James Obermaier
5/1/2024
MU3999 – Music Minor Capstone

The Pipe Dream

Project Concept

This project originally drew inspiration from the classic music box concept. I wanted to imitate the experience of having a stand-alone installation play music on its own. To amplify this captivating experience, I wanted the sound to have an ethereal, dream-like quality. What this meant to me is having the installation play notes with a slow attack and long sustain. This envelope would give a soft quality of tone, reminiscent of some rubbing their wet finger on the edge of a wine glass.

In terms of the timbre, I wanted the sound to be "pure," where the notes emphasize the fundamental frequency as the most prominent in their spectrum. Another important aspect of this installation is that the sound should be produced entirely acoustically, having no electronic amplification. This was aimed to enhance the stand-alone installation quality of the instrument, ensuring that all the sound heard comes from the instrument itself.

Musical and Visual Requirements

This installation was meant to be capable of playing any length of music as well as being able to be played live by a performer via a keyboard. The installation was also meant to be able to control certain dimensions of the music being played; specifically note velocity, duration, and tempo. These requirements mandated the use of a MIDI-compatible input, which provides live information on these musical dimensions.

The goal of this project was to create a dream-like, sustained sound. Because of this, I imagined the installation being used in the same context as a background/textural element.

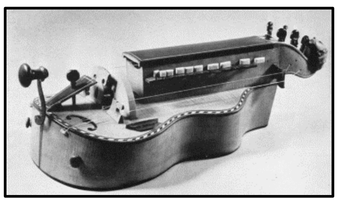
Visually, I wanted the mechanisms driving the sound to remain mostly hidden. I wanted some hint of what might be happening; if a large resonance tube was needed, for example, that can remain seen by the viewer. This requirement was to preserve a captivating, magical experience being created from the installation. With too much revealed about its operation, I was worried that experience might be lost on a viewer.

Prior Art

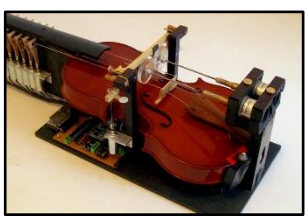
The background research conducted to inform this project will be separated by the main mechanism used for excitation of the sounding object. These categories are the friction wheel, bow mechanism, and electromagnetic actuation. Further descriptions of these excitation methods, prior art using these excitation methods, and insights gained from these works are listed below.

Friction Wheel

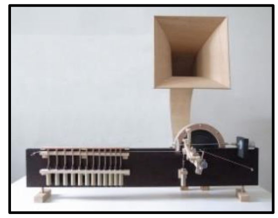
The friction wheel is a wheel of some material covered in rosin, or other substance which increases surface friction, meant to be rubbed against a sounding object. This actuation method is incredibly common in stringed robotic music machines and has been used in other machines such as friction idiophones as well.



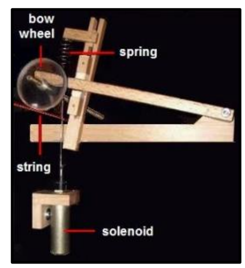
A classic example of the rosin wheel mechanism can be found in an instrument called the Hurdy Gurdy. The hurdy gurdy is a stringed instrument where the strings are excited by a rotating rosin wheel. This wheel is attached to a hand powered crank.



Pitch is controlled by a keyboard which presses small arms onto the strings at different lengths. The hurdy gurdy also features several drone strings which are played at a consistent pitch to accompany the melody strings (Turchet, 2016). The rosin wheel in the hurdy gurdy is traditionally made of wood with the edge covered in rosin. The edge of the wheel is made to be continuous, acting as a continuous bow (Winternitz, 1943).



The StringThing is a stringed musical machine invented by Martin Riches. This instrument has two methods of excitation, a bowing mechanism, and a separate plucking mechanism. The plucking mechanism is controlled using a solenoid which pulls a plectrum back and forth across the string. The bowing mechanism consists of a plexiglass wheel finished on the edge with coarse sandpaper and covered with violin rosin. The wheel is mounted on a lever arm which is pulled down onto the string by a solenoid and restored back to position with a spring. It is mentioned that an application of rosin lasts for around 10 minutes of playing at a time (Riches, 2013).



Another instrument by Martin Riches is the Automatic Viola. This is a very similar instrument to the StringThing, it even appears to feature a similar bowing mechanism. Here, two rosin wheels (with the same construction as the StringThing) excite two strings on a Viola. The rosin wheels appear to be lowered and raised using a similar solenoid and spring mechanism that is seen on the StringThing. The pitch is controlled with a series of finger mechanisms which push down on the string to change their vibrating length (Riches, 2015).

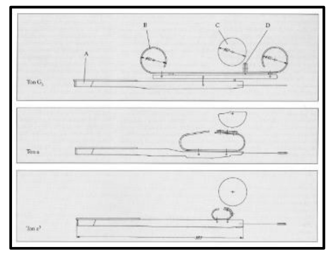
The instruments I've mentioned thus far utilize strings as their sounding/vibrating object. Another class of instrument called

friction idiophones use a non-sounding object to rub against a sounding object to produce sound. With an idiophone, all the sound that is produced is made from the instrument itself. Just as with stringed instruments, the non-sounding object must have the correct friction characteristics to induce vibration in the sounding object.

I wanted the installation to sound ethereal, with a "pure" timbre. This led me to research Benjamin Franklin's glass harmonica. This instrument features a series of tuned glass bowls stacked one after the other on a turning rod. The bowls are set into vibration by the player's wet fingers. It gained popularity in the mid-18th century for its ethereal tone and quality of timbre, but there were several complications.

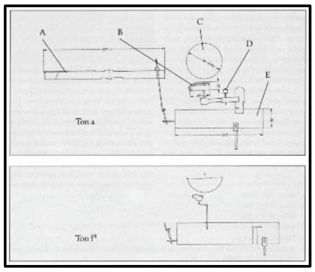
Most notably, the glass bowls were extremely fragile and subject to breaking during transportation. Another complication was the lack of keyboard interface. At the time, many instruments were made using a keyboard (Piano, harpsichord, clavichord, organ, etc.) and consequently many trained musicians of that time were unfamiliar with the glass harmonica. Having a keyboard interface would allow pianists and organists to easily play this kind of an instrument (Heise, 2007).

These issues were something that famous physicist Ernst Chladni was looking to solve. In 1800 he finished construction of his instrument which he named the Clavicylinder. This instrument took inspiration from the glass harmonica, but instead of the glass sounding object being rotated, the Clavicylinder uses non-sounding glass cylinders to excite a sounding tine. The sounding tines were made of curved iron rods and featured a felt-covered friction rod attached to them. These tines are raised so the friction rod contacts the rotating glass cylinders to induce vibration (Heise, 2007).



