The Hydraulophone

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May 13, 2011

I. Abstract
A hydraulophone is an instrument that uses water to create sound. It consists of a row of two pronged pipes where one is a jet that is part of an interactive keyboard and the other one is an outlet that faces a spinning disc. When a user restricts the jet in the keyboard, fluid is diverted to the spinning disc and a certain frequency is produced. It reaches beyond the traditional sections of an orchestra consisting of strings, percussion, and woodwinds [1]. Additionally, the unique build of the instrument, a velocity-sensing keyboard that has endless keys, allows for new ranges of sound and music [2].

II. Motivation and History

The word "hydraulic" means of or involving a fluid, especially water, under pressure [3]. Additionally, the word comes from the Greek word for "water organ" [4]. The first water organs date back to the 1st century BC in Greece but work in the field has continued into the 21st century [5].

Figure 2.1: The Hydraulis of Dion invented by Ctesibius (Ktesibios) in Alexandria. Greek archaeologists recovered this fragmented hydraulis (water organ) with 19 bronze tubes dating from the 1st Century BC [6].

Water organs are organs that use water power to push air and create sound [5]. The fundamental difference between hydraulophones and water organs is how each creates sound; hydraulophones use water to make sound, and water organs use air to make sound. Despite the difference, the overall idea of using water in instruments is what unites the two and makes water organs' history relevant to studying hydraulophones [5].

The first record of hydraulophones is by Steve Mann who began designing, constructing, and playing them in the 1980s after earning degrees at McMaster University and Massachusetts Institute of Technology [7] [8]. Steven Mann is now a professor at the University of Toronto in the Department of Electrical and Computer Engineering [8].

I first came across the instrument in a YouTube video [9]. I was initially drawn to the playful and fun nature of the instrument and the interdisciplinary combination of music, art, and physics. As I researched the instrument more, I began wondering how the instrument was constructed and how water could create sound.

Hydraulophones open the gateway to being able to predict different qualities of a fluid based on some initial information [10]. For example, using the frequency and volume of a sound made by fluid and a couple other parameters to figure out which of an array of jets is being blocked. Similar analysis would be useful in any system involving hydraulic sound including plumbing or fuel lines. Technological advancements in "acoustic-based fluid flow analysis" would lead to more efficiency in those industries [10].

The design in itself is noteworthy for pushing beyond the normal limits of sound and music. Two instruments similar to hydraulophones are pianos and organs. All three instruments have keyboards with keys that are velocity sensitive meaning the volume of the note depends on how hard or soft a note is struck. With pianos, at whatever velocity you initially strike a key that note will start at that volume and then start decaying and becoming quieter. A pianist can't change the volume while the note is being played. Organs are slightly different in that in some constructions the notes don't decay, meaning the note stays at one volume the entire time, but you again can't change the volume of the note while playing it. With both instruments, the user is stuck with a volume after a key is initially struck and the sound will only be produced for a finite period. With hydraulophones, notes have infinite key travel, and users have the ability to modify the volume of a note while playing it. Glass harmonicas have a similar ability but lack a keyboard. Hydraulophones are a unique entity with their velocity-sensing keyboard with keys that never bottom out and whose volume can be changed with the note is being played.

One of the appealing aspects of the instrument is the visual component. It's fascinating to be able to play music-using water, a durable and fun medium to work with. Also, it's incredibly interesting to be able to see the quality of a sound change as the spray from the jet changes. Due to the build of the instrument, the spray from the jet is inversely proportional to the volume and timbre of the sound produced. Most instruments don't have a visual demonstration of the quality of sound and in that way hydraulophones are revolutionizing the field of music.

III. Theory of Operation

On a hydraulophone, each jet is independent and represents a different note. This means that a user can block multiple jets at the same time and create chords. When a jet is not being blocked, the water from the hose goes directly from the hose up to the top jet outlet. Although there is a side outlet connected to a spinning wheel, water doesn't escape into the side due to the vacuum made by the water going up. The vacuum is created by the high velocity of the fluid coming out which creates low pressure on the side, drawing a vacuum (Bernoulli's Principle) [11].

When a jet is blocked on a hydraulophone, the water is diverted to the side outlet, which goes to a spinning disc. The disc consists of circles of holes that are evenly spaced where each circle of holes corresponds to a specific jet/key. When the fluid is diverted to the spinning disc, depending on whether there is a hole or no hole, there is a compression zone (no hole) or rarefaction zone (hole). The result is a series of compressions and rarefactions that make up a sound wave of a particular frequency [2].

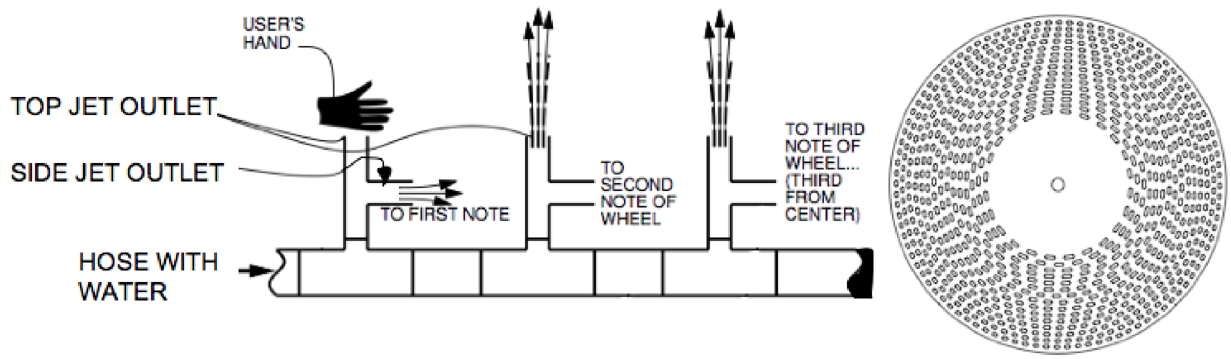


Figure 4.1: The diagram above shows the effect of blocking or not blocking a jet outlet on a hydraulophone [2].

Pitch in music is another word for frequency [13]. The frequency of the sound wave produced by a specific jet depends on how fast the disc is spinning, the radius that the given water jet hits the disc, and the distance from the center of two consecutive holes at a given radius. The equation for frequency would be as follows:

$$\text{Frequency (Hz)} = \frac{\text{Radius (meters)} * \text{Angular Speed (radians per second)}}{\text{Distance Between Holes (meters)}}$$

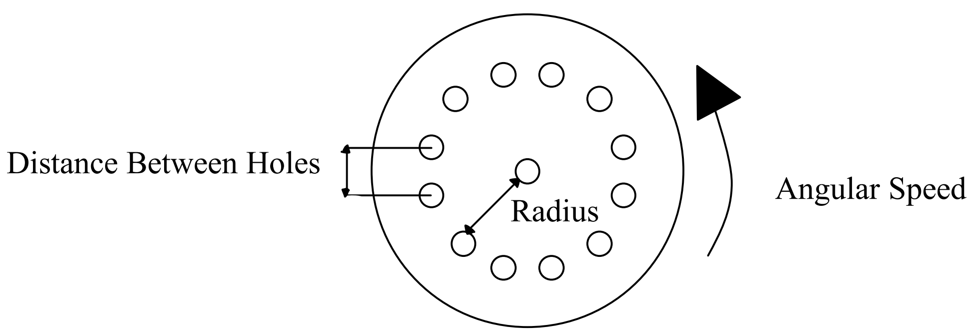


Figure 4.2: The diagram above shows the factors on the spinning disc that contribute to the pitch of a note being played on a hydraulophone.

