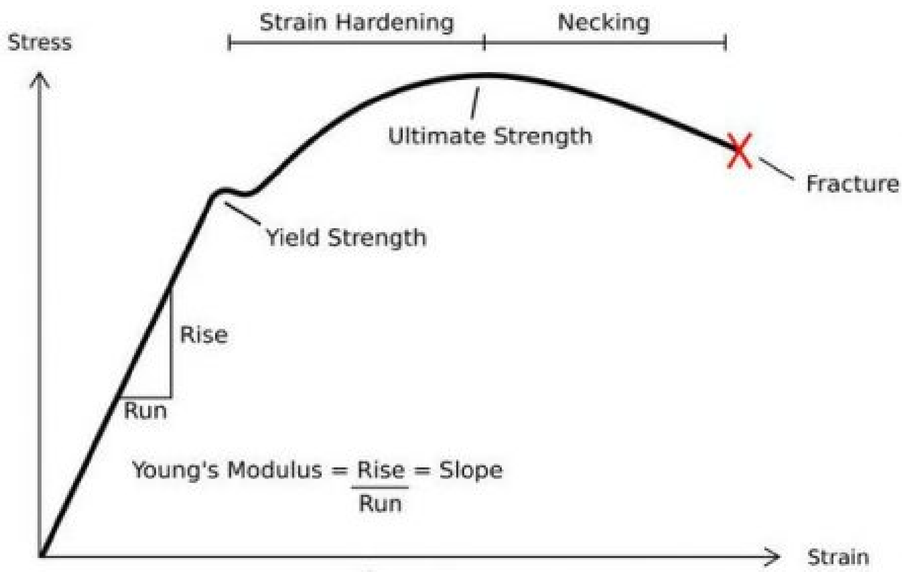


Figure 24: Stress-Strain Curve of Steel String [12]

From here, Young's Modulus is represented by Eq. 12, which relations tensile stress and axial strain, which can be seen below:

$$E = \frac{\sigma}{\epsilon} \tag{12}$$

where E is the Young's Modulus, σ is the tensile stress, and ϵ is the axial strain. Since tensile stress is the relationship between tension force in the string $[F_T]$ and the cross-sectional area of the string $[A]$, a combination of the tensile force with Eq. 11 yields the following:

$$\sigma = \frac{16 f^2 L^2 M}{\pi d^2} \tag{13}$$

where M is the unit weight of the string $[kg]$, and d is the diameter of the string$[m]$. Using this relationship, it can then be determined the yield stress of the string given known properties of the string itself.

5 Concept Embodiment

5.1 Initial Embodiment

For the initial embodiment of the vibration station, we designed the prototype in SolidWorks to encompass the design parts shape and properties. Below are CAD drawing and a bill of materials of the initial embodiment.