The choice to add the friction rod was to reduce the mechanical noise associated with the rotating cylinder contacting the friction rod. According to Chladni, by having the tines excited indirectly in this way, mechanical noise would be reduced without loss of sound from the tines. Additionally, the choice of the tines being curved seemed to have no effect on the fundamental frequency and had negligible effect on the tine's timbre. Chladni noted the function of the instrument would mostly be for longer, slurred passages as opposed to shorter, faster passages. He also noted that the volume of each tine could be controlled by varying the pressure applied to the keys on the keyboard (Heise, 2007).

Another example of a similar friction idiophone is the Terpodion invented by Johann David Buschmann in the early 19th century. Buschmann was a glass harmonica player but set out to construct his own friction instrument. The Terpodion also features a central rotating cylinder as its non-sounding object. This rotating cylinder was made of wood and was treated with a layer of rosin. The wooden cylinder would contact wooden or metal tines which would serve as its sounding object. These tines would be covered on the end with a felt or suede cloth for better vibration. For better acoustic amplification, the vibrations from the tines would be transmitted to the wooden soundboard below them. In this instrument, the volume of the tines could be controlled by varying the pressure applied to the keys.



The tone of the Terpodion was said to be like the glass harmonica, sometimes being said to mimic certain wind instruments. Listeners described the instrument as excelling at slower, choral passages and if being played by a skilled enough player could also play a selection of faster pieces. The disadvantages seemed to come mainly from the use of wood in some of the tines. When the instrument was kept in more humid environments, the wood would expand, changing its sonic characteristics. It also seemed to require frequent repairs.

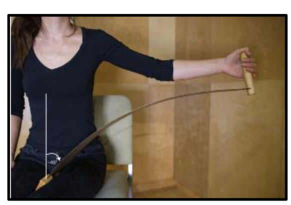
Overall, these friction instruments provide a good foundation for some design choices that could aid in the creation of my instrument. Most notably, the use of metal tines seems to be desirable not only due to their glass-like timbre, but also to avoid wood movement due to environment as seen in the Terpodion (Heise, 2007).

The use of a friction wheel also seems to be very common and has been made with a wide variety of materials like plexiglass, wood, and glass. Using a friction wheel would allow for a seemingly endless bow to play any length of passage necessary.

Finally, the use of a friction rod to contact the friction wheel could help reduce mechanical noise and provide a better overall acoustic environment for the sounding tines. This friction rod could also help couple the friction wheel with a better friction surface than the tine itself, allowing for the choice of tine material to be unrelated to its surface characteristics in relation to the friction wheel.

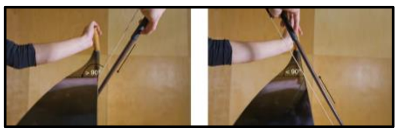
Bow Mechanism

Bows, like those made for violins or cellos, are the traditional way a performer would play friction idiophones. This can be seen on instruments like the bowed musical saw or the bowed vibraphone.



The bowed musical saw is a thin metal plate instrument, as the name implies, originally made from a hand saw. The saw is typically held on one end between the legs and the other end in one of the player's hands. It is bowed along its edge to create sound and bent to vary pitch, increasing tension as it is bent (Stuckenbruck, 2016).

Oliver Doucet, a Canadian saw player, preferred his saw to have a rounded edge. He claimed that the rounded edge allowed for optimal sustain as the bow was able to seamlessly transition on and off the saw following the curve of the edge (Stuckenbruck, 2016).



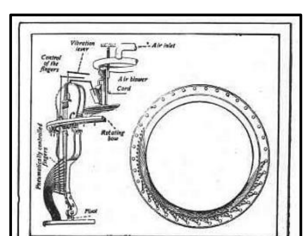
For optimal bowing, the bow should be played downward at an angle greater than 90º and upward at an angle less than 90º with respect to perpendicular (Stuckenbruck, 2016).

The vibraphone is a tuned bar instrument, typically made of aluminum, which can be played with mallets (impulses) or bowed (continuously). It is bowed in the same way as the musical saw, moving a bow vertically along its edge. For both of these instruments, where the bow is played is of importance. The musical saw must be played at the inflection poin of the bend, what is referred to as the "sweet spot" and the vibraphone bar must be played at the ends of the bars. The bowing location, varying edges, as well as attack angles of non-sounding object might be important factors to cosider in my design (Inácio, et al., 2001).

The standard bowing movement mentioned above has been used in humanoid style robots to play instruments like the violin.

Take, for example, the violin playing robot from Toyota. This robot is extremely complex in its motion, being able to emulate most of the playing characteristics of a human violin player. The violin is affixed to the robot's body and one of its arms is dedicated to fingering the strings on the neck. This arm can adjust to maneuver hand rotationally around the neck to move between the strings. The hand has 4 fingers which press on the strings to change its pitch. The fingers can vary pressure applied on the string to provide a tremolo effect. The other arm is dedicated to holding and maneuvering the bow. This arm has a shoulder, elbow, and wrist joint which all work together to move the bow back and forth along the strings just as a human player would. It can rotate slightly to move from string-to-string and vary pressure on the strings when necessary (Kusuda, 2008).

More practically for my instrument is a circular bowing mechanism found on instruments like the Hupfeld Phonoliszt-Violina. This player piano features 3 violins mounted within a rotating circular bow. The bow is wound with horsehair in a manner to create one continuous surface. The violins are turned and



THE VIOLIN AND ITS PNEUMATIC CONTROL.

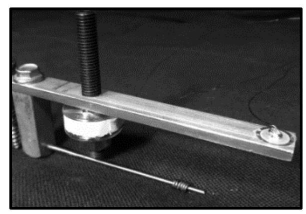
pressed onto the rotating bow to set them into vibration. This mechanism would allow for any string material to be wound the same way, resin applied, and tested for an alternative bow material to horsehair. Obviously, this bow can also be replicated with horsehair as it is on the Hupfeld Phonoliszt-Violina (Nass, 2017).

Electromagnetic Actuation

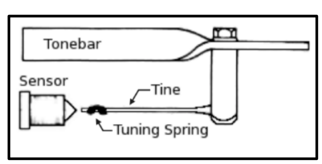
The last actuation method I researched was electromagnetic actuation. The theory behind this method is powering an electromagnetic with positive and negative voltage to push and pull a ferrous material into vibration. If the frequency of that vibration matches the resonant frequency of the ferrous material, that object will be set into resonance. This can be utilized on instruments which utilize a ferrous material as their sounding object like certain kinds of strings, tines, and bars.

The EBow (Energy Bow) is a handheld device which uses electromagnetic actuation to vibrate electric guitar strings. This device in its most basic usage can provide the player with infinite sustain, holding out the fundamental frequency to provide consistent vibration. The player can, however, manipulate the position of the EBow relative to the string to create different effects like a violin bowing effect, tremolo, and even exciting other harmonics besides the fundamental (Heet sound products, 1996).

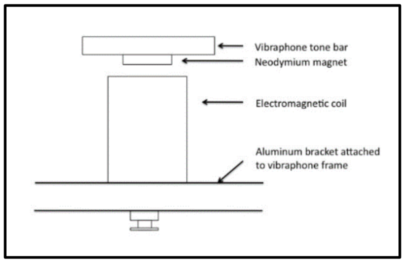
Another interesting example of electromagnetic actuation is with the electromagnetically actuated Rhodes piano. The Rhodes piano is like a traditional piano, but when a key is pressed, the hammer strikes a steel tine. This steel tine has a moveable spring attached to control the frequency of vibration. Attached to this tine is a tone bar which is tuned to the tine's frequency to provide reinforcement of the fundamental and sustain. On the axis of the tine is placed a passive electromagnetic pickup to record the vibrations to be amplified (Shear & Wright, 2011).



The electromagnetically actuated Rhodes Piano made by Gregory Shear uses homemade electromagnets attached to the tone bar of the Rhodes piano to excite the tine. The electromagnet is driven with a simple sine wave input tuned at the tine's fundamental frequency. Shear notes that the signal from the electromagnet tends to get read directly by the pickup, but the direct signal from the electromagnet is filtered out with simple circuitry involving phase cancellation. Additionally, more circuitry is used for more advanced filtering and the addition of other features such as aftertouch for velocity control. Here, the use of electromagnetic actuators was able to



achieve a similar timbre to that of the passively radiating tine and tone bar. Something to note from this project is if electromagnetic actuation is to be used to excite a tine, careful attention should be given to the input signal driving the electromagnetic. Irregularities in this signal could lead to inefficient driving of the resonant frequency of the tines or even unintentional resonance of unwanted harmonics (Shear & Wright, 2011).



Perhaps the most relevant example of this kind of actuation as it pertains to my instrument is the EMVibe. The EMVibe is a modular electromagnetically activated vibraphone. A vibraphone bar is typically made of an aluminum alloy, which is not magnetic, and can therefore not be driven directly by an electromagnet. To compensate for this, a neodymium magnet is affixed to the underside of each vibraphone bar. The full system consists of a dedicated magnet and electromagnet for each vibraphone bar, each with their own audio amplifiers (Britt, Snyder, & McPherson, 2012).

An interesting note with this project was regarding the driving signal of the electromagnet. They claim that because the vibraphone bars only have a limited number of vibrating modes, that the audio signal does not need to be "clean". Basically, a clean sine wave is not required to drive the electromagnet to produce a clean sine tone from the vibraphone bar. Instead, an amplifier sends a bipolar pulse wave at the right time to produce a sine wave movement in the vibraphone bar. This seemed to be a successful method to allow for amplification without needing a heat sink. One challenge that is mentioned is in regard to scaling this project. Only 8 electromagnets were feasible with this design, as the team of inventors were restricted to an 8-channel digital-to-analog converter (Britt, Snyder, & McPherson, 2012).

The tone of the EMVibe is described as ethereal. The tone is pure, and the attack is slow, increasing over time until achieving full resonance. The fundamental response appears to be the most prominent, lacking some of the overtone additions seen when the vibraphone is played with a mallet or bowed. Although the timbre is slightly different, for the purpose of long, drawn-out passages electromagnetic actuation seems to be an appropriate solution (Britt, Snyder, & McPherson, 2012).

This line of actuation is extremely compelling. After reading the various implementations of electromagnetic actuation, it seems that all that is needed to resonate an object is an electromagnet and a permanent magnet. By affixing the magnet at the antinode of the object and driving the electromagnet at the object's resonant frequency, the object should theoretically be set into resonance. This actuation method could lead way to a very customizable and versatile installation.

Objectives and Goals

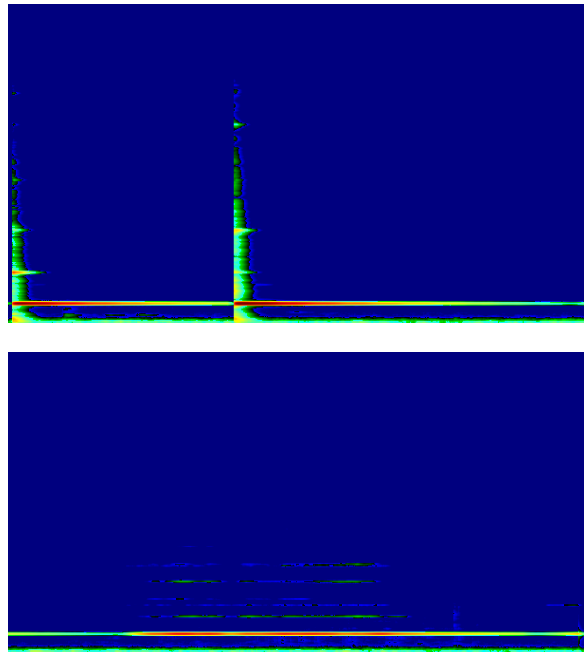
Before beginning experimentation, it was necessary to set out some objectives and goals. These helped guide the experimentation and construction of the installation. It is important to note that as I worked on the project, more objectives were added. Therefore, this list will be a growing and changing list. The objectives I set out at this stage are shown below:

1. Find the sound (the sounding object) of my instrument.
2. Choose an actuation method.
3. Create a way of interfacing the sounding object and the actuation method.

Experimentation

The first step in the experimentation was testing the timbre of various metal objects. Most of the items I tested were metal pipes of various shapes and sizes. For each of these pipes I generated a spectrogram with the aim of finding the object with a loud fundamental and minor contribution of overtones. Below is a picture of each of the bars stacked in order from bottom to top (1-13 respectively) and the corresponding spectrograms. Each spectrogram shows a few impulses when struck and a bowed section.