Timbre is the tone of the sound being played and equivalent to figuring out whether a sound is brighter or darker [14]. Generally speaking using water to produce sound has more dark sounding qualities [2].

The volume and timbre of a particular note mostly depend on how much you push down on a given water jet. The origin can be set at the very top of the jet outlet (refer to *Figure 4.3*). The quality of sound is then dependent on the user's displacement from the origin meaning closer to the origin and very little displacement yields brighter, higher volume notes and farther away yields lower volume, darker notes. Displacement and sound tone are inversely proportional. The more you push down a given jet, the more water will be diverted to the side jet outlet to the spinning disc. The greater amount of water interacting with the spinning disc, the higher the sound level because more water is going through it [10]. Given that some water does escape into the side nozzle, even when a key is not being pressed, a note is always being played, just softly. The displacement can be thought of as being a very large number or infinite since the water jet can travel infinitely far when no finger is obscuring the jet. Thus when no jets are pressed, the instrument makes a drone sound that comprises of every note being played softly at the same time [2] since infinite displacement creates sound just very low volume sound.

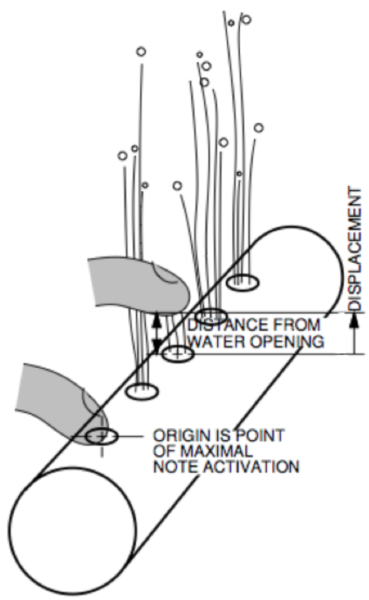


Figure 4.3: The diagram above shows the origin in the displacement model [2].

Other factors affecting the sound of each note include the temperature of the water. Cold water has a more viscosity than hot water [15]. Thus hotter water has less resistance meaning the quality of sound produced will be slightly louder. Though this effect is very small and may not be noticeable.

Lastly, embouchure effects sound quality [15]. This means if you block the water more towards the center of the hole or towards the side of the hole, the quality of the sound produced will be different. Water from the jet comes out fastest at the center and thus when you block the center of the jet, more fluid is diverted to the side outlet which means a louder, brighter sound is produced.

IV. Design

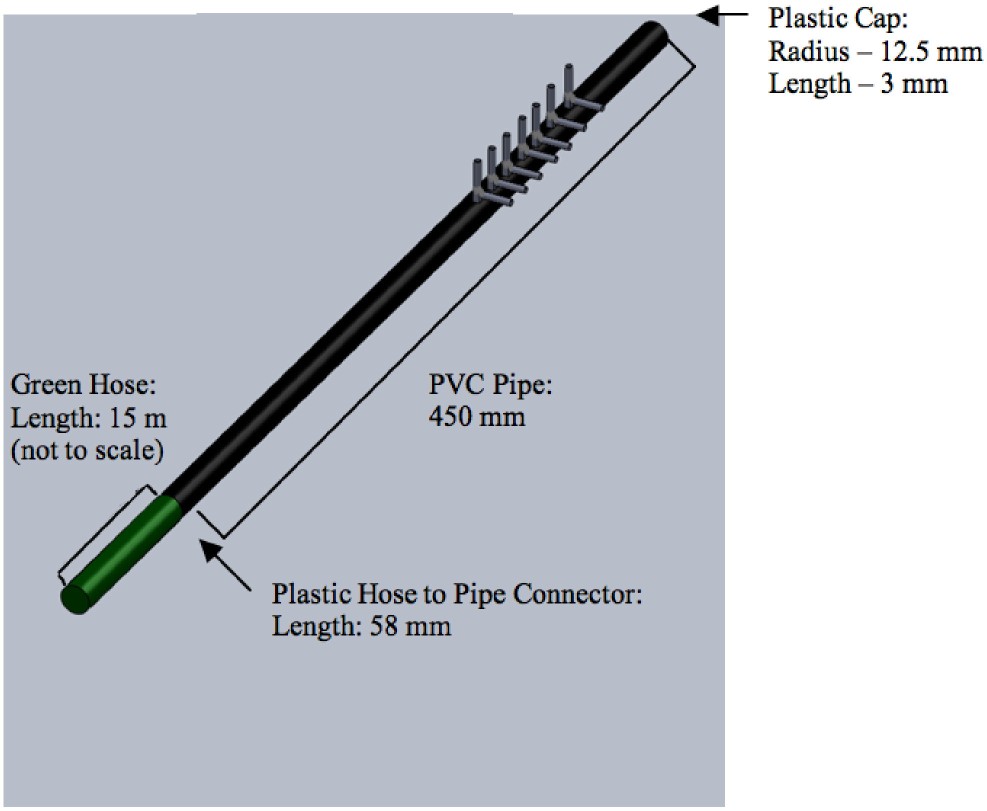


Figure 4.1: The diagram depicts the main body of the hydraulophone. There are two-pronged outlets (the L shaped objects) that represent each note. The total number of keys is 8. The third octave was used.