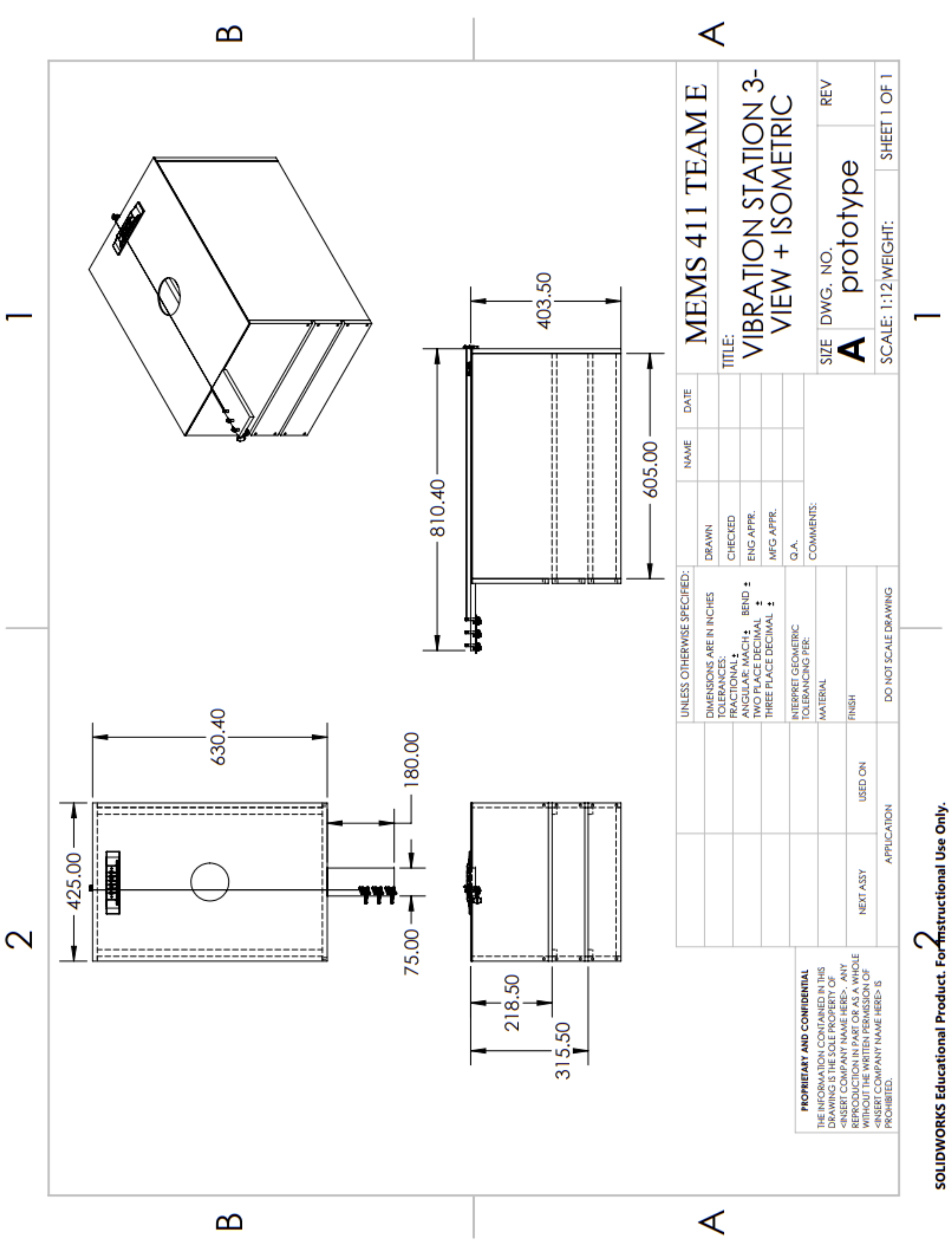
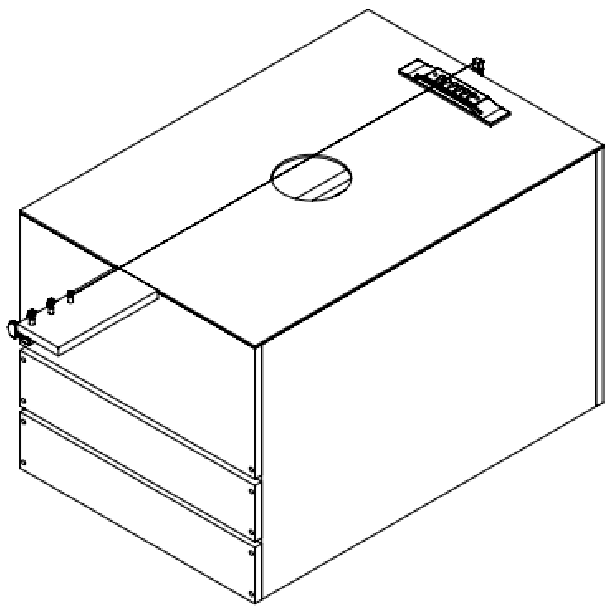


Figure 25: Assembled projected views with overall dimensions



ITEM NO.	PART	DESCRIPTION	QTY.
1	Back	1/2" Sanded Plywood	1
2	Side & Bottom	1/2" Sanded Plywood	3
3	Front middle & bottom pieces	1/2" Sanded Plywood	2
4	Track	1/2" Sanded Plywood	4
5	Front top piece	1/2" Sanded Plywood	1
6	Top piece	1/8" Tempered Hardboard	1
7	Handle	1/2" Sanded Plywood	1
13	Tuning keys	Musiclily Pro 3+3 Acoustic Guitar Tuning Pegs (Appropiate screws included).	1
14	L-brackets	1" x 1/2" Zinc corner brace	10
15	Wood screws	6 x 1-5/8-in Grabber construction screws (Item No. X400YZ)	10
16	Guitar bridge	DISENS 6 string acoustic guitar wooden bridge	1
17	Sparkfun 10kg load cell	Sen-13329	1
18	String	D'addario Pl010-5	1
19	Screws for L-brackets	#8 x 1/2 in. Philips Truss-Head Standard Thread Wood Screw	20

MEMS 411 TEAM E

TITLE: VIBRATION STATION ISOMETRIC AND BOM

SIZE A | DWG. NO. prototype | REV

SCALE: 1:12 | WEIGHT: | SHEET 1 OF 1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM. TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

DRAWN | CHECKED | ENG APPR. | MFG APPR. | Q.A. | NAME | DATE

COMMENTS: Screws and corner braces are not included in the drawing, but are included in the BOM.

NEXT ASSY | USED ON | APPLICATION

Figure 26: Assembled isometric view with bill of materials (BOM)

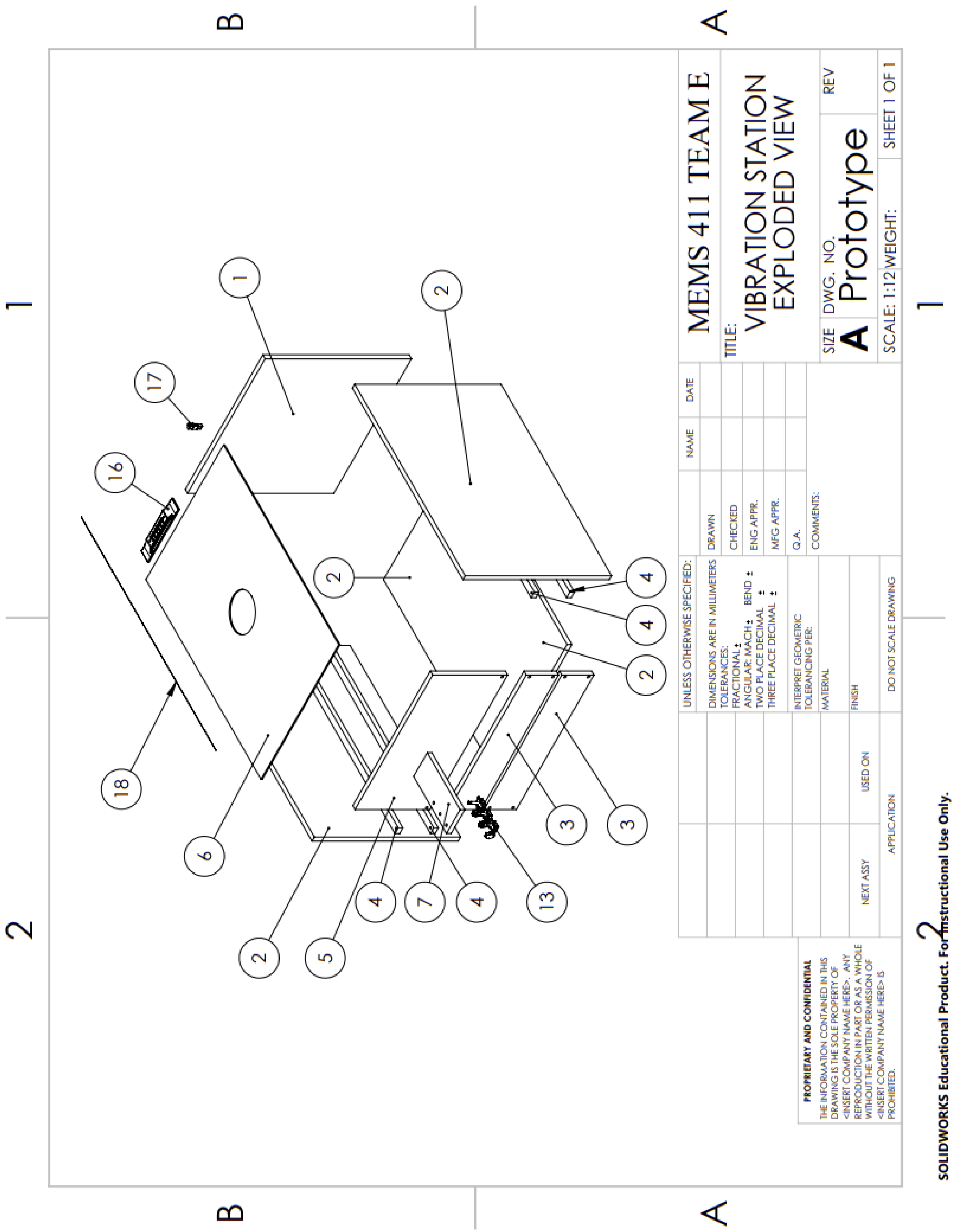


Figure 27: Exploded view with callout to BOM

5.2 Proofs-of-Concept

In developing proof of concepts, our team focused on engineering concept's related to geometry, the main one being natural frequency and its relationship to tension. Initially, we were going to vary the length of the string and the tension to observe the frequency, though soon discovered that setting the length and varying the tension was the better method. We discovered that a standard string length (from one fixed end to another) was 25.5 in. Our team used this length in our initial prototype. Having a volume where the string could reverberate and produce a note was also important to our proof of concept. Our team used plywood and other cheap building materials to assemble a box to observe the relationship between tension and frequency, (this structure later developed into our initial prototype). With a phone app we were able to read a note (i.e the frequency) then calculate the tension. To calculate the tension [lbf] we used an equation given by the guitar string provider D'Arddario shown in equation 14 with given specs of the strings.

$$T = \frac{UW * (2 * L * f)^2}{386.4} \tag{14}$$

where T is tension, UW is the unit weight, L is the length of the string from one fixed end to the other, and f is the frequency [13]. For proof of concept experiments we used a 0.01 gauge plain steel string with a unit weight of 0.00002215 lb/in, set length L of 25.5 in, and tuned to a B with an associated tension of 246.9 Hz. The calculations for tension are shown below.

$$T = \frac{0.00002215(lb/in) * (2 * 25.5in * 246.9Hz)^2}{386.4} = 9.089lbf - in \tag{15}$$

The tension calculated above will then be compared with the tension read by the strain gauge in our initial prototype. With this simple calculation we were able to determine the type of strain gauge we would need. Though the phone tuner may have had inaccuracy's, following this engineering model guided our dimensions and model for the initial prototype.

Because we know the material of the string we know the modulus of elasticity is 30500 ksi for plain steel and the string used has a 0.25mm (0.00984252in) diameter so the rated yield strength is then between 399000 and 418000 [ksi] [14]. Calculating the stress at a frequency of 246.9 Hz (as used in the Proof-of-concept) using the basic definition of stress (force per unit area) produces the stress at this tension below.

$$\sigma = \frac{9.089 * lbf - in}{\pi(0.00984252in)^2} = 924psi \tag{16}$$

The calculated stress is well below the strings yield stress, but these calculations and research in the proof of concept phase are important to keep in mind as we design the max allowable tension for our prototype.

The final stage of proof-of-concept was to experiment with strain gauges and load cells to measure the string tension. For this proof-of-concept, our team simply connected the strain gauge, load cell and Arduino Leonardo to ensure the circuit was set up correctly and the sample code for the load cell (provided by SparkFun Electronics) would run.

5.3 Prototype Performance Goals

We set three prototype performance goals we aimed to achieve in this initial design and build of the device. These goals are as shown below.

1. The body volume can be adjusted to at least three different sizes.
2. String tension can be measured within a reasonable range.
3. The user can fully tighten the string and pluck it as hard as feasible without exceeding the string's max rated load.

On the CAD model in Fig. 25, two holes are located on the front of the front of the device for slats to be inserted. This holes allow for three adjustable volumes to be examined. A strain gauge is bolted to the end of the design as shown Figs. 25 and 27 to measure the string tension. The final prototype performance goal will be checked through calculations to ensure the string's max rated load.

5.4 Explanation of Design Changes

Most design changes were a result of realizing our current model wouldn't accommodate our all performance goals or design safety. One example of adapting our design occurred when we were mounting the string and keys. We realized the dimension of the box was to short to accommodate the desired string length and mounting the keys in the desired orientation on the box was difficult. In the end we added a short attachment to our prototype to mount the keys and string such that the desired length and orientation was acquired. This attachment, however, provided more of an instrument appearance as it resembled a small handle, known as a headstock, of an acoustic guitar.

In our initial prototype we decided on few changes to better align with our performance goals. One of which was more drastically changing the volume of air within the box. The air volume of the box in our prototype is adjusted by sliding slats in at various locations along the height of the box as depicted in the CAD drawings above (Figs 25, 26, and 27). In the initial prototype, we chose the first hole for a slat is 8.6 in from the top and the second to be 12.42 in from the top creating two various volumes. After construction and experimenting with tuning and frequency, we realized these volume changes were not drastic enough to change the sound produced by our instrument. For our second prototype we plan to place the first volume slat 2 in down and our second volume slat 10 in down.

