The Construction and Initial Measurements of an Acoustic Reflectometer

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Introduction

The design of a new reflectance spectrometer, reflectometer, has been motivated by the desire to study acoustic properties of musical instruments such as flutes, organ pipes, and recorders. These instruments produce a tone with a narrow jet of air that is set into oscillation through interacting with a normal mode of vibration of a cylindrical or conical chamber. This tube will have many small holes drilled into it. By closing the holes with their fingers, a musician can change the effective length of the tube thereby changing the frequency of the normal modes and the air jet. Since the recorder produces tone through the interaction between an air jet and a hollow chamber it is of interest to study each half of this system separately to better understand their functions.

Previous studies of flutes, organ pipes, and recorders [1] [2] [3] have measured either the impedance or admittance of the fully assembled instrument. In order to measure the impedance (Z) or admittance (Y) of a wind instrument it is necessary to simultaneously know both the sound pressure (P) and the volume velocity (u) of a pressure wave in the instrument since $Z = P/u$ and $Y = 1/Z$. In order to achieve this, previous work has employed a resistive element coupled to a sound source, which leads to low acoustic pressures being used in the experiment.

For the present work, a reflectometer will be used so that it is not necessary to know the volume velocity in the instrument. This simplifies data collection and allows for a design in which higher pressure amplitudes can be achieved. After the reflectance of a sample has been measured the reflection coefficient can easily be converted into an impedance or admittance value if desired.

Design of the Reflectometer

The reflectometer consists of a microphone preamplifier, an array of microphones, a long narrow tube, a sound source, and a computer. The microphone preamplifier is a Firepod® built by PreSonus. This unit has eight microphone preamplifier inputs and eight analog outputs. All sixteen of these input/output channels can operate simultaneously. The Firepod converts the microphone signals into 24-bit values that are transmitted to the computer through a firewire cable. The signal processing is performed in Matlab. The microphones used are 10mm electret microphones. These microphones have a very flat frequency response up to at least 10000 Hertz. In the current setup the sound source is a small 2" tweeter. This speaker has a fairly flat response between 200 and 1200 Hertz. This range of frequencies is the same as the playing range of a tenor recorder, the instrument to be studied.

Figure 1 shows a diagram of the layout of the reflectometer. During an experiment, a Matlab program produces a sine wave of known frequency, though in practice any arbitrary waveform can be produced. This sine wave signal is sent to the Firepod whose output port has been connected to an audio amplifier and the loud speaker. The loud speaker is connected to a plastic tube through a plastic fitting of small volume that has been attached to both the speaker and tube with airtight seals. The volume and length of the fitting has been kept as small as possible to keep unwanted resonances out of the frequency range of interest, 200 to 1200 Hertz. The seals between the fitting, tube, and speaker must be airtight in order to have the maximum amount of pressure transmitted down the tube, as well as to prevent external sounds from entering the tube and adding noise to the microphone signals.

Inside the tube at the speaker end there is an attenuator of between one and two feet in length, the attenuator is not shown in figure 1. The purpose of the attenuator is to prevent the tube from having strong resonances. A tube with no strong resonances is desired because if the sound pressure in the tube reaches a high enough level then the microphones will start introducing distortion into their signals, which will make later analysis difficult. In addition, the air jet in a recorder or flute has a nonlinear response to pressure. If the air jet is to be studied the system needs to be able to deliver a constant sound pressure to the air jet so that this nonlinear behavior can be measured. This is most easily obtained if the tube has no strong resonances.

After the attenuator is an array of microphones placed along the unobstructed length of the tube. At present six microphones have been used but future work will use up to eight microphones. Each microphone measures the pressure versus time at its position in the tube. The Firepod measures all of the microphone signals while also playing a sine wave signal through the speaker. After the microphones is the open tube end. At this point any object whose acoustic reflectance is desired can be attached.

Determining Reflectance

When a signal is sent to the speaker it produces pressure wave within the tube. This wave passes through the attenuator and past the microphones to the end of the tube. This pressure wave is called the incident wave. At the end of the tube the pressure wave reflects off of the object whose reflectance is being measured. This reflected wave may be of the same or different amplitude than the incident wave. The reflected wave might also experience a phase shift upon reflection. All of the information about the wave's change in phase and amplitude upon reflection is contained in a complex number, the reflection coefficient. The reflected wave will travel down the tube in the direction opposite the incident wave and past the microphones. Since the sine wave signal is played on the speaker for a one second period, the microphones will be measuring both the incident and reflected waves simultaneously.

Once the microphone data has been recorded it can be processed in Matlab to determine the properties of both the incident wave and the reflected wave. These properties will include the wavenumber, attenuation within the unobstructed length of the tube, the amplitudes of both waves, and the phases of both waves. Once these six numbers have been determined the reflection coefficient can be calculated. The complex reflection coefficient is the ratio of the reflected wave to the incident wave.

Initial Measurements

Once the reflectometer was believed to be working properly it was tested against a few simple cases where the reflection coefficient can be calculated. The simplest case is a close-ended tube. The reflection coefficient for a close-ended tube is $R = 1 + i*0$ where $i = (-1)^{(1/2)}$. The next simplest case is an open-ended tube whose reflection coefficient is $R = -1 + i*0$. For these two cases the reflectometer measured values very close to those expected. It should be noted that these reflection coefficients are for a pressure wave and are different in sign than if volume velocity has been measured.

The magnitudes of the reflection coefficients for an open ended tube, a tube closed with a thick plastic sheet, and a tube closed with 1/4" aluminum plate are shown in figure 2. From the graph it can be seen that the magnitude of the reflection coefficient is the same for both of the close-ended tubes. The phase shifts upon reflection were also the same for the tubes closed with aluminum and plastic. It can also be seen that an open-ended tube shows a reflection coefficient slightly less than a close-ended tube due to a small amount of the pressure wave radiating from the end of the tube.

Once the reflectometer had been tested by measuring the reflectances of some well-known cases and was seen to be working well, a special fitting was made so that the fipple, or mouthpiece, of a tenor recorder could be fit to the end of the tube. First the reflectance of the fipple was measured with no air flowing through it. Since the fipple has a small slot in it so that the air jet can form and oscillate, the fipple acts as neither a perfectly closed tube nor an open tube but something in between. In this case the magnitude of the reflection coefficient should still be one but the complex part of it will be non-zero. Figure 3 shows the magnitude of the reflection coefficient for the fipