MUSICAL PHYSICS:
THE STUDY OF VIBRATING COLUMNS OF AIR IN MUSICAL INSTRUMENTS

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Purpose

I was trying to figure out how music is produced in a pipe organ, flute, and other brasses and woodwinds. I was also wondering if musical instrument making depends totally on the skill and experience of the draftsman, or if there is some kind of mathematical connection.

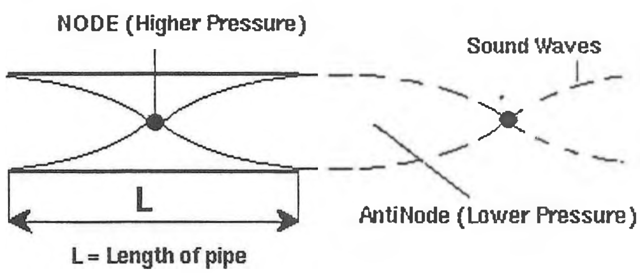
Hypothesis

I suspect that it depends on both. There must be a mathematical explanation - but how accurate is it? Well, I will study this problem and make experiments. I will try to make a 15th century pipe organ using 20th century test equipment.

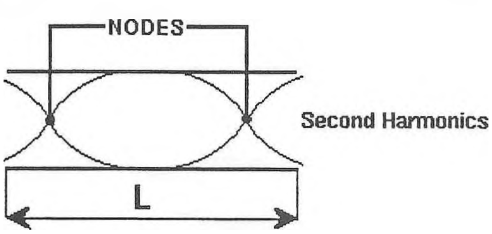
Theory

I did some studies and found out that all pipe instruments produce sound from vibration of the standing sound waves in a column of air in the pipe. Frequency of the tone played depends on the length of the pipe. I also found out that vibrations of the air column is set up by the vibrating lip of the player of brass instruments and by the airstream directed against one edge of an opening for woodwind instruments. The air within the tube vibrates with a variety of frequencies, but only certain frequencies persist. They are called resonant.

Theory of the Open Tube

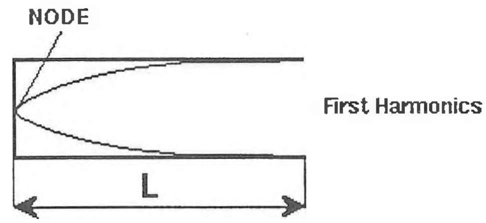


The graph within the tube represents standing waves (motion of air molecules) for air to vibrate, there must be at least one NODE within the tube. If the frequency doubles - there will be two nodes - and the tone will sound one octave higher, say C to C_1 it is called SECOND HARMONICS. I can easily demonstrate it in my experiment.

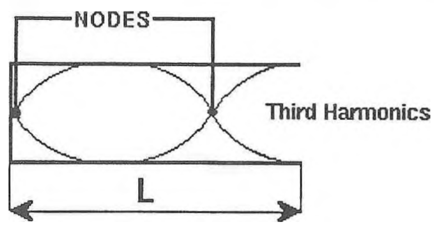


As you see it, the pipe will vibrate in resonance every time the tone is increased 1 octave - C to C_1 to C_2, etc.

Theory of the Closed Pipe



For the closed pipe, there is always a NODE at the closed end and an ANTINODE at the open end. The only difference is that there are only ODD HARMONICS presented so the pipe will be in resonance only every second octave, like C_1 to C_3 to C_5, etc.

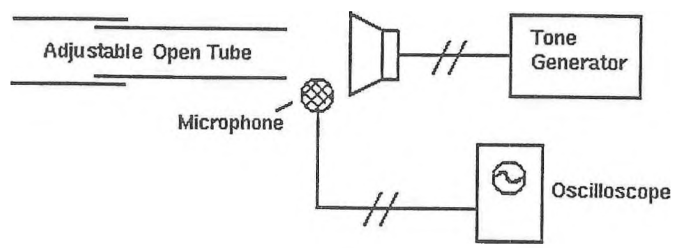


I also discovered that for the same frequency - say 440 Hz = note A, the length of the open pipe must be 2x longer than for the closed pipe (open pipe - 162 mm; closed pipe - 81 mm).

