Construction and Properties of a Tubulum

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Physics 406

Final Lab Report

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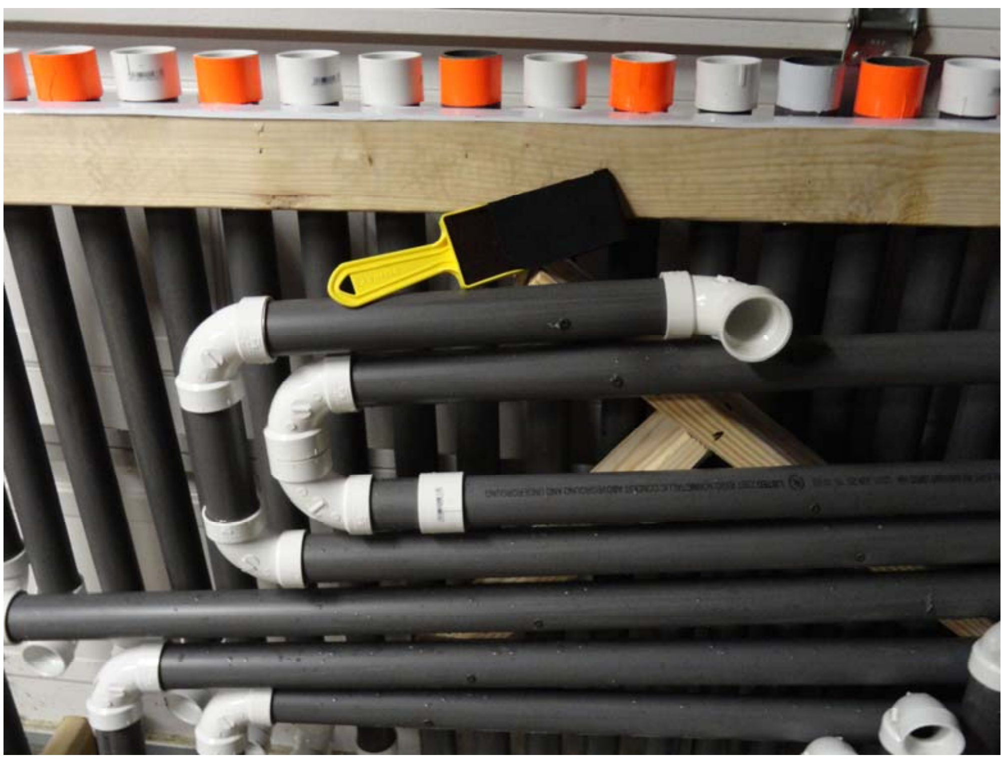

Purpose

For my final project I wanted to build a musical instrument from scratch, using only well-established principals and creativity. To keep myself from cheating by looking up directions online, I chose to build a tubulum, since I couldn’t find any useful information on it’s construction. A tubulum was also a fitting choice, given the tools required to build it, my love of strange sounds, and my ADHD-driven affinity for drumming on things.

Theory

The tubulum is a collection of tubes of differing lengths. The pitch of each tube is determined by its length. This makes it a form of wind instrument. However, the column of air inside the tube is vibrated by a flattened, rubbery “beater” slapping one end of the tube, which gives it properties of a percussion instrument. The combination of these elements result in a sharp, yet airy sound that resonates after the initial slap of the beater.

With most percussion instruments, the beater is used to vibrate the instrument, which in turn vibrates the air around it, creating sound. With the tubulum, however, the beater itself moves the air. When the beater hits the open end of the tube, it bounces back, which sends a pocket of high-pressure air into the tube. The pocket of air resonates in the tube at a frequency determined by its length and the width of the openings. Therefore the tubulum can be thought of as series of Helmholtz resonators.

Since each tube serves only as a resonator, it’s best to use materials that dampen vibrations caused from being struck directly while reflecting sound waves from an external source. PVC piping works well. A wide rubber hose would be ideal if the inner wall didn’t absorb the sound waves. The beater needs to have a flat, rubbery surface with which to strike the end of the tube. It needs to be soft enough to not vibrate the pipe upon impact, yet heavy enough to move air quickly.

The length (L) of each tube is determined by the desired frequency (F), the velocity (V) of sound in air, and an end correction factor (C) in the following formula: [$L = V/(2F) – C$], where $C=0.33x$(diameter).

