Physics Term Project

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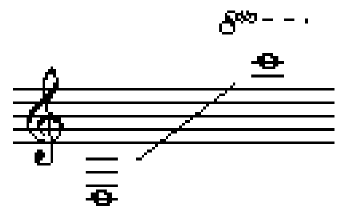
The Physics of the Clarinet

The clarinet, in the simplest possible explanation, is a pipe with a reed on one end and a bell on the other. The reed vibrates and creates the sound, the holes change the wavelength of the note, and the bell directs the sound waves. Its origins are in the German chalumeau, a recorder-like instrument first played in the medieval ages. The original instrument, limited in range by the length of the instrument and the embouchure of the player, has evolved into the woodwind instrument with the largest range of possible frequencies, extending over four octaves (from 147 Hz to 1976 Hz). The clarinet is also interesting from the perspective of harmonics, where its shape makes it favour certain harmonics over others.



The Range of the Clarinet. The 8 indicates that the note is in fact an octave above, a note too high to appear on the staff. (Source: www.philharmonia.co.uk)

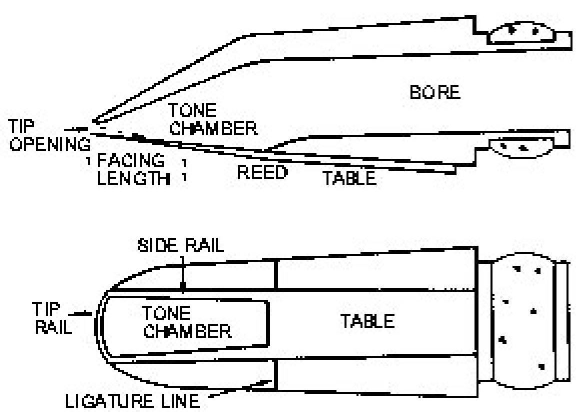
To explain the physics behind the clarinet, I have broken the operation of the clarinet into three sections, the reed, the wavelengths and the harmonics, with a short experiment demonstrating a key point in each topic.

A brief introduction to the physics of sound:

Sound is made up of waves created by changes in pressure of matter, such as air molecules. Sound can travel through many different mediums, but in a clarinet it is air molecules. It is a form of mechanical energy that moves from high pressure to low pressure. It can be described as a sine curve, with the period marking the frequency, or how high or low the note sounds, and the amplitude marking the intensity, or how loud or soft the note sounds. The velocity of the sound equals the frequency times the wavelength, and since air will travel at the same speed at the same temperature, the shorter the wavelength, the higher the note.

In music, notes are specific frequencies that are called by their note name (ABCDEFG), their accidental (sharp, flat, or natural), and by their octave (0-8). If the frequency of a note is above what has been set by the international convention, but not high enough to be considered the next note up, it is called sharp. If the frequency of the note is below, it is called flat. The magnitude of flatness and sharpness is a fraction described as "cents".

The Mouthpiece



The clarinet mouthpiece (source: www.eatonclarinets.com)

The mouthpiece, reed and ligature are essential to the creation of sound in the clarinet. The reed and the mouthpiece create a gap in which the reed vibrates, which produces sound waves, and the ligature holds the reed in place. The reed and the bore of the ...es the resonance of the reed with their ...sed to create the note. Younger players tend to "squeak" a lot, which is the sound of the resonance of the reed.

Clarinettists can change the volume, or the intensity of the sound wave, by increasing the pressure of the air flowing from their mouth to the mouthpiece. At some point, however, the pressure will be so high that the reed bends and forces the gap between the mouthpiece and the reed to shut. The mouthpiece will not function within a range of pressures that are too weak and too strong, effectively defining the possible "operating points" of the clarinet. In general, the more control the player has over the part of the instrument that vibrates, the greater the range of volumes possible. A Flute mouthpiece is metal and does not move, and can really only play one dynamic- pianissimo. Clarinets have a bit of leeway, but bass clarinets, contra-alto clarinets and saxophones can play a lot louder because their reeds and the gaps between the mouthpiece and reed are greater. Brass instruments can play the loudest of the winds because the vibrating part of the instrument is their own lips, which they can control with their embouchure.

In this first experiment I will attempt to prove that volume is dependant on the mouthpiece pressure by examining whether expanding the gap between the reed and the mouthpiece improves the operating points of the clarinet and allows louder sounds to be produced.