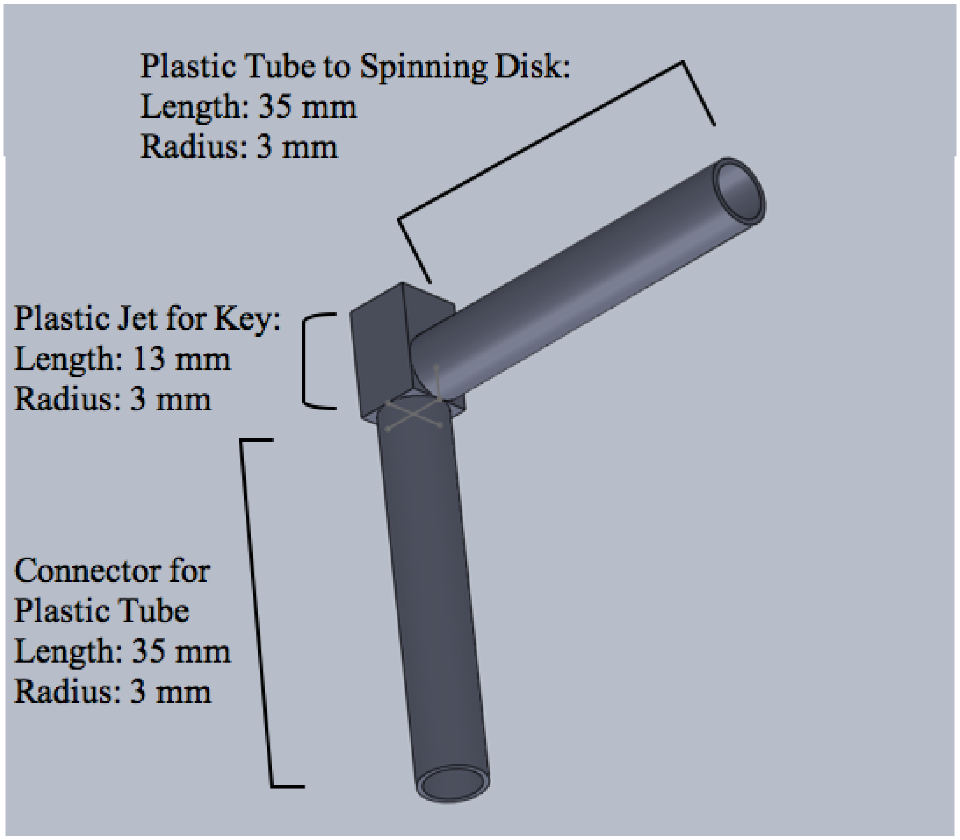


Figure 4.2: The diagram represents a sample two-pronged outlet. The outlet facing up is the jet that the user interacts with while the outlet facing right is the outlet that has water that goes to the spinning disk. The last outlet connects the two-pronged outlet to the tube.

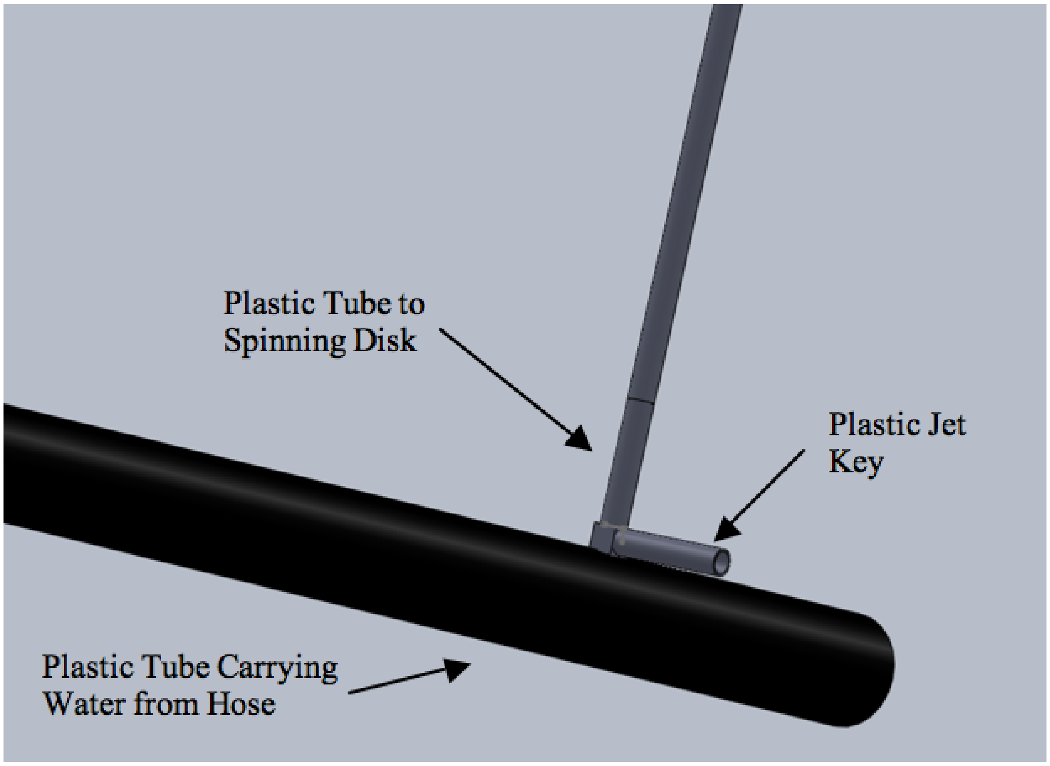


Figure 4.3: The diagram depicts a close up of the connection. The two-pronged outlet will be attached to the main body with PVC pipe glue.