Another major safety and usability design upgrade we realized was accessory had to do with sliding in and out the volume slats. We noticed that it was difficult to slide in and out the slats without a handle particularly if one had difficulty with fine motor skills. It was also apparent that the small opening in the box may be a finger trap for small fingers. With both these apparent design issues, we decided to add a soft "handle" which would be placed along the upper and lower edges of the slat to increase grip and seal off any gaps and inherently increase the acoustics of the box. Additionally, plexi-glass or a clear covering will be placed over the string leaving only a small opening for strumming. This design change will protect the user from potentially being injured due to string breaking.

6 Design Refinement

6.1 FEM Stress/Deflection Analysis

Three major engineering relationships are present on the string component of the guitar, that being the tension the string undergoes when at rest or plucked, the natural frequency, and that of the yield stress of the string itself.

It should be noted a small variation from the expected initial prototype from *4.4 Engineering Models / Relationships* manifested itself due to limitations in components. Translating the tension reading measured by the force sensor into a frequency is not feasible due to the slow sampling rate of the Arduino. That being said, the force of tension on the string was instead used to calculate the frequency and expanded on in that section, but will be quickly reiterated here.

The first engineering principle is that of the string tension and how it alters the note played. It is initially defined in Eq. 9, where the tension in the string is crucial to determining the frequency with respect to tension. There are known tension forces in string instruments to produce a vibration or note, where the string we are using is tuned to produce a B. Alterations of the tension changes the aforementioned natural frequency of the string, thus changing the note produced. Here, it is assumed that the string is uniform, and the forces acting on the string by being coiled at one end are neglected. Calculated below is tension force produced that is required to play the note B:

$$T = \frac{0.00002215(\frac{lb}{in}) * (2 * 25.5in * 246.9Hz)^2}{386.4} = 9.089lbf - in \tag{17}$$

Alterations in natural frequency have not changed since it was initially introduced, though there are some assumptions that are made in calculating the natural frequency. The first is that when the string is plucked, the most ideal vibration is emitted each pluck, producing the natural frequency. The second is that location where the string is plucked is negligible, thus the natural frequency can be determined at any tension. The unit weight, γ of the B string is provided in the specifications as 0.00002215 lbf/in [13].

$$\rho = \frac{\gamma}{g} = \frac{0.00002215\frac{lbf}{in}}{386.4\frac{in}{s^2}} = 5.732 * 10^{-8}\frac{lbm}{in^3} \tag{18}$$

Below is a sample calculation of the derived first natural frequency, using Eq. 8 and idealized values:

$$\omega_1 = \frac{\pi}{L}\sqrt{\frac{T}{\rho}} = \frac{\pi}{25.5in}\sqrt{9.089lbf - in * (5.732 * 10^{-8})\frac{lbm}{in^3}} = 1551.31\frac{rad}{s} = \frac{1551.31\frac{rad}{s}}{2\pi} = 246.9Hz \tag{19}$$

where ω_1 is the first natural frequency of the system [rad/sec], L is the scale length of the string (25.5 in), T is the tension of the string (9.089 lbf-in for note B), and ρ is the density of the string (calculated in Eq. 18) [13].

Both of the above engineering principles, tension and frequency, were proved in the initial prototype demonstration. The tension for a B note was calculated as shown above. Using a phone tuner, the prototype was tuned to a B note and the tension was measured with the attached strain gauge. The measured tension was 9.1 lbf-in. Using this tension in Eq. 19, a frequency of 1552.25 rad/sec (247.05 Hz) is calculated. Thus, these measurements and/or calculations based on the measurements agree with the theory behind note B.

Lastly, the yield stress of the string is mainly dependent on the material it is used from. This principle has not varied since its inclusion, and dependent on the string instrument, it varies in material. In the prototype constructed, the string that is commonly used in guitars is used, which is carbon steel. The material used allows for determination in not only how much the string needs to be tightened or loosened to produce the desire vibration, but also allows for calculation of how much the string can be tightened before yielding and breaking. As shown in Fig. 24, it plots the stress and strain a string will undergo before yielding, as well as defines the calculation for Young's Modulus. Again, the string is assumed to uniform and cylindrical. Calculated below is the tensile stress the guitar string will undergo given certain parameters:

$$\sigma = \frac{T}{\pi d^2} = \frac{9.089 * lbf - in}{\pi(0.00984252in)^2} = 924psi \tag{20}$$

6.2 Design for Safety

Below are the five risks associated with the design, in not apparent order.

6.2.1 Risk #1: String Break

Description: Too much tension applied to the string could result in string popping off or breaking, potentially hitting a user.
Severity: Critical
Probability: Frequent
Mitigating Steps: Installation of raised plexi glass over the top of the design to act as a shield.

6.2.2 Risk #2: Pinch Hazard

Description: User can wedge finger in opening for volume changing drawers
Severity: Critical
Probability: Likely
Mitigating Steps: Installation of large handles to drawers will block the user from being able to reach inside of the volume changing drawers. Additionally, drawers are configured such that its nearly impossible to fit a finger inside.

6.2.3 Risk #3: Sharp Corners

Description: Raw materials used is primarily plywood, where if left unsanded, could result in the user puncturing the skin or receiving a splinter.
Severity: Critical
Probability: Occasional
Mitigating Steps: Sand all corners as much as humanly possible to limit sharp edges.

6.2.4 Risk #4: Tip-Over Hazard

Description: Pulling on the drawers may result in too much force being applied to the design as a whole, causing the design to tip over.
Severity: Marginal
Probability: Occasional
Mitigating Steps: Design the box such that it is bottom heavy.

6.2.5 Risk #5: Tuning Key Failure

Description: The initial tuning key construction could break off after sometime due to lack of support, as well as wear on the actual tuning key.
Severity: Negligible

Probability: Unlikely

Mitigating Steps: Add additional supports to the tuning key to prevent injury. Additionally, selection of a more sturdy material for that part of the deign.

A heat map of the detailed risks above, provided in Fig. 28 below, will identify the most important risks to be accounted for.

Probability that something will go wrong

Severity of risk: Category	Frequent Likely to occur immediately or in a short period of time; expected to occur frequently	Likely Quite likely to occur in time	Occasional May occur in time	Seldom Not likely to occur but possible	Unlikely Unlikely to occur
Catastrophic					
Critical	String break	Pinch hazard	Sharp corners		
Marginal			Tip-Over hazard		
Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial					Tuning key failure

Figure 28: Heat map of risks for Vibration Station.

From Fig. 28, the risks are evaluated. The string breaking imposes the highest risk as it is critical and could occur frequently as it is in the top left corner of the heat map in the red zone. The tuning key failure is very unlikely and would cause little to no harm if the incident were to occur. Thus, this risk is placed in the bottom right (green) area of the heat map. Overall, the risks can be evaluated from the heat map and used to refine the design based on the severity and probability the proposed risk will occur.

6.3 Design for Manufacturing

In terms of large scale components in the design, there are a total of 18 total parts, ranging from cuts of wood, to an Arduino, to the tuning key. With respect to the number of threaded fasteners, there are a total of 34. The vast majority of the fasteners are used in conjunction with L-brackets, while appropriate wood screws are also used.

Additionally, there are eight theoretically necessary components that are crucial to the operation of the design. They are as follows:

- Force Sensor
- Tuning Key

- Guitar String
- Bridge
- Arduino Leonardo
- Digital Display
- Computer
- Drawers
- Jumper Wires

The above components are necessary due to their unique purpose that can not be replicated by a simple construction of wood and fasteners. In essence, there are 3 major purposes that a combination of the components have, which are measurement of the tension force, production of a musical note, and quantitative display of the tension force. All of which overlap at one point or another in achieving each purpose, the most important component that of the force sensor, which is calibrated to measure the tension in the string, as well as send that measurement to the Arduino, computer, and digital display.

In an effort to limit the number of theoretically necessary components, the only changes can be made constructing the drawer mechanism into one solid piece, where instead of three separate wooden boards being attached to the front, unify all the pieces. Additionally, the drawer mechanism itself can be more representative of a traditional drawer, making up the entire front of the design. With those changes being said, it is near impossible to eliminate one of those components as exclusion of just a single component would render an entire concept of the design useless. A combination of the force sensor, Arduino, and jumper wires could be redefined as a singular part, as well as the bridge, tuning key, and guitar string as another.