Experiment 1: Increasing the Mouthpiece Gap

Purpose:

To determine if placing a piece of paper between the reed and mouthpiece on a clarinet will increase the loudest possible noise on a given note.

Hypothesis:

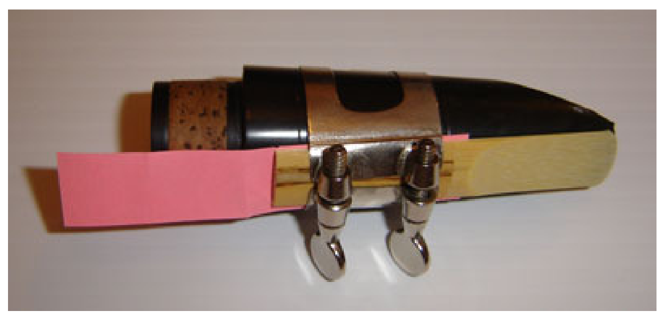
Increasing the gap should result in greater loudest possible noise on every note because the operating point on the mouthpiece should be increased and that the reed will have a larger space to vibrate.

Materials:

Clarinet, reed, sound sensor, clarinettist, data studios.

Procedure:

- set up the sound sensor and open data studios
- record sound of clarinet player playing the note G3 at loudest possible for 1.5 seconds
- using the trace function, find the value of the highest point on the recording
- repeat three trials on G3, plus three trials for notes C4 and G4
- repeat entire experiment with a piece of paper between the reed and the mouthpiece


Clockwise from top left: mouthpiece gap without paper, mouthpiece set-up with paper, mouthpiece gap with paper.

Results:

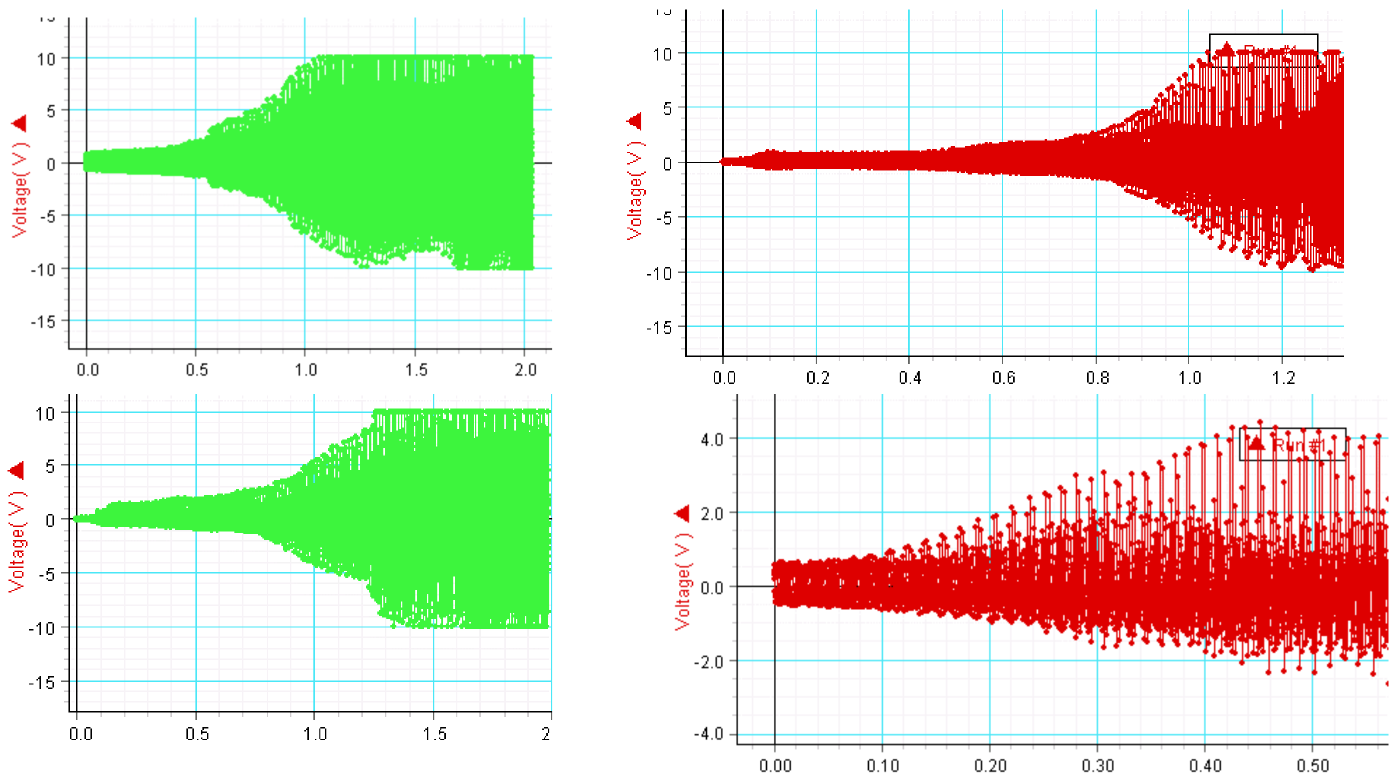
Clarinet Player 1

Note	Without paper (V)	With Paper
G3	6.80 5.156 5.654 Average: 5.87	6.978 4.966 6.610 Average: 6.185
C4	4.707 4.976 5.117 Average: 4.933	6.314 7.378 6.745 Average: 6.812
G4	5.479 4.248 5.493 Average: 5.073	7.424 7.902 7.909 Average: 7.745

Clarinet Player 2

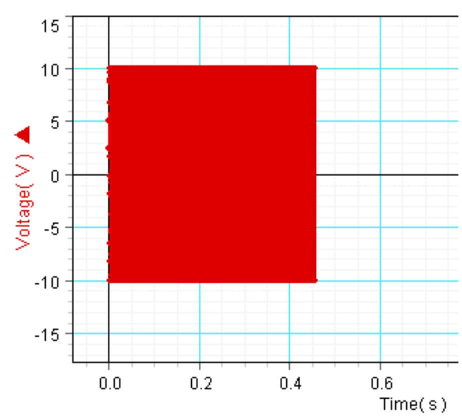
Note	Without Paper (V)	With Paper (V)
G3	6.001 5.899 6.178 Average: 6.026	7.388 6.758 6.055 Average: 6.734
C4	4.204 4.844 4.512 Average: 4.52	5.377 5.247 4.868 Average: 5.164
G4	4.917 4.551 4.591 Average: 4.686	5.313 6.172 5.235 Average: 5.573

Samples of the resulting voltages when both clarinettists played G4, gradually increasing the pressure. Green represents the results with the paper; red represents the results without paper.



Observations:

- The loudest the sensor could record was 10V. The notes in the Clarino register and higher are much louder than the notes in the chalumeau register. When player 1 played the note C5, all that was produced was one thick square. No results were taken from notes in the upper registers.



- It was difficult to keep the distance from the sensor exactly the same for every trial because the clarinet players were different heights, and forcing them into a position that was not natural for them to play in
- Every third or fourth point, there was one point that went off the top of the graph. This may be because of the overtones and harmonics of the note played, which sound louder in relation to the lower register notes. These points were ignored.
- The computer recorded sound at a slower rate than the player played the noise.

Discussion:

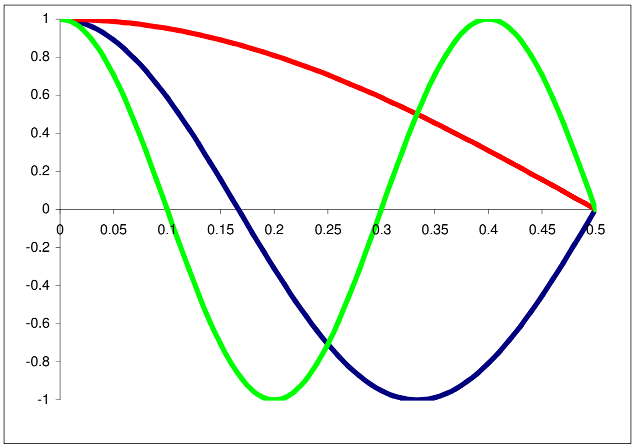
It is very hard to be very accurate on this experiment because of the equipment used and the fact that humans are creating the pressure, not a machine. The clarinettists played differently on every note, because they lack the consistency of a machine. The first notes played are softer than the later notes, probably because it takes a bit of time to get used to playing with a piece of paper between the reed and the mouthpiece. Any time humans are involved, there is likely to be a bias. To avoid this bias, the clarinettists were not informed of the hypothesis before playing, and three trials were taken on every note. The results would probably have had less sampling error if more than three trials were taken, but it takes a lot of energy and stamina to play loudly, and the results could have been affected by fatigue if more than three trials were taken. Even though the clarinettists were not informed, it is hard to hide the fact that there is a piece of paper between the reed and the mouthpiece. It would have been interesting to have several different thickness of paper to compare the effects, but it is impossible to make a sound out of the clarinet with more than one piece of paper between the reed and the mouthpiece, and many types of thinner paper dampen the sound produced.