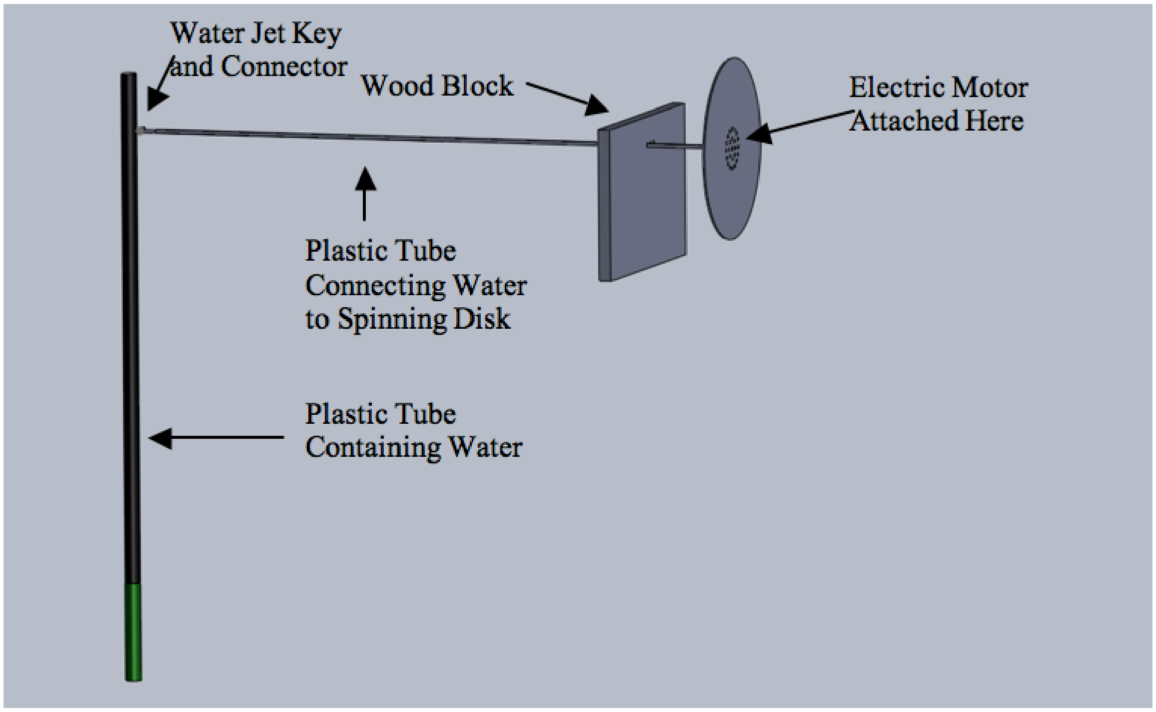


Figure 4.4: The diagram shows a perspective view of set up. The spinning disk will be attached to an electric motor where both are resting on a wooden board, not depicted in the picture. The wood block is resting on the same board and will be strapped down using L-clips. The plastic tube that connects the user interaction with the spinning disk is a flexible pipe although it is shown being hard in the picture. Also the main body plastic tube will probably perpendicular to its position as shown above.

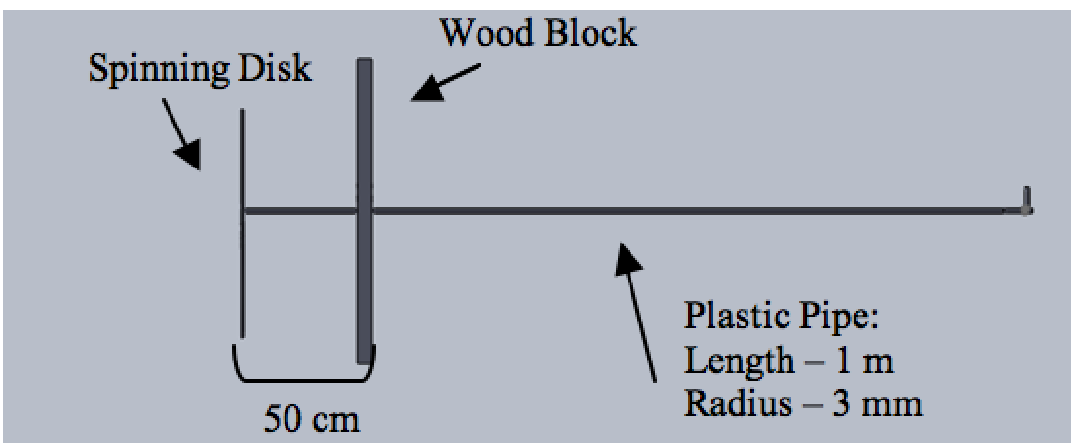


Figure 4.5: This diagram shows a side view of the set up.

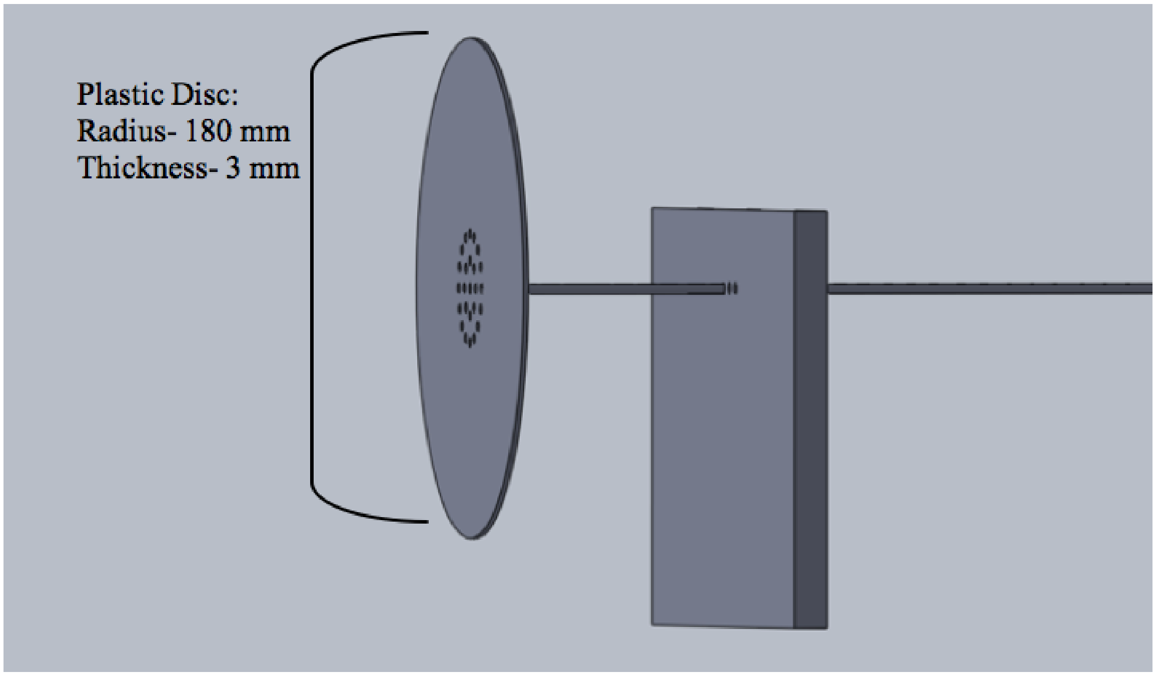


Figure 4.6: The diagram depicts a close-up perspective shot. Each radius of holes corresponds to a jet outlet on the main body.