6.4 Design for Usability

The Vibration Station design is optimized for simplicity such that it should be apparent what a user will need to do to successfully interact and yield the lessons taught by the design. Some impairments such as vision, hearing, physical, and control might still make the design unusable without certain implementations. Vision being the least likely to influence our design comes as a result due to the design being created to make it obvious how the user should interact with it. There are 3 major components that can be manipulated, all in different locations, and distinguishable, as the design is reminiscent of a guitar. Hearing is the most influential, as one of the primary purposes of the design is to let the user hear how the sound changes when certain components are altered. In the case of a hearing impairment, multiple displays will output frequency in tension force in the string to visually show the difference in the users manipulations. An additional feature could be implementing multiple strings so that different pitches and frequencies could be achieved. A physical impairment might manifest itself with respect to more precise movements of the hands to adjust the design. Of the three major components, two of them require a distinctive movement of the finger to illicit the intended design purpose. With those considerations in mind, larger versions of the components, such as the tuning key and drawer mechanism are constructed such that they are easier to handle, and therefore can be manipulated. Additionally, an implementation of a large handle on the tuning key, as well as an automated string pluck could mitigate the physical impairments. Lastly control impairment is taken into account by making each adjustable component easy to move, as well feature visual additions in case the simple adjustment of each component is not enough. This can lead to distraction, but the visual aids are not the major part of the design, as emphasis will be place on the actual box itself. This impairment can be mitigated some by painting the box in such a fashion to highlight the maneuverable components.

7 Final Prototype

7.1 Overview

Based on the design changes mentioned in the Section 5.4, a final prototype was constructed. For the prototype, the same strings, strain gauge, and load cell were used. The wood chosen for the final prototype was 7-ply birch plywood. Design features such as a protective shield and tuning stop were added. Additionally, the sharp corners and edges were sanded down and rounded to prevent any potential injuries. The stop was integrated by using fishing wire and an anchor. The string was strung between the gears and tied down to an anchor when the string was at the max tension we wanted the demonstration to achieve (about 12 lbs). An acrylic shield was installed on the top to prevent potential injuries if a string was to break. To achieve the design goals, two drawers with handles were created to obtain three various volumes. Additionally, the strain gauge, load cell, and Arduino was used to measure the string tension within a reasonable range. After performing material testing for the stop, the tuning key began to wear and the tension measurements became more sensitive. However, the final prototype was able to achieve all of the prototype goals.