Conclusion:

The average voltages with the paper are louder than the average voltages without the paper for all notes examined and for both clarinettists. The hypothesis is correct. Adding to the gap expands the range of the clarinet, but it is impossible to determine how this affects the tone quality, which is a hard quality to measure using sensors.

Frequency and Wavelength: How to get different notes.

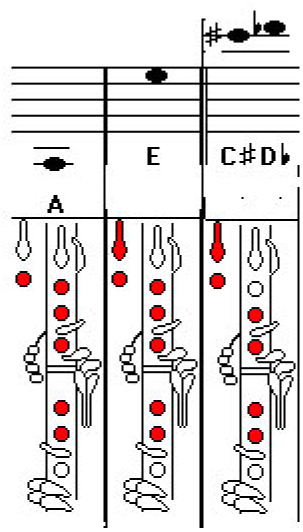
All wind instruments operate by increasing the length of the air canal or by changing embouchure. The Trombone does this by extending or shortening the slide, the trumpet and horns by changing the pathway of the air. In woodwind instruments, holes are covered and uncovered using pads or the fleshy, pointy part of fingers. The lowest note is produced by covering all the holes; to create higher notes the player must remove their fingers. As said before, the pitch of sound depends on the frequency, and since the players can't physically control the speed of the air in their instrument, to change the note they must be changing the wavelength.



The Chalumeau (red), Clarino (blue) and Altissimo (green) notes can be played using al most the same fingering because of harmonics

The clarinet is unique in the fact that it is a closed pipe. At the bottom of the clarinet (the part called the bell) the pressure of the air is close to the pressure of the surrounding air, and the pressure is greatest in the mouthpiece. If you think of the sound waves being produced by the clarinet as following a sine curve, then the distance from the highest pressure to where the pressure is zero is one fourth of the period. The distance between the point of the highest pressure to the point where the pressure is equal to the surrounding air must be one-fourth of the wavelength of the frequency of the note produced. This distance can be changed by taking keys off in sequence.

Assuming that the velocity of the air in the clarinet is 342.8m/s, and using the formula $f\lambda=v$, then $f=v/(4L)$ where L is the measured distance between the mouthpiece and the lowest open hole on the clarinet. The clarinet is a closed tube, compared to the flute, which is an open tube, meaning that the sound waves must start at maximum pressure and end at regular pressure. This means that a lot of harmonics will not work, as they start from no pressure and end in no pressure. The range of wavelengths on a clarinet is limited to the length of the instrument, but when the speaker key is used, a whole new range of sound can be produced on a higher harmonic. The speaker key opens a hole that is not big enough to shorten or "short circuit" the wavelength, but it is big enough to lower the pressure enough so that the sound wave can travel fast enough to produce the new harmonic. There are three ranges produced by different harmonics on the clarinet, called the chalumeau, clarino and altissimo registers.



The notes A3, E5, and C#6 all have similar fingerings in three different registers

If the wavelength of a note produced on the chalumeau register is 4 times the length of the mouthpiece to the key, then a note produced on the clarino register (with the speaker key) using the same fingering must have a wavelength of 4/3 times that length. A note produced in the altissimo register should have a wavelength of 4/5 times that length. This fraction is the distance between the original max on the sine curve to each subsequent point where the sine function equals zero. The next experiment will prove this idea.

Experiment 2: Wavelength in a closed tube

Purpose:

to determine the relationship between and the length of the key to the mouthpiece and the wavelength of the note produced.