Measurements

To test the validity of the equation relating pipe length to frequency, I used a chromatic tuner to measure the resonant frequencies of differing lengths of tubes. The tuner displays which even temperament note the frequency is closest to, along with the number of cents above or below it. Using the logarithmic equations for the even temperament scale and a list of note frequencies, I calculated the frequencies of sample lengths of pipe ranging from .43 meters to 3.36 meters.

All measurements were taken on straight lengths of 1.5 inch diameter PVC conduit with straight fittings on both ends. The larger diameter fittings served to botch standardize poorly-cut pipe ends and catch more air when played, thereby creating a louder sound.

The velocity of sound in air had to be calculated because I had no way to measure it directly. The speed of sound is dependant on temperature, humidity, and pressure. I used usairnet.com to get local air pressure readings. I used a portable, digital thermometer/humidity meter for the other two variables. I calculated the speed of sound to vary between 344m/s to 348m/s for the range of conditions that would be reasonable to expect indoors. Therefore it was crucial to have an accurate measurement of V.

The results are charted below. As predicted, the difference between the measured wavelength and the measured tube length varied by an amount that stayed constant, rather than varying with length. The rms of the differences was 1.56cm. Given the diameter of 4.8cm, the measured end correction constant was (.325)D, which is very close to the predicted value of 0.3.

Tube Length	Frequency	Wavelength	Note	Difference	Variables
0.45	374.29	0.464	F3#+20	0.0138	25 celcius
0.74	229.74	0.756	A3#-25	0.0157	55% hum.
1.16	148.54	1.169	D+20	0.0138	101.2 kPa
1.57	109.68	1.583	A2-10	0.0178	347.22m/s
1.85	93.03	1.866	F2#+5	0.0161	D=0.048m
3.07	56.32	3.083	A1+41c	0.0127	RMS=.0156
3.36	51.47	3.373	G1#-15c	0.0184	C=(.325)D

It is important to note that during my initial measurements, I found the difference between the two measurements to vary as a function of length. I did not realize, however, that the ambient temperature was changing as I was taking my measurements. This change correlated to the length of pipes I was measuring, which initially led to false conclusions. It also led to much re-adjusting as I built the actual tubulum.

Since many of the pipes had to be quite long, 90 degree elbow fittings would be required in the design of the tubulum if I ever wished to get it out of my garage. Therefore, I had to measure what effective wavelength an elbow fitting added to a pipe. I measured the wavelength of a 1.84m pipe to be 1.93m. I then cut the pipe in half and attached the two pieces together using the elbow fitting, as shown below:



The new wavelength was measured at 1.859m, which differed from the uncut pipe by 8.1cm: the effective length of the elbow fitting. I chose this method to measure the effective length of the fitting to make it easy to calculate the length of uncapped pipes that would need to be cut. Using this method, the total length of pipe could be measured out and cut into pieces, and I would only have to subtract 8.1cm for each fitting. The pipe slides approximately 2cm into each end of the fitting. Therefore, an elbow joint at the end of a pipe adds 10.1cm to the length. Straight fittings add approximately 2 cm to the end of a pipe.

Implementation

I considered several designs for the tubulum. My priorities were keeping it small enough to fit on my bike rack and keeping it as cheap as possible. I wanted all the lower pipe ends to face straight out towards the audience while not extending out too far, so I most of the pipes end with an elbow joint. I also had to make sure none of the pipes would end behind other pipes. This required me to measure out strips of paper whose (scaled) dimensions were the same as the pipes and try different ways of folding them together. In the end, I came up with a 2-octave equal-temperament design. It spans from 2c to 3b, with tube lengths of 2.63m and 0.683m, respectively. Here is the chart:

Note	Frequency	Wavelength	Tube Length	Stats
C(2)	65.406	2.649	2.633	24 celcius
C#	69.269	2.501	2.486	50% humidity
D	73.416	2.360	2.344	v=346.5
D#	77.782	2.227	2.212	101.2 kPa
E	82.407	2.102	2.087	Dia.=0.048m
F	87.307	1.984	1.969	
F#	92.499	1.873	1.857	
G	97.999	1.768	1.752	
G#	103.826	1.669	1.653	
A	110	1.575	1.559	
A#	116.541	1.487	1.471	
B	123.471	1.403	1.388	
C(3)	130.813	1.324	1.309	
C#	138.591	1.250	1.234	
D	146.832	1.180	1.164	
D#	155.563	1.114	1.098	
E	164.814	1.051	1.036	
F	174.614	0.992	0.977	
F#	184.997	0.937	0.921	
G	195.998	0.884	0.868	
G#	207.652	0.834	0.819	
A	220	0.788	0.772	
A#	233.082	0.743	0.728	
B	246.942	0.702	0.686	

It was 24 degrees celcius and 50% humidity when I was building/tuning this thing. If you're going to build one, I can not emphasize enough how important it is to keep your environment stable when fine tuning a tubulum. As shown in the charts below, one with warmer, humid air and the other with cooler, dry air, the lowest “key” changes by 2.4cm. This is quite noticeable, considering the range of conditions is easily what you'd expect in any Loomis classroom.