7.2 Documentation

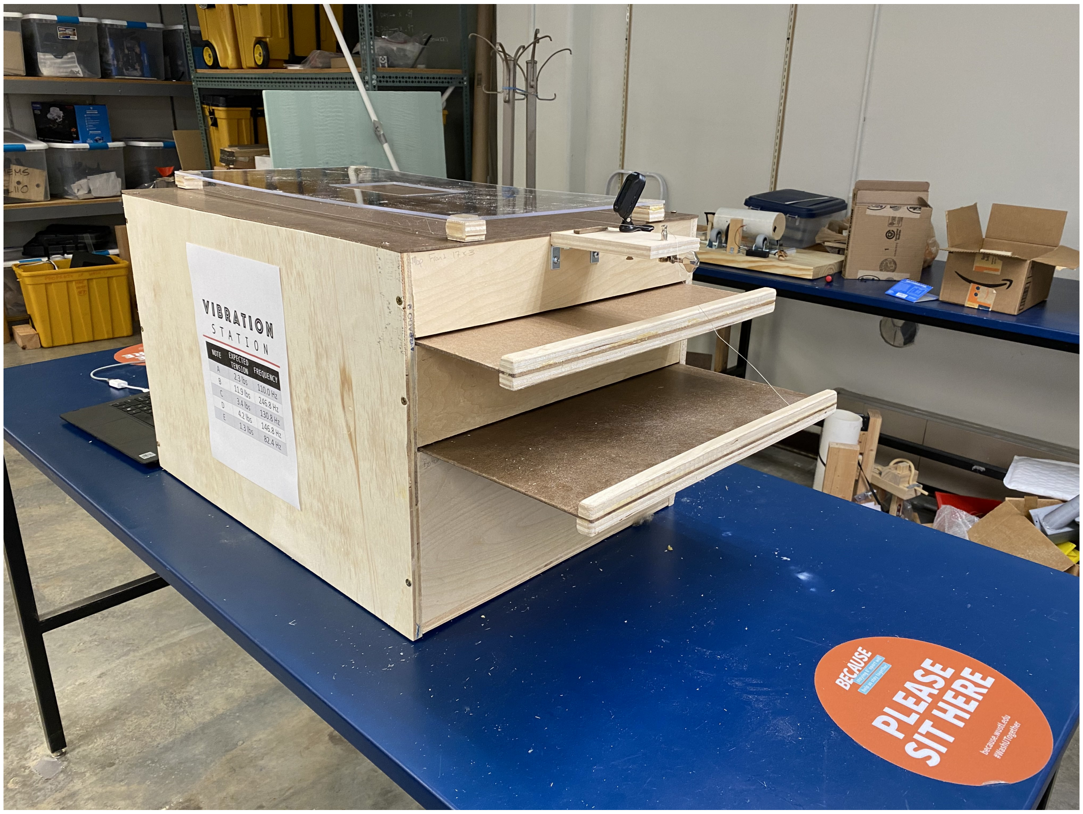


Figure 29: The Vibration Station

Figure 30: Top View of The Vibration Station

Figure 31: Closed Drawer View of Vibration Station

Figure 32: String Stop on The Vibration Station

8 Discussion

8.1 Project Development and Evolution

Does the final project result align with its initial project description?

- Yes, the final project did align with its initial project description. There are areas where the final project could have further enhanced the users learning experience. The prototype goals were all achieved; however, further improvements could have been made to improve upon the goals.

Was the project more or less difficult than expected?

- The project was slightly more difficult than expected for the majority of the parts of the demonstration. With the team having very little experience with string instrumentation, there was much initial research that had to be conducted. As the process progressed, the team was able to successful complete the prototype goals and learn how these goals could have been further improved.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

- The team could have spent more time on the concept generation and concept embodiment portion in the design process. With more time spend in these areas, more research on better materials as well as optional stop options could have been determined. Consequently, better sensors could have been chosen to heighten the users experience.

Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

– The stop was fairly hard to integrate into the design. There were several issues in determining the best material for the string used in the stop as well as how to ensure it will not go above the strings max rated load. As far as tuning the guitar, the team did not run into many issues. However, with little experience with electronics, it took time to figure out how to use the strain gauge to measure the string tension. We tried to include frequency; however, our strain gauge was not sensitive enough.

In hindsight, was there another design concept that might have been more successful than the chosen concept?

– No, the team believes we chose the best concept. If anything, the concepts could have been more morphed together.

8.2 Design Resources

How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

– The codes and standards most relevant to this project were chosen based on the project idea and the customer. Knowing the design would be located in a hands-on museum, safety was a main concern. The team researched standards relating to this concern and decided on using a safety standard for kids toys. Additionally, the properties of the strings were useful in determining their max stress. A standard relating to what these properties must be for musical instruments were chosen. Though these standards were taken into consideration, they were not a major influence in the design concepts.

Was your group missing any critical information when it generated and evaluated concepts?

– At the beginning of the process, the string material properties were not heavily researched before generating and evaluating concepts. Through more extensive research, strings with better material properties could have enhanced the prototype. Consequently, the material properties of all of the parts could have been helpful information to know before evaluating concepts. The plywood we used initially did not behave as well as we anticipated.

Were there additional engineering analyses that could have helped guide your design?

– Finite element analysis could have been conducted on the string based on the string's properties. This would have potentially given a more clear understanding of the loads the string could endure. A stress-strain analysis could have been completed to determine the ultimate yield stress of the string material of choice.

If you were able to redo the course, what would you have done differently the second time around?

– If we were able to redo the course, more thorough planning could have been conducted before meeting to construct our prototypes. This would have lead to a more effective use of our time. Specifically a more defined timeline of when to be starting actual construction of the prototypes.

Given more time and money, what upgrades could be made to the working prototype?

– For this prototype, a more sensitive sensor with a higher sampling rate could have been upgraded this initial prototype. With the upgrade, the device would have also been able to measure the frequency. Additionally, higher quality strings and tuning keys could have been purchased to further improve the prototype. The wood used in both prototypes could have been of higher quality.

8.3 Team Organization

Were team members' skills complementary? Are there additional skills that would have benefited this project?

- No one on the team had experience playing string instruments. This made it particularly difficult when learning about tuning a guitar appropriately and the best materials to choose, especially for the strings. The team and our project would have greatly benefited by one of us having experience with string instruments or by talking and learning from someone with more experience with string instruments.

Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

- Our experience further inspired us to look more in-depth at vibrational principles. This project gave the team an idea of what research development could look like in industry. It allowed us to determine for ourselves if this was something we could see ourselves pursuing.

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