Object 1



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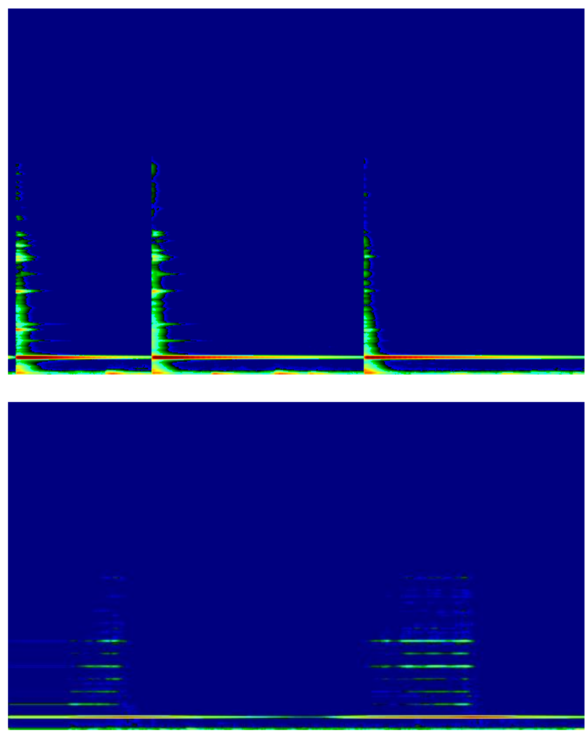

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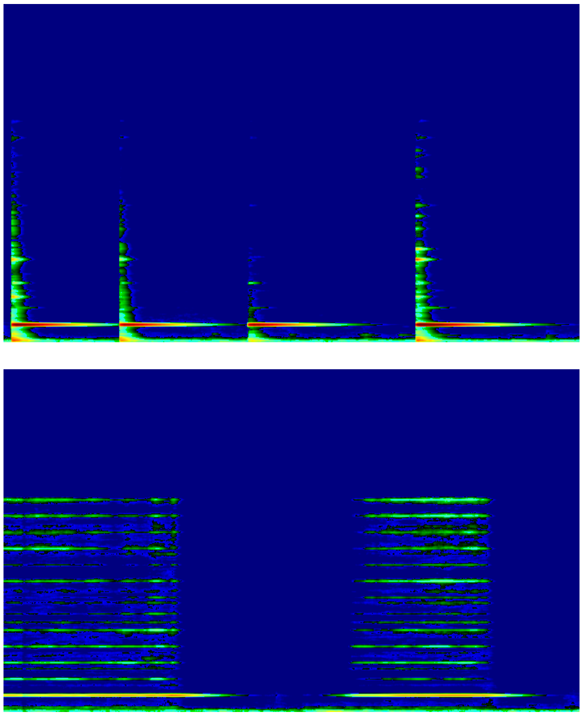

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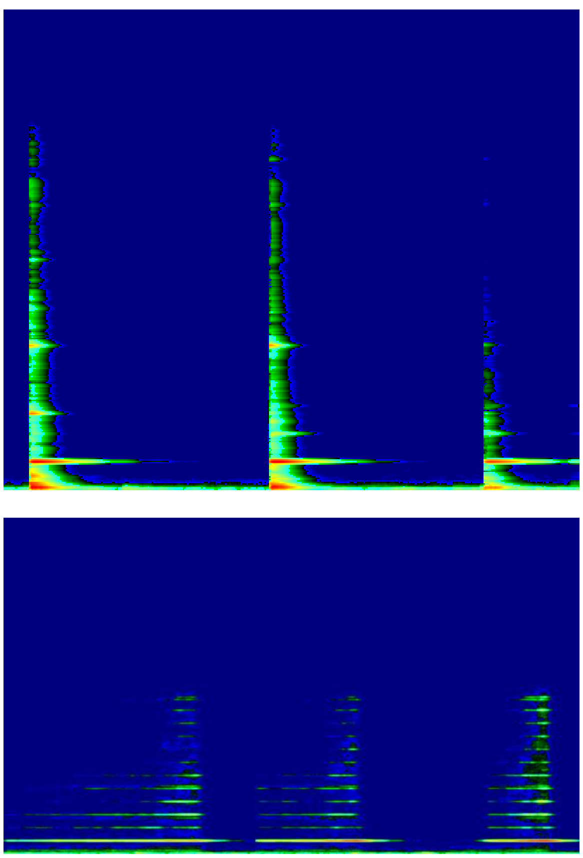

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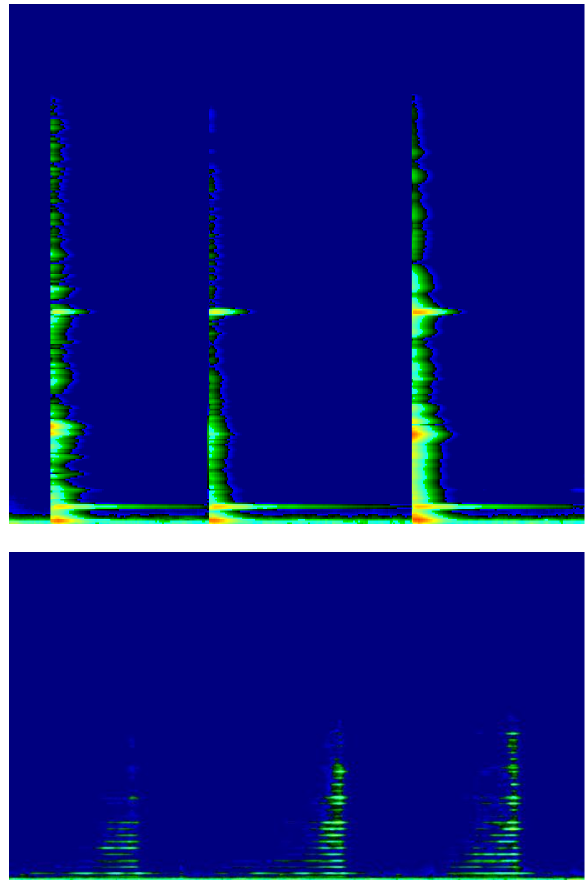

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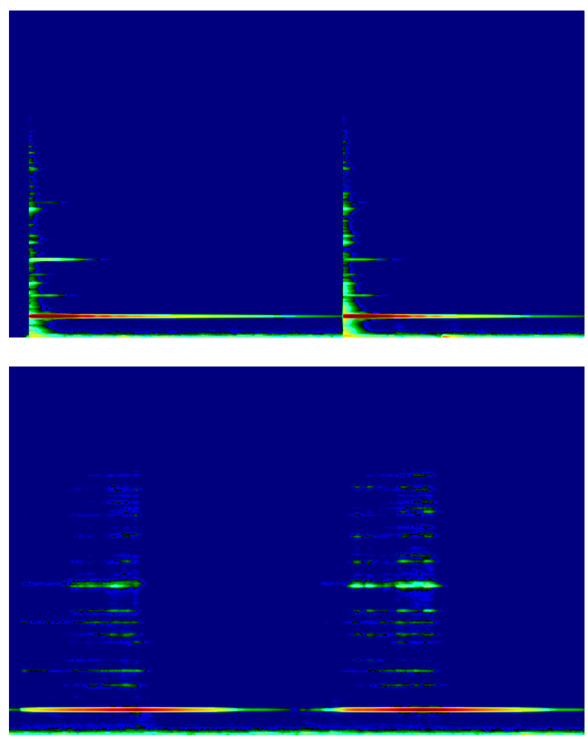
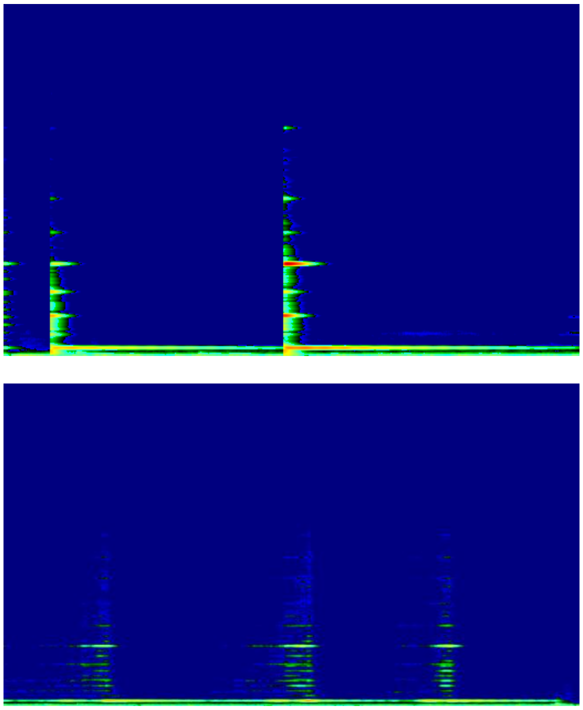


Object 7



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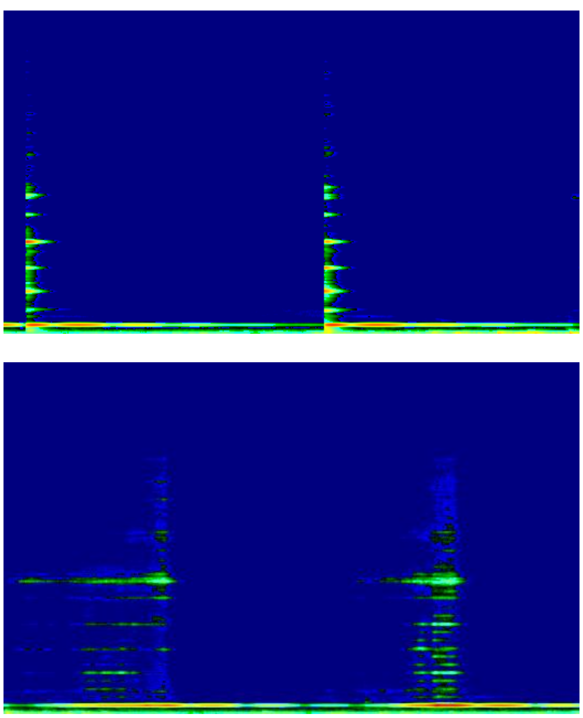
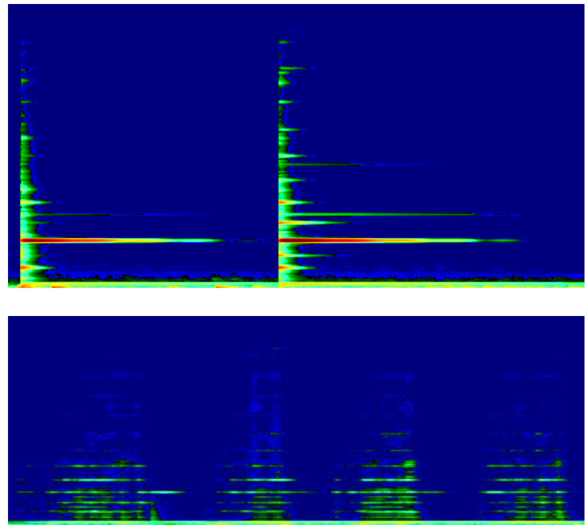
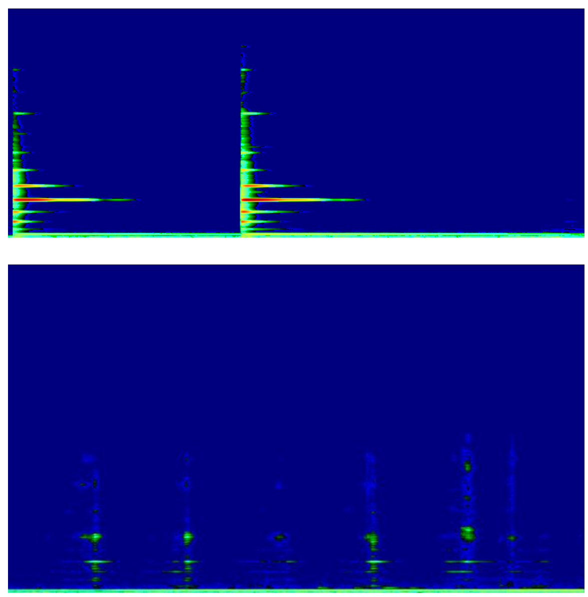


Object 9



Object 10



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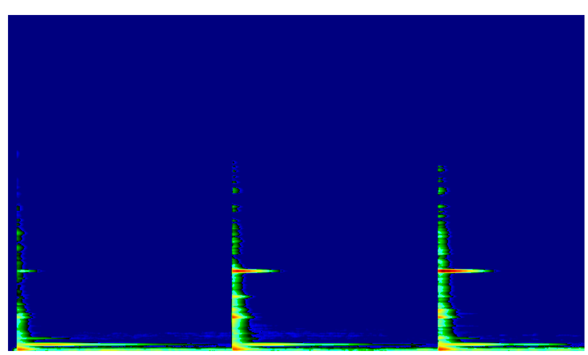

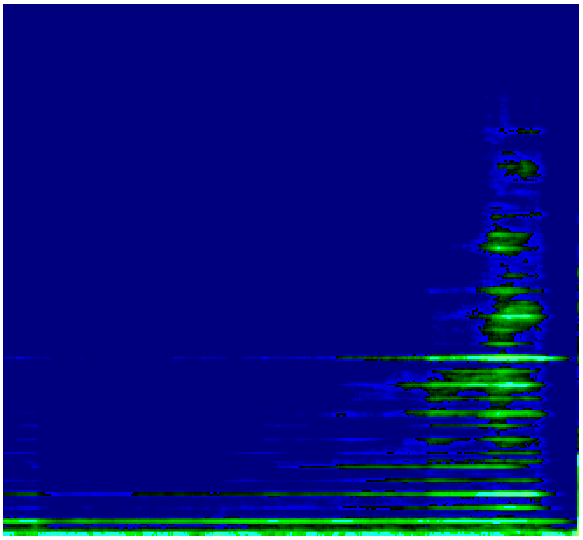

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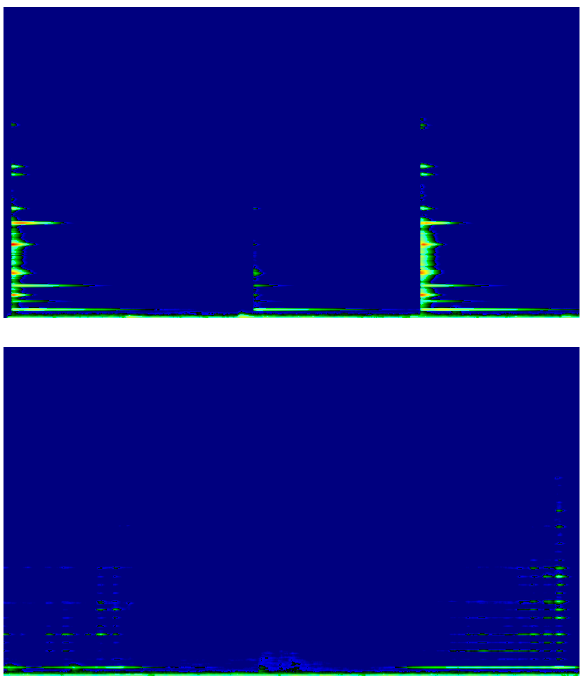
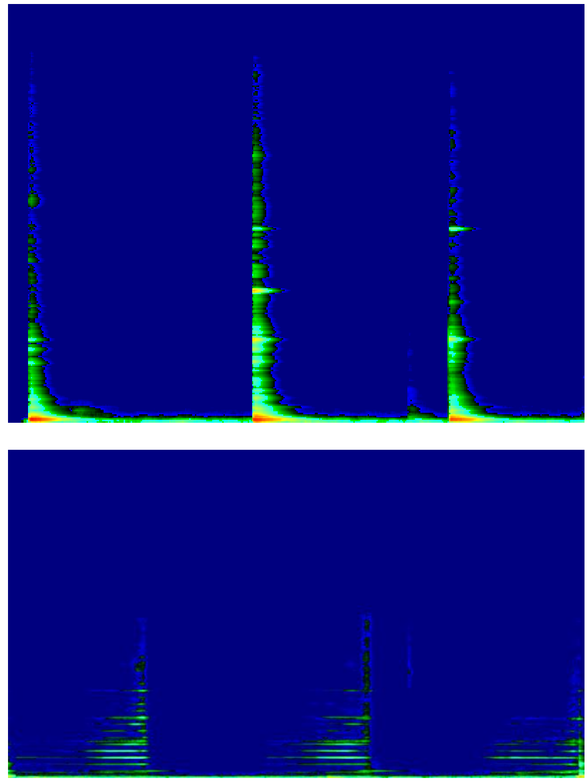


Object 13



These spectrograms revealed some interesting insights into the objects that were tested. Most notably, the difference in spectrum response between an impulse and bowing is quite apparent. Generally, when the bars are bowed there is significantly less contribution from the overtones, making the fundamental much more noticeable. This is an explanation for why the sound of a bowed idiophone tends to have a dream-like quality to it.

From these spectrograms I decided to choose object 6 as my sounding object due to its balance of frequency spectrum. It has a loud fundamental frequency which outshines the harsher overtones, while still maintaining a bright quality of tone. The way I would describe its sound is glass-like. This object is a square extruded pipe made of 6061 aluminum alloy with a T6 temper that Is available from most manufacturers.

With the sounding object chosen, I had completed my first objective and began experimenting with the second objective; the actuation method.

To begin experimentation, I got behind a vibraphone and began testing different kinds of surfaces to see what made the tine vibrate most effectively. Ideally, the vibraphone tine's sound would be much louder than the surface rubbing against the tine. I'll refer to the relationship between the wanted noise (vibraphone tine) to the unwanted noise (surface rubbing against tine) as the signal-to-noise ratio (SNR). Below are descriptions of various items I tested and the accompanying description of the noise I was able to produce with them.

Small Rubber Belt

This is a small rubber belt I pulled from spare parts of a 3d printer. One surface was a very smooth rubber and the other had evenly spaced rubber teeth. First, I pulled the belt tight and ran the smooth end against the corner of the vibraphone tine. As expected, this didn't produce much noise and the SNR was very low (Most of the sound came from the belt rubbing against the tine). I then tried the teethed side against the tine, and it gave similar results to the textured ping pong paddle. Overall, it seems textured surfaces are not going to give the results I'm looking for.

I then tested the smooth side again after I applied rosin. This did manage to produce some resonance, although it was very quiet. From what I could tell, the belt was too thin and didn't provide enough surface area for a large enough friction force.

Large Rubber Belt

This is a thick rubber belt usually used in cars. One side of the belt is wider than the other, with the cross section looking like a trapezoid. I first tested both sides without rosin and in either case I got poor results. After applying rosin, the thinner side gave similar results to the previous thin belt. The wider side, on the other hand, gave promising results. Once a certain amount of pressure was applied, the tine was set into resonance quite noticeably. Although the sound of the belt against the tine was noticeable, there was still a satisfactory SNR.

Violin Bow

The violin bow is the traditional way to bow to the vibraphone. With rosin, the violin bow gave great results having the sound I was looking for. I will note, the sound of the horsehair against the tine is quite noticeable, and if this instrument is meant to be played acoustically then limiting the sound of the horsehair against the tine might be desirable.

Leather Pad

This is a circular leather mousepad. To play this, I rolled it into a cylinder and rubbed the surface against the end of the tine the same way as a violin bow. Without rosin, this produced poor results. With rosin, however, this gave great results. The sound of the leather against the tine was almost unnoticeable compared to the sound of the tine resonating. Arguably, this gave a better SNR than the violin bow. It is worth noting, however, that the tine was set into resonance much faster than the violin bow. In other words, it took much less travel of the leather pad to produce the same amount of resonance when compared with a longer travel of the violin bow. Leather may be a good material to turn to for the friction surface of my instrument.

After testing these bowing materials, I decided that the violin bow and leather pad, both with an application of rosin, were giving the best results. The next step was to assemble a test fixture and see what kind of response I can get. In my mind what this test rig consisted of was a simple fixture to hold the bar in place, allowing movement in one axis. The bar would slide along this axis until the object contacted a rotating friction wheel which had either horsehair or leather with rosin on it. This would excite the bar and I'd be able to measure its response.

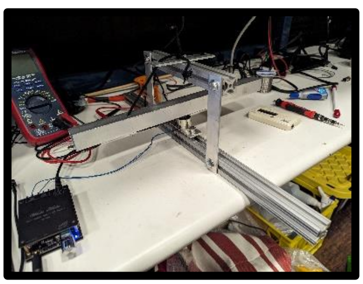
Before I built this, however, I wanted to test electromagnetic actuation. At this point, my preferred choice was this method of actuation as it would significantly decrease the mechanical complexity of the installation and the mechanical noise associated with its operation. Also, because I was limited by time, it was essential to conduct tests that cost the least amount of time first and make decisions early on my objectives.