Hypothesis:

The length of the mouthpiece to the note will be equal to ¼ λ for the notes on the chalumeau register, ¾ λ on the clarino register, and 5/4 λ for the altissimo register

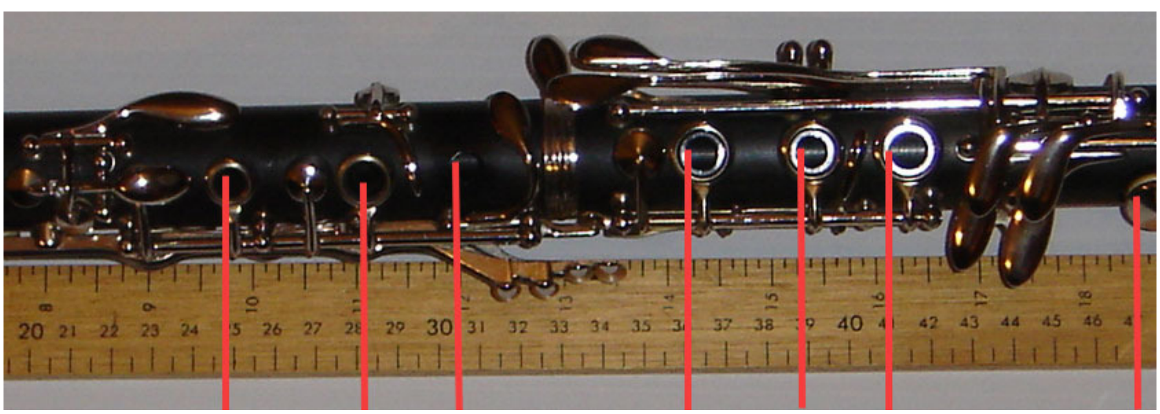
Materials:

Data studio, computer, sound sensor, clarinet, metre stick

Procedure:

- hook up the sound system to the computer and open the FFT graph in data studios
- play note and stop the recording while the note is still playing.
- Use the trace function to determine the frequency of the highest amplitude. Repeat three times to make sure that the frequency was not an irregularity caused by a surrounding sound or a strange squeak.
- Measure the distance from the top of the mouthpiece to the lowest open hole.

The measured lengths of the tone holes on the clarinet. Only the last six were used, because the length ends at the next hole after the lowest covered, not the at the lowest covered. It is hard to see because of the lighting in this picture, but there is a bit of a lip to the upper tone holes, so the measurement starts further towards the centre than it does on the lower tone holes.



Results:

Chalumeau Register

Note Name	Frequency (Hz)	Measured Length (m)	Measured Wavelength(m)	Calculated Wavelength	Percent difference
G3	176	0.47	1.88	1.95	3.5%
	176	0.47	1.88	1.95	3.5%
	176	0.47	1.88	1.95	3.5%
A3	197	0.41	1.64	1.74	5.8%
	197	0.41	1.64	1.74	5.8%
	197	0.41	1.64	1.74	5.8%
A#3	207	0.39	1.56	1.67	6.7%
	209	0.39	1.56	1.64	4.9%
	209	0.39	1.56	1.64	4.9%
C4	235	0.36	1.44	1.46	1.2%
	235	0.36	1.44	1.46	1.2%
	235	0.36	1.44	1.46	1.2%
D4	264	0.305	1.22	1.30	6.2%
	264	0.305	1.22	1.30	6.2%
	264	0.305	1.22	1.30	6.2%
E4	295	0.28	1.12	1.16	3.4%
	295	0.28	1.12	1.16	3.4%
	295	0.28	1.12	1.16	3.4%

Clarino Register

Note Name	Frequency (Hz)	Measured Length (m)	Measured Wavelength (m)	Calculated Wavelength (m)	Percent Difference
D5	425	0.47	0.627	0.81	22.3%
	425	0.47	0.627	0.81	22.3%
	425	0.47	0.627	0.81	22.3%
E5	609	0.41	0.547	0.533	2.7%
	609	0.41	0.547	0.533	2.7%
	609	0.41	0.547	0.533	2.7%
F5	640	0.39	0.520	0.536	3.0%
	640	0.39	0.520	0.536	3.0%
	640	0.39	0.520	0.536	3.0%
G5	724	0.36	0.48	0.473	1.5%
	725	0.36	0.48	0.473	1.5%
	724	0.36	0.48	0.473	1.5%
A5	811	0.305	0.407	0.423	3.9%
	812	0.305	0.407	0.422	3.6%
	811	0.305	0.407	0.423	3.9%
B5	890	0.28	0.373	0.386	3.3%
	890	0.28	0.373	0.386	3.3%
	890	0.28	0.373	0.386	3.3%