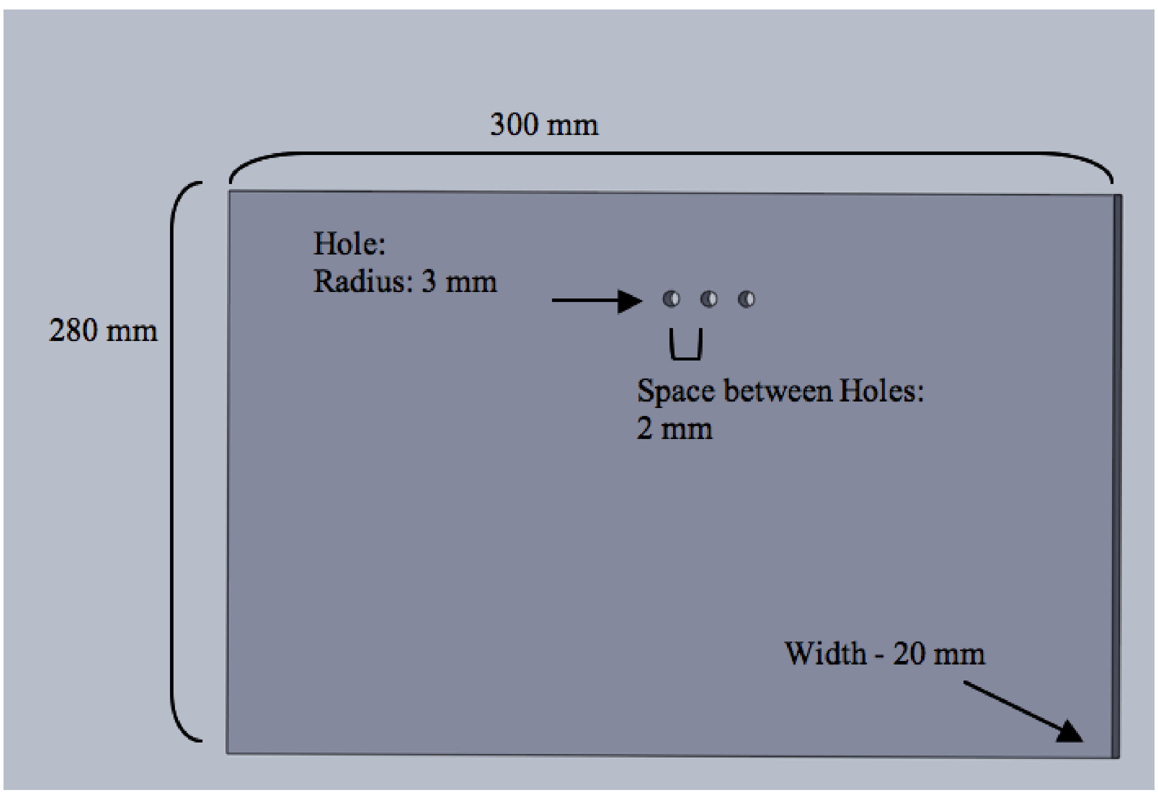


Figure 4.7: The diagram depicts a perspective shot of the wooden block that connects the tubes with the spinning disk. The holes ended up being spaced more jaggedly so that they could be more than 2 mm apart.

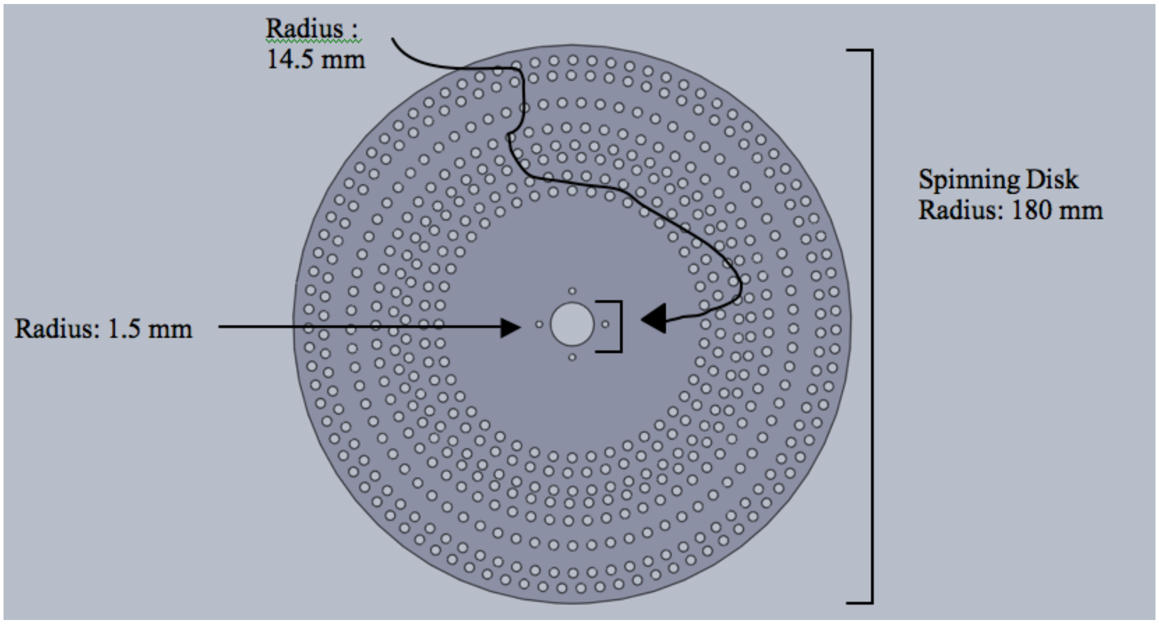


Figure 4.8: The diagram depicts the spinning disk that has groups of holes that are set at distances corresponding to data explained in the results section. Each set of holes (holes all at the same radius) corresponds to a water jet pipe/note. The disk had thickness of 3 mm and was laser cut from plastic.

Figure 4.9: The picture shows the setup of the hydraulophone with everything connected. The board is stuck to the table with 7 clamps, 4 of which are shown in the picture. The plastic bag in the mid right corner is covering the power supply.