Note	Frequency	Wavelength	Tube Length	Stats
C(2)	65.406	2.635	2.619	22 celcius
C#	69.269	2.488	2.472	10% humidity
D	73.416	2.347	2.332	v=344.67
D#	77.782	2.216	2.200	101.2 kPa
E	82.407	2.091	2.076	Dia.=0.048m
F	87.307	1.974	1.958	
F#	92.499	1.863	1.848	
G	97.999	1.759	1.743	
G#	103.826	1.660	1.644	
A	110	1.567	1.551	
A#	116.541	1.479	1.463	
B	123.471	1.396	1.380	
C(3)	130.813	1.317	1.302	
C#	138.591	1.243	1.228	
D	146.832	1.174	1.158	
D#	155.563	1.108	1.092	
E	164.814	1.046	1.030	
F	174.614	0.987	0.971	
F#	184.997	0.932	0.916	
G	195.998	0.879	0.864	
G#	207.652	0.830	0.814	
A	220	0.783	0.768	
A#	233.082	0.739	0.724	
B	246.942	0.698	0.682	

Notes	Frequency	Wavelength	Tube Length	Stats
C(2)	65.406	2.660	2.644	26 celcius
C#	69.269	2.512	2.496	60% humidity
D	73.416	2.370	2.354	v=347.95
D#	77.782	2.237	2.221	101.2 kPa
E	82.407	2.111	2.096	Dia.=0.048m
F	87.307	1.993	1.977	
F#	92.499	1.881	1.865	
G	97.999	1.775	1.760	
G#	103.826	1.676	1.660	
A	110	1.582	1.566	
A#	116.541	1.493	1.477	
B	123.471	1.409	1.393	
C(3)	130.813	1.330	1.314	
C#	138.591	1.255	1.240	
D	146.832	1.185	1.169	
D#	155.563	1.118	1.103	
E	164.814	1.056	1.040	
F	174.614	0.996	0.981	
F#	184.997	0.940	0.925	
G	195.998	0.888	0.872	
G#	207.652	0.838	0.822	
A	220	0.791	0.775	
A#	233.082	0.746	0.731	
B	246.942	0.705	0.689	

Results

I was able to complete the tubulum, albeit with a bit more trial and error than I had expected. The project reminded me that no matter how good your measurements are, things will always need adjusting when applied in the real world. When I completed the chart on page 5, I went to the garage to measure the longest and shortest pipes on my project. To my surprise, the shortest was within 1cm of the predicted value, and the longest pipe was within 2cm! –Barely enough to notice a difference in pitch.

There was no way to measurably predict what design for the paddles (beaters) would be best. I tried using foam from gym floor squares, but it was too light to deliver enough force to the pipe opening. I ended up using plastic paint scrapers for handles, with felt furniture pads glued onto them. The felt pads were stiff enough to form a solid air seal when smacked against the pipe ends. To give them more weigh and the right texture, I cut a mouse pad in half and wrapped it over the felt, with the rubbery side facing out. I used hot glue to hold everything together. It works pretty well! It's in the picture on the title page.

Altogether, materials totaled about $150. I easily spent five full days working on this, two of which were spent measuring and planning. My hope is that anyone interested in building a tubulum could save themselves two days by reading this report.

Conclusion

After my presentation in class, I wrapped the “black keys” in orange duct tape to distinguish them from the other notes. So far I've learned to play the Batman theme song and the beginning of “Like a Virgin” by Madonna. It's been nice to use my knowledge of physics to actually build something. Many aspects of music seemed arbitrary before I took this class, but after working with the equations and tuning an instrument for the first time, it makes perfect sense now. I look forward to wasting many hours learning how to play Nintendo theme songs on my new creation. The finished product is below:


FARM FRESH EGGS
KEEP REFRIGERATED


FARM FRESH