Observations:

- The results were taken the by the same person playing the clarinet, and with both hands on the clarinet the mouse had to be clicked by hitting it with the bell of the clarinet. On many trials the bell missed the mouse and hit the sound sensor. Notes that would be affected by this are G3, A3, A#3, D5, E5, and F5. The other notes can be played using only one hand.
- The clarinet was not warmed up on the first couple of notes played. The notes are low enough that it shouldn't be an issue.
- It is difficult to measure the exact length of the mouthpiece to key when the clarinet is a different shape than the metre stick.
- It was impossible to measure the frequency of notes in the altissimo register because of either the set up or the equipment. However, the frequencies of notes collected by the University of New South Wales of the altissimo register fit the hypothesis.

Discussion:

The frequency measured for D5 is an error. According to the frequencies collected by the UNSW, the frequency should be 523. 425 is a harmonic of that note. That is why the percent difference is so high for that note compared to the others. There were a few assumptions made in this experiment, the first that the length should be measured exactly from the tip of the clarinet to the middle of the open note, and that the speed of the air molecules would be the same every time, at around 342.8m/s. The school was pretty warm at the time that the results for this experiment were taken, so the speed of the air molecules could be faster. The results could never be 100% accurate, because the clarinet is not uniform shape the whole way down. Physicists who study wind instruments use "end corrections" to calculate the wavelength.

Conclusion:

The hypothesis is correct; the wavelength is 4L on the chalumeau register and 3L/4 on the clarino register. Frequencies taken by UNSW fit the hypothesis about the notes in the altissimo register.

Application:

If a note that is supposed to have a frequency of 220 Hz has a 210 Hz in a room with a temperature of 20 degrees Celsius, what can be done to bring it back in tune?

Solution 1 – extending the barrel

220 is part of the chalumeau register, so λ=4L.

$$\frac{f}{4L} = v$$

$$\frac{f'}{4(L+x)} = v$$

$$\frac{220}{4(L+x)} = \frac{210}{4L}$$

$$220L = 210L + 210x$$

$$10L = 210x$$

$$x = 0.476L$$

∴ the length of the clarinet should be extended by a factor of 1.476L

Solution 2 – Changing the temperature

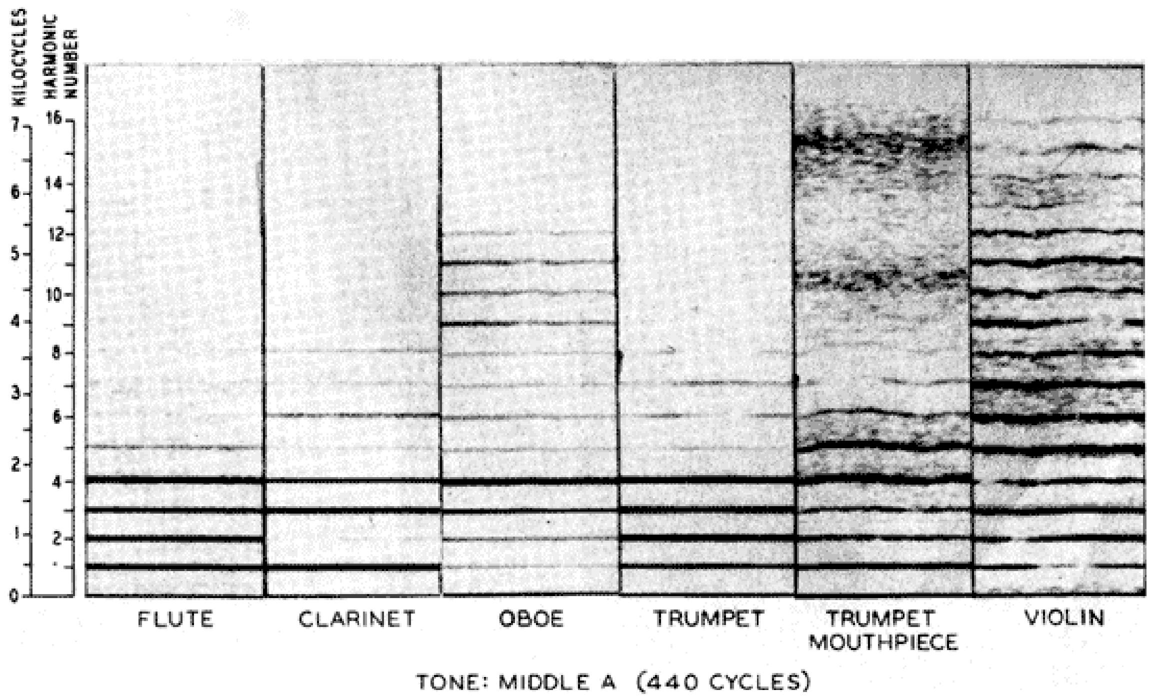
The velocity of the air depends on the temperature of the air, given the formula v=331+0.59Tc