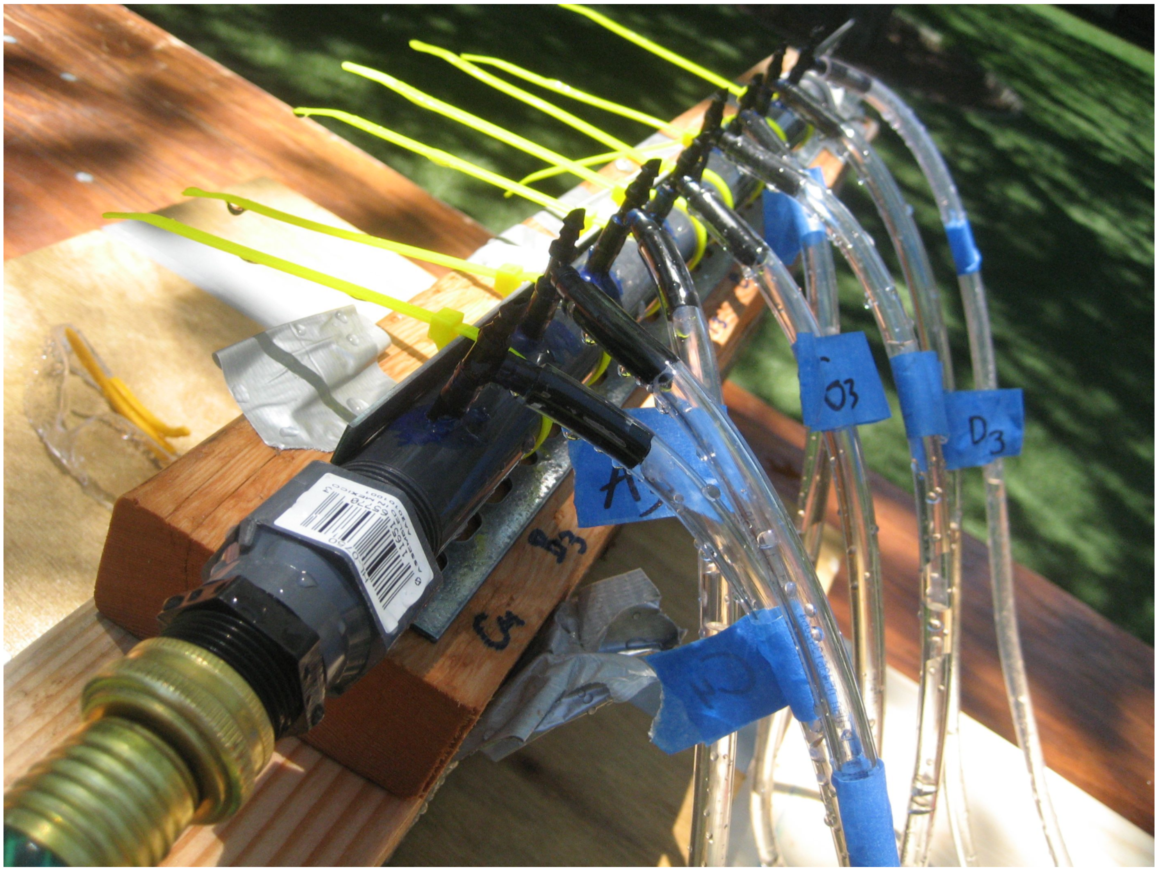


Figure 4.10: The picture depicts the pipe that is connected to the hose (the gold and green nozzle on the lower left). The yellow zip-ties hold the pipe in place and the wood props up the wood so the water from the tubes is flowing downhill. Each tube and outlet is labeled with the respective note it plays.

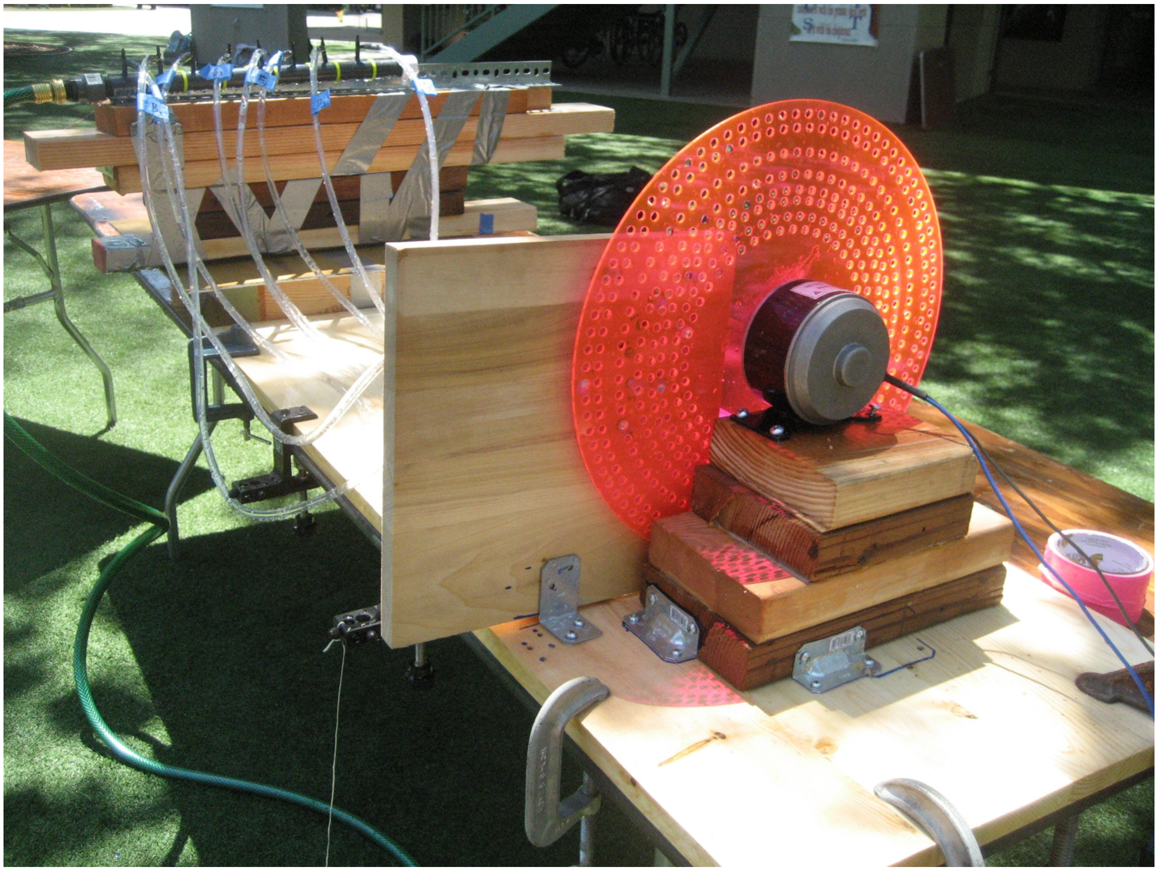


Figure 4.11: The picture shows a more close up perspective on the electric motor. It's bolted with 4-inch bolts so that it won't become unscrewed at 22 volts. The brackets and clamps are to insure more stability at faster speeds.

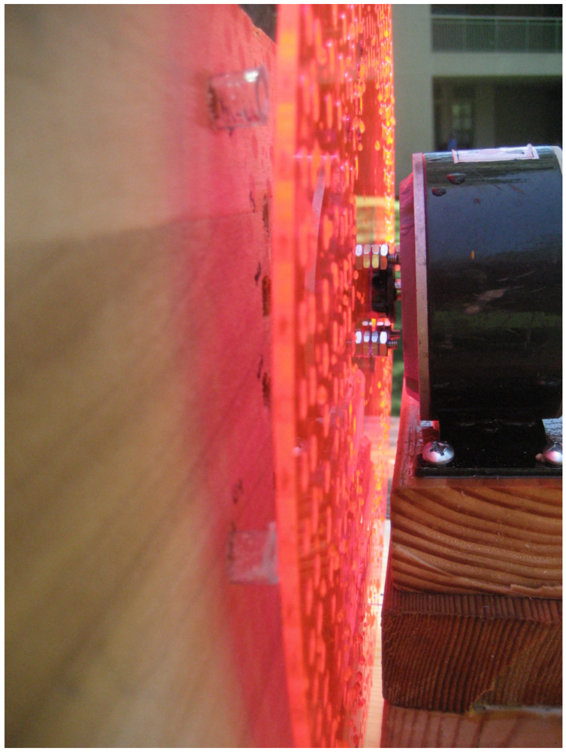
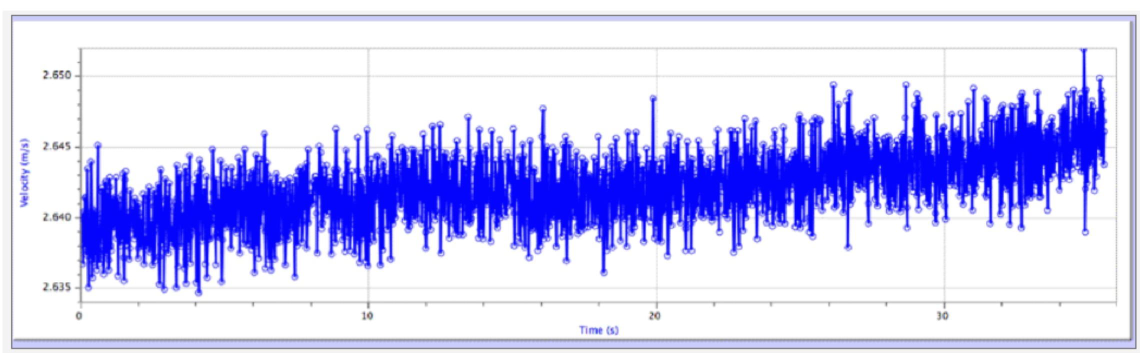