Test and Experiment Results

Basically, I made four experiments with interesting results.

Open Pipe Experiment No. 1.



1) I calculated the length of the pipes from the formula and recorded it in the table.

2) I placed an adjustable open pipe on the table with a speaker as the source of vibrations (tone) - say 440 Hz = note A, which was supplied by the tone generator.

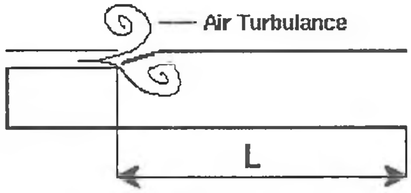
3) Then I slowly adjusted the length of the pipe and at the same time I observed the wave form on the oscilloscope. At the certain point I noticed increase in the volume and wave pattern grew taller due to the increase of volume of the sound because the pipe was in resonance with the frequency of 440 Hz.

4) I measured the length of the pipe and recorded it on the table. The difference between the calculated and tested length was 34 mm.

I them repeated the procedure 8 times for all notes of the musical scale between C to C_1. Then I cut all 8 pipes from plastic water pipes and made a small electronic pipe organ. The pipes are removable so they can be used in other demonstrations like the seashell theory. When you hold a seashell next to your ear, you are just hearing the "tube" that resonates to certain frequencies in the spectrum of background sounds and one pitch is dominant. By listening to all pipes in a certain order you can produce a tune.

Open Pipe Music Experiment No. 2

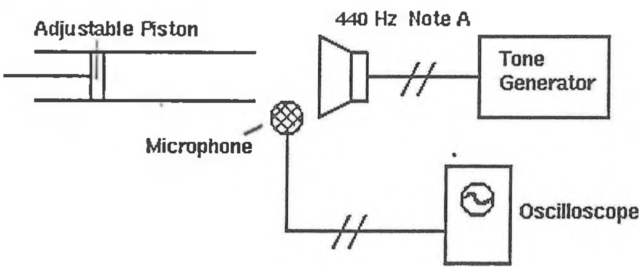
I calculated all the lengths of the pipes for the musical scale of C_1 to C_2. Then I made eight whistles according to the length I calculated.



After this was done, I played each note and tuned the whistle by trimming them (by ear) with a piano. I found this extremely difficult to do, and they are still somewhat out of tune by a few H. There is also a big difference between "calculated" and "tuned" lengths. Perhaps because of air turbulence.

Closed Pipe Experiment No. 3

This experiment is the same in principle as experiment No. 1. The only difference is that the pipe is CLOSED at one end with an adjustable piston.



I calculated the length for 440 Hz as 195 mm. The resonance length tested as 190 mm. I didn't repeat this experiment for other notes. As I see it, the same type of testing could be used to find the resonant frequency in any hollow object of any shape which would be impossible to calculate.

Closed Pipe Music Experiment No. 4

This is somewhat like experiment No. 2, except that the pipe is closed at one end. I calculated the lengths of the pipes for the notes C_1 to C_2 in the musical scale. Then I cut all the pipe 1/2 cm longer and plugged the bottom with wooden plugs. I tuned them by adjusting the plugs in or out of the pipe. This was very successful and the difference between the calculated length and the tuned length was very small as you see in the table. You can play pipes like blowing across the top of a pop bottle. The sound made is flute-like and sounds rather nice.

Conclusions

As I see it, there is more to it in making a musical instrument than just theory. Those old craftsmen of the 15th century were very good at DOING PHYSICS without actually knowing it - THEORY came later.

I had no problem with my experiments and testing, but I had some difficulty before I used the oscilloscope in experiment 1 and 3. I was trying to use different powders in the glass tube so it would form wave patterns - as the books recommended - but it would only work when the volume was very loud. I also found it difficult to work with sound as you can't see it and it varies too much.

I could have improved the testing by using an oscilloscope to greater extent by calibrating. I also could have studied different patterns of waves of different instruments, but this was the first time I used the oscilloscope.

Bibliography

Giancoli, Douglas C. Physics.

Doing Physics - Pipe Music, The Physics Teacher, March 1987, Volume 25.

Note: The actual tables of results from the four experiments as well as a diagram of the audio generator and oscilloscope patterns appeared in the complete report.