$$210(342.8) = 220(331 + 0.59Tc)$$

$$Tc = -6.4$$

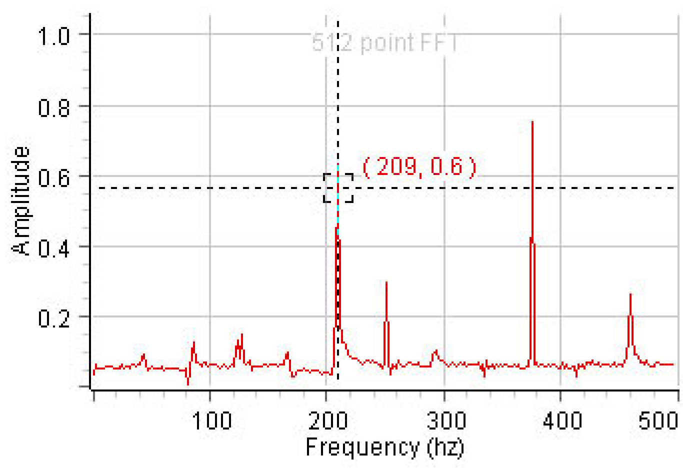
The temperature of the room should be lowered to –6.4 degrees Celsius.

Harmonics



Most instruments favour all harmonics; the clarinet seems to favour only the odd harmonics and the fourth harmonic. (Source: Waves and the Ear)

The clarinet produces a rich, mellow tone. The flute produces a clear sounding tone. What makes this difference? The answer is harmonics.



Although the fourth harmonic is too high to be registered on the graph, the octave below that note, (about 380Hz) appears prominently on the FFT, showing that it is an important note

When a note produced by any musical instrument is composed of only one frequency, the note is called a pure tone, and looks the most like a sine function. Add harmonics, and other frequencies, and this perfect sine function begins to look more complex. The flute produces a clearer sounding tone because its wave form is simple, while a clarinet produces a mellow tone because it also produces many other frequencies along with the frequency of the note played, which gives it a more complex wave form.

The flute and most instruments favour all harmonics, but the clarinet is a bit different. Since it is a closed tube, it favours the odd harmonics, the harmonics that start high and end low. It also favours the fourth harmonic, because even though one end is a lot smaller than the other, the clarinet is not completely a closed pipe. As said before in the mouthpiece part of this project, there is a small gap between the mouthpiece and the reed. The frequency of the fourth harmonic occurs when the wavelength equals the length of the mouthpiece to the key. It also happens to be two octaves above the original note, a note between the third and fifth harmonics.

Conclusion:

The clarinet's mellow sound is produced by a unique set of frequencies and harmonics due to its shape. Although the range of notes produced by the clarinet created by placing fingers over holes to extend and shorten the wavelength, opening the speaker keys can force the clarinet into a different harmonic and produce completely new ranges of notes. Increasing the gap between the mouthpiece and the reed up to a certain point can alter the loudest possible sound.

Bibliography

Edwards, L. et all. (2003). *Physics.* Toronto: McGraw-Hill Ryerson. Pages 374-438

Stevens, S. S., Warghotsk, F. (1965). *Sound and hearing, Life science library.* New York: Time-Life Books.

Taylor, C. (1992). *Exploring music The science and technology of tones and tunes*. Bristol: IOP Publishing, Inc.

Willem, A. Bergeijk, V. et all. (1960). *Waves and the ear.* New York: Double Day and Company, Inc.

Wolfe, J. (2002). *Clarinet acoustics: an introduction.* http://www.phys.unsw.edu.au/~jw/clarinetacoustics.html retrieved May 13th, 2006.