Figure 4.12: The picture shows a close up on the side. It shows how close the plastic tubes were to the plastic spinning disc. Electric tape is cushioning the disc so that it has a more tight fit and doesn't wobble.

V. Results

Motor at a Constant Speed

In order to figure out whether the electric motor I used could run at a constant speed, I attached a wood piece with masking tape to the motor. And used a photo gate to calculate how frequently the masking tape passed by the sensor.



Graph 5.1: The velocity in meters per second of the motor at 20 volts versus time in seconds. This is data outputted by the LabQuest.

At 20 volts, the data points fluctuate between 2.635 m/s and 2.65 m/s (.015 difference). The average velocity after 1 minute was 2.64 m/s. I calculated rotations per second by figuring out that the radius of the motor was .096 m and thus the circumference (2*pi*r) was .603 m. So in 1 second, the motor went 2.64 m and if each rotation is .603 meters than the motor did 4.3781 rps.

$$\text{Speed (rps)} = \frac{\text{Speed (m/s)}}{\text{Radius (m)} * \text{Pi} * 2}$$

$$\text{Speed (rps)} = \frac{2.64 \text{ m/s}}{.603 \text{ m} * \text{Pi} * 2}$$

$$\text{Speed} = 4.3781 \text{ rps}$$

17 volts using similar methods yielded 3.1218 rps. This all didn't take into account the load of the plastic disc with nails thus it probably spun slower with the load. I tried both voltage outputs with my motor even though my calculations were for 3 rps.

Determining Hole Placement

When creating the disc, a difficult task was determining where to put the holes in order to gain the desired frequencies. The chosen scale went from C3 to C4 (8 notes) in order to be a scale that could play the most number of songs at a commonly heard octave.

Note	Frequency (Hz)	Wavelength (cm)
C3	130.8	264
D3	146.83	235
E3	164.81	209
F3	174.61	198
G3	196	176
A3	220	157
B3	246.94	140
C4	261.63	132

Chart 5.2: A chart of the frequencies and wavelengths of the given notes.

There were three different methods used to figure out hole placement. The first method was setting each of the holes at set radiuses and at 4.3781 rps. Then figuring out the distance between the holes using the following equation where intended frequency, radius, and angular speed are known:

$$\text{Distance Between Holes (meters)} = \frac{\text{Radius (meters)} * \text{Angular Speed (radians per second)}}{\text{Intended Frequency (Hz)}}$$

Note	Intended Frequency (Hz)	Radius (m)	Distance Between (m)	Number of Holes
C3	130.8	0.02	0.004204893	30.59856866
D3	146.83	0.04	0.007491657	33.94808541
E3	164.81	0.06	0.010011528	37.95535529
F3	174.61	0.08	0.012599507	40.13290405
G3	196	0.1	0.014030612	44.99579346
A3	220	0.12	0.015	50.46548246
B3	246.94	0.14	0.015590832	56.61314004
C4	261.63	0.16	0.016817643	59.95546671

Chart 5.3: A chart of the frequencies and radius. At 4.3781 rps, the distance between is a calculation using the above equation. The number of holes is the distance between + the diameter of each hole (3 mm) divided by the circumference.

The number of holes isn't a hole number which is an issue since you haven't have .61 of a hole. I next tried to hold the distance between the holes at certain constants, but that failed for the same reason. With the rounded number of holes, I used the following equation to calculate frequency for both methods:

Frequency (Hz) = Angular Speed (rps) * Number of Holes

But the yielded frequencies in both methods were off by 4-8 Hz from the intended frequencies.

The last method I tried was writing a program (Appendix B) that ran through different numbers of holes and rps numbers to determine whether a given frequency was within 1.5 Hz of the desired frequency. I ended up finding that 3 rps was the smallest rps that yielded non-decimal number of holes and within 1.5 Hz of every desired frequency.

Note	Intended Frequency (Hz):	Speed (RPS):	Number of Holes:	Calculated Frequency (Hz):
C3	130.8	3	44	132
D3	146.83	3	49	147
E3	164.81	3	55	165
F3	174.61	3	58	174
G3	196	3	65	195
A3	220	3	73	219
B3	246.94	3	82	246
C4	261.63	3	87	261

Chart 5.3: A chart of the intended frequency, speed, number of holes, and calculated frequency. The calculate frequency is the speed multiplied by the number of holes (equation shown above).

This yielded the most accurate hole data out of all three methods. And using *ToneGen*, I played different songs that were off by 2 Hz and to the 35 people I asked (not randomly) 3 of them could tell that it wasn't the right pitch but all of them thought the songs still sounded fine and like the original. I used "Mary had a Little Lamb" and "Twinkle Twinkle Little Star" as samples.

In order to get the most consistent sound, I wanted the holes at each radius to be equally spaced and have the same distance as the diameter of the hole.

Note	Diameter of Tube (mm)	Ideal Circumference (mm)	Radius of Circle (mm)	Rounded Radius of Circle	Edited Circumference (mm)	Absolute Difference between Ideal Circumference and Edited Circumference
C3	6.35	558.8	88.9357822	89	559.2034923	0.403492339
D3	6.35	622.3	99.04212109	99	622.0353454	0.264654589
E3	6.35	698.5	111.1697277	111	697.4335691	1.066430903
F3	6.35	736.6	117.2335311	117	735.1326809	1.46731906
G3	6.35	825.5	131.3824055	131	823.0972752	2.402724759
A3	6.35	927.1	147.5525477	148	929.9114255	2.811425463
B3	6.35	1041.4	165.7439577	166	1043.008761	1.608760992
C4	6.35	1104.9	175.8502966	176	1105.840614	0.940614064

*Chart 5.4: A chart including the ideal circumference (number of holes * diameter of tube * 2) and the edited circumference (2 * pi * the rounded radius). The absolute error is at most 3 mm. This error shouldn't affect pitch (the frequency) since the frequency was calculated independent of radius.*

Using the rounded radius and the number of holes, I created the disc in *SolidWorks* and laser cut it onto 3 mm thick pink plastic.