To test this method of actuation I simply affixed an electromagnet to the center of the square aluminum pipe with superglue and held an electromagnet closely to it. The electromagnet was being driven by an audio amplifier which was outputting a sine wave at the bar's resonant frequency. The audio amplifier was driving the electromagnet with around 7 volts rms.

This test gave satisfactory results, resonating the bar with the pure, glass-like tone that I was seeking. With this method of actuation being both simple and successful, I made the decision to choose electromagnetic actuation as my method of actuation. This decision was made with the understanding that I only had about 4 more weeks to work on this project, so I did not have the time to fully explore the friction actuation methods previously outlined. With a viable actuation method, I completed my second objective; finding the actuation method for the installation.

With objectives 1 and 2 completed, it was time to begin objective 3, interfacing the sounding object with its actuation method. This would be the first step to creating the final instrument.

The Pipe Dream – First Iteration



The first thing I built was a simple frame which held a tuned bar above an electromagnet. The bar was hung using a piece of string which had knots tied on the underside of the bar. The string runs through the nodal points of the bar, allowing for the free vibration and increased sustain of the bar. The stringed wrapped around a piece of aluminum extrusion stock which was affixed to another piece of extrusion stock that served as the base for the instrument. The electromagnet was affixed to the base and was connected to the audio amplifier.

The purpose of this frame was to test how the distance from the electromagnet affected the sound of the resonance. I found that the closer the bar was to the electromagnet, the louder the response was. It is also important to note that the higher the current of the excitation signal was, the louder the response was as well. The optimal distance I found was adjusting the length of the string to be just a centimeter or so above the electromagnet. It should be close enough to where the permanent magnet is attracted to the electromagnet, so when the bar is displaced, the permanent magnet attracts the bar back towards the electromagnet. This makes the bars self-centering.

With this set up, I also tested different waveforms using a waveform generator supplying 5 volts rms. From this I determined that the ideal waveform was a continuous one; any waveform with sharp edges, like a square or sawtooth wave, introduced unwanted harmonics to the output. This testing left me with two viable options – a triangle wave and a sine wave. I noticed with the triangle wave there was some strange cancellations happening, leading to an unsteady tone, and I opted to pursue a sine wave to be the excitation signal.

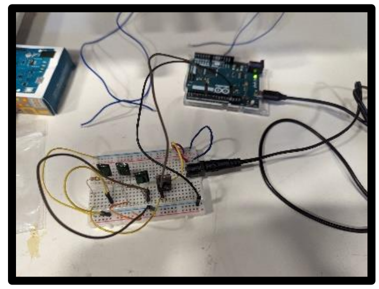
The Pipe Dream – Second Iteration

Coming in to the second iteration I had one main goal – To achieve polyphony. The previous iteration relied on an audio amplifier to drive the signal, which means if I went with this option that I'd need to have a dedicated audio amplifier for each electromagnet. This becomes bulky, inconvenient, and inexpensive so my first step was choosing a different excitation method.

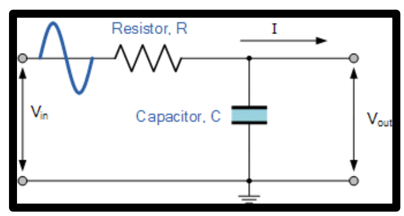
The first thought I had was to utilize a microcontroller like an Arduino for fast prototyping. Using the Arduino would allow me to use various pins to control the excitation of several electromagnets. I was also familiar with the implementation of reading MIDI information using an Arduino, so this seemed like a viable route to take. The only issue is that the Arduino can only output digital signals, restricting the output to be 1 of 2 possible values. Since I was looking to generate a continuous signal, figuring out a way to generate a continuous signal was the first challenge.

Before I began building the circuit, I needed to make a frame for the installation that could support a second bar. Using a similar design as the first iteration, I utilized 2 pieces of aluminum extrusion stock to support 2 hanging bars. On the bottom piece of extrusion stock, I affixed an electromagnet underneath each bar. This construction allowed for simple adjustment of both the bar height and position, as well as the position of the electromagnets. Now that the frame was built, it was time to begin circuit experimentation.

The first thing I did was use the tone() function in Arduino. This function simply outputs a square wave at a set frequency for a certain duration out of one of its digital pins. As expected, the resulting tone was quite harsh. Although the fundamental was most prominent, there were unsatisfactory contributions from the overtones associated with a square wave. This was not a viable option.

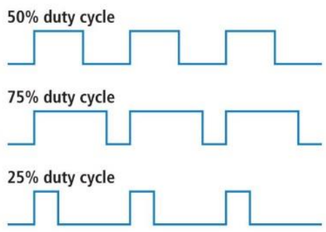


My next thought was to create a filtering network to run the square wave through. The theory behind this approach was the fourier series - that just like any wave, a square wave is simply a sum of a set of specific sine waves at various frequencies, including its fundamental frequency sine wave. By setting the cutoff frequency of the filtering network to be just above the fundamental frequency, I could filter out the additions from the overtones and have a pure sine wave.



I tried several filtering networks including a first, second, and third order passive RC low pass filter, and an active Sallen-Key filter (Storr, 2022).

Unfortunately, none of these filters worked sufficiently. Alone, the passive filtering network would attenuate the signal to be almost inaudible. Even after I added a simple N-Channel MOSFET to amplify the signal with an external power supply, the signal still contained the unwanted overtones and gave a harsh response. The active Sallen-Key filter did not provide enough attenuation of the overtones and led to a harsh response. At this point, I decided filtering a square wave was not a viable option.



The next option I explored was utilizing PWM (Pulse Width Modulation). PWM is a technique which modulates the on-time of a square wave signal. The percentage on time is referred to as a duty cycle – where 0% duty cycle is a flat line at 0 and 100% duty cycle is a flat line at peak output. By varying the duty cycle, you can simulate outputting a continuous signal as the average current that is delivered will be values in between 0% and 100%, even though the signal is still digital and only output either 0% or 100%. This technique has been used to control the brightness of LEDs and to control the speed of electric motors (Dee, 2015).

Theoretically, by continuously varying the duty cycle of the PWM signal according to a calculated sine function at a set frequency, the sine signal can be simulated using a digital signal. By outputting this PWM signal from a digital pin on the Arduino, the signal being sent to the electromagnets can be controlled, routed, and sent all from the microcontroller. By utilizing the analogWrite() function, I wrote a simple code to output a PWM signal to the electromagnet.