If the sound from the hydraulophone had been louder, I would have used a sound probe to find the frequencies of the different notes and then graphed the note versus the difference in calculated and actual frequency. If there were some correlation, I would correct the difference in my next model.

I ended up not spinning the motor at 14 volts (the intended voltage to get 3 rps) because the sound of the electric motor would over power the sound of the hydraulophone and the disc was in tune with itself so it didn't actually matter which speed I spun the disc at. I ended up playing "Mary Had A Little Lamb" [16] with water, which sounded audible and correct.

The volume of the sound was proportional to the amount of water displaced [17] though the sound difference is very slight. The timbre of the sound was overall very fuzzy and high. The hydraulophone worked very well and clearly with air, but was much more interesting and fun with water.

If I had more time, I would have loved to run a statistical test to see if there was statistically different frequencies produced using different temperatures of water.

VII. Conclusion

When running the hydraulophone, pressing down on a given note at different distance (meaning one's finger was closer or farther from the hole) changed the water pressure in a way one could visually see. Unfortunately, the volume of each note produced wasn't very loud which was partially due to the racket the motor was making which drowned out all other sounds. Additionally, it was difficult to play chords since the water pressure over powered the disc and would change the speed. To combat this issue, I would make a disc that had more inertia.

Potential fixes for the problem include remaking the plastic piece that binds the spinning disc and motor so there is a better connection and less wobble. Using metal instead of plastic for the spinning disc so that it is sturdier and heavier against the water flow. Also, having water flow from both directions at the disc so that the pressure from one side would be balanced by other side.

In general, I think I should have used a microphone or amplifier so that the volume would be more audible.

Whiles my hydraulophone, I learned a lot. I feel like the project helped me realize I need to manage my time better on scientific projects and that while nothing is efficient and everything take 3 times as long as you expect, it's important to keep going and not take extended breaks from it. I learned how to use *SolidWorks* extremely well and how to use almost every machine in the ASR room. Coming from August 2010 where I didn't even know how to strip a wire, I think I've come a long way. I really enjoyed the amount I learned about music theory and the role math and physics plays in that discipline. Overall I think the project was a success, and I appreciate how much I accomplished.

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[17] “Water Displacement - Hydraulophone,” 2011,
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VII. Appendix

Appendix A

Part Description	What needed for	Cost	Where you'll buy it
Electric Motor	To turn the plastic disc	-	Already in ASR room
Plastic disc with circles of holes	To create compressions and rarefactions	$20	Tap Plastics
Wood Block with holes	To connect plastic tubing to plastic disc	$10	Orchard Supply
50 m long clear plastic tubing with 3 mm diameter	To connect side nozzles to spinning disc	$25	Orchard Supply
8 sprinkler connecters	To create jet outlets and pipe for water	$5	Orchard Supply
Wood Pieces	5 blocks of wood will be used to hoist the keyboard up and 1 board to place all parts on	$15.50	Orchard Supply
Hose	A water source for the instrument	-	Home
10 L clamps	To bolt all parts down specifically the wood block and electric motor	-	Already in ASR room
Plastic PVC Pipe connector	To connect the PVC pipe to the hose	$2.49	Orchard Supply
10 Zip Ties	To bolt the PVC pipe down	4 * $5.50	Already in ASR room
Metal Bar	To bolt the PVC pipe down	-	Already in ASR room
Plastic PVC Pipe	To connect water and create enough pressure within	$15	Orchard Supply

Appendix B

The following program was written in Java in Eclipse. It was used to determine the best RPS and use an error of plus or minus 1.5 Hz.

```
public class hydraulophone {

	/**
	 * @param args
	 */

	static int TWO = 0;
	static int THREE = 0;
	static int FOUR = 0;
	static int FIVE = 0;
	static int SIX = 0;
	static int SEVEN = 0;
	static int EIGHT = 0;
	static int NINE = 0;
	static int TEN = 0;
	static int ELEVEN = 0;
	static int TWELVE = 0;
	static int THIRTEEN = 0;
	static int FOURTEEN = 0;


	public static void main(String[] args)
	{
		System.out.println("Frequency:		RPS:		Number of Holes:");
		generate(130.80);
		generate(146.83);
		generate(164.81);
		generate(174.61);
		generate(196.00);
		generate(220.00);
		generate(246.94);
		generate(261.63);
		System.out.println(	"TWO: " + TWO);
		System.out.println(	"THREE: " + THREE);
		System.out.println(	"FOUR: " + FOUR);
		System.out.println(	"FIVE: " + FIVE);
		System.out.println(	"SIX: " + SIX);
		System.out.println(	"SEVEN: " + SEVEN);
		System.out.println(	"EIGHT: " + EIGHT);
		System.out.println(	"NINE: " + NINE);
		System.out.println(	"TEN: " + TEN);
		System.out.println(	"ELEVEN: " + ELEVEN);
		System.out.println(	"TWELVE: " + TWELVE);
		System.out.println(	"THIRTEEN: " + THIRTEEN);
		System.out.println(	"FOURTEEN: " + FOURTEEN);
	}
```

```
public static void generate(double freq)
{
	for (int i = 1; i <= 20; i++)
	{
		for (int j = 0; j <= 100; j++)
		{
			int m = 0;
			double holes = (double) j;
			double rps = (double) i;

			double temp = holes * rps;

			double dif = temp - freq;
			if (dif < 0)
			{
				dif = dif * -1;
			}

			if (dif < 1.5)
			{
				// System.out.println(freq + "                    " + rps + "                    " + holes);
				if (rps == 3)
				{
					System.out.println(freq + "                    " + rps + "                    " + holes);
				}
				if (m == 0)
				{
					if (rps == 2)
					{
						TWO ++;
					}
					else if (rps == 3)
					{
						THREE ++;
					}
					else if (rps == 4)
					{
						FOUR ++;
					}
					else if (rps == 5)
					{
						FIVE ++;
					}
					else if (rps == 6)
					{
						SIX ++;
					}
					else if (rps == 7)
```

```
                                        {
                                                SEVEN ++;
                                        }
                                        else if (rps == 8)
                                        {
                                                EIGHT ++;
                                        }
                                        else if (rps == 9)
                                        {
                                                NINE ++;
                                        }
                                        else if (rps == 10)
                                        {
                                                TEN ++;
                                        }
                                        else if (rps == 11)
                                        {
                                                ELEVEN ++;
                                        }
                                        else if (rps == 12)
                                        {
                                                TWELVE ++;
                                        }
                                        else if (rps == 13)
                                        {
                                                THIRTEEN ++;
                                        }
                                        else if (rps == 14)
                                        {
                                                FOURTEEN ++;
                                        }
                                }
                                m ++;
                        }

                }
        }
    }


}
```