The resulting sound from this signal was interesting. It sounded better than just sending a square wave, as the contributions from the harsh overtones were significantly less noticeable. However, the sound still contained what sounded like scratching in addition to the fundamental of the bar. I suspected that this scratching sound was because I was utilizing the analogWrite() function rather than controlling the PWM function manually within my code.

I rewrote a PWM loop in my code which manually triggers a high and low state based on a sine wave function, as opposed to relying on the analogWrite() function. This gave a viable response, with imperceptible contributions from harsh overtones. The quality of sound achieved was glass-like and was exactly what I was looking for. I duplicated the code, changed the frequency of the second PWM function, and changed the pin and achieved polyphony! I now had a frame which could support two bars and a signal that could viably excite the bars.

One caveat to this method is it is relatively quiet. When I tried using an N-Channel MOSFET to amplify the signal with an external power supply, the overtones which I had successfully removed from the signal were reintroduced. This made me realize that if I were to amplify the PWM signal, I would need a more complex amplifier circuit paired with filtering stages to achieve the best sound. Unfortunately, at this point I did not have the time to explore this. Therefore, I decided to sacrifice the option to achieve the full volume potential and simply excite the bars directly from the microcontroller.

The last thing I wanted to test was the effect of utilizing various electromagnets with various permanent magnets. The pictured electromagnets all are rated for 5V at 1A with the leftmost magnet having a holding force of 25kg, the middle having a holding force of 10kg, and the rightmost having a holding force of 5kg. I tested these electromagnets paired with various sizes of neodymium and ceramic permanent magnets. My hypothesis going into this is that not only will the strength of the permanent magnet affect the amplitude of the response, but the diameter of the permanent magnet in relation to the diameter of the electromagnet would also affect the response. The idea behind that thought being that the greater the surface area of the permanent magnet, the greater the interaction with the generated magnetic field form the electromagnet there would be.

After testing these pairs, the best response I was able to achieve was by pairing the 10kg holding force electromagnet with the ceramic disk permanent magnet. One important insight I found was that the diameter of the permanent magnet should match the diameter of the core of the electromagnet for optimal response.

With an excitation signal selected and an electromagnet/permanent magnet pairing selected it was time to begin assembling the final iteration of the installation.

The Pipe Dream – Third Iteration

The first thing I did in the third iteration of the installation was switching the microcontroller from an Arduino to a Teensy 4.0. Teensy 4.0 is a common microcontroller for use in MIDI-related projects and has native MIDI capabilities. By utilizing the existing Teensy MIDI libraries, writing code to read MIDI from a DAW (Digital Audio Workspace) like Ableton was incredibly simple. At this point, I had a microcontroller which could accept MIDI input of one or several notes via USB. From this I could parse the note number, MIDI channel, and note velocity.

I then created code which would take the note number of an incoming MIDI event and send out the corresponding PWM signal I created in the previous iteration to a specific digital output pin. By copying this code 12 times and connecting the correct note number to the correct signal output, I was able to turn a MIDI note in a DAW like Ableton into a PWM output from the Teensy. From here, it was just a matter of creating 10 more tuned bars and a frame to hold them before I had my finished third iteration.

The process of tuning these bars required a significant amount of time and patience. The most efficient workflow I found to tune the bars was as follows:

1. Cut the bar to the approximate length that corresponds to the desired frequency.
    a. Using a previously tuned bar as reference is helpful for the approximation.
2. Strike the bar next to a tuner, and if the bar is flat begin filing one of the ends of the bar to remove mass.
    a. As mass is removed, the resonant frequency of the bar increases and will therefore make the bar sharper.
    b. Continue the process of filing and striking until the bar is in tune.
3. Once the bar is in tune, measure the center of the bar and super glue the permanent magnet to the bar.
    a. By adding mass, the bar from the permanent magnet, the resonant frequency is lowered slightly.
4. Repeat step 2 with the new bar until it is in tune again.
5. Measure and mark where the nodes on the bar are and drill 2 holes where the strings will attach to the bar.
    a. Theoretically, this should have negligible effects on the pitch if drilled at the nodes.

Each of the bars took me approximately 30-45 minutes to create and I created 12 bars representing a full octave from C6 to B6.

The final edit I made to the frame was using threaded rod to create the frame. This allowed the top piece of extrusion that the bars hung from to have an adjustable height. This change proved extremely helpful in the initial set up of the instrument, where fine tuning the height of each bar in relation to the electromagnet is critical.

The fully constructed frame is pictured below. As previously mentioned, the Pipe Dream can accept MIDI information from a DAW and sounding a corresponding aluminum bar. This can be monophonic or polyphonic MIDI data withing the 6th octave (C6-B6 or MIDI numbers 96-107). It has a very bright tone, ethereal, glass-like tone. The sound of the instrument is reminiscent of a finger rubbing the edge of a wine glass.

Discussion and Recommendations

This project was completed by one person in 7 weeks who has a limited background in creating musical machines. I say this to emphasize the versatility of this concept – If I can make this with this level of success in this short of time, then others can create much more with this concept. If someone with a greater background in circuitry, signal processing, Arduino experimentation, mechanical design, acoustics, etc. than I were to build upon an installation like this one, there are many improvements that could be made.

In terms of mechanical aspects of this project, finding a better way to mount the bars is certainly desirable. Right now, the installation requires each bar to be adjusted manually which can be quite fragile and challenging. Finding a more permanent way to hold the bars in place, while still allowing free resonance would be something worth exploring.

In terms of circuitry, there exists several ways to approach the issue of controlling an analog signal from a digital source. Exploring various Digital to Analog Converter ICs (DACs) or Digital Signal Processing ICs (DSPs) is the most obvious route in my mind, as these are ICs designed to tackle the exact circuitry challenges I faced in this project. Additionally, amplification circuitry is something I would recommend adding to this installation. Each electromagnet has specifications for a specific voltage and current rating, so creating an amplifier circuit to supply the electromagnet with sufficient current would give a better response from the bars.

One last recommendation I'd have for future work is to explore more musical dimensions with this project. By varying the maximum duty cycle, various maximum amplitudes can be achieved which can be mapped to note velocity. This would not only allow for duration control, but also velocity control. Additionally, exploring multiple excitation methods might be desirable. If it is required, a slightly different frame design could support striking the bars as well. These changes could add more musical possibilities and interactions with this installation.

The most significant takeaway from the Pipe Dream project is its versatility. This concept can extend to any object that makes sound and any kind of excitation signal. As long as the nodes and antinodes of an object are known, a permanent magnet can be affixed to it and it can be excited. Not only this, but future installations don't necessarily need to be a standalone installation. The sounding object and electromagnets can be placed in arrays around a space to create a multi-dimensional soundscape. This would require a redesign focused on modularity; however, this is certainly a route worth exploring.

All in all, the Pipe Dream concept is incredibly versatile and can extend to a wide range of applications. I look forward to seeing how far this project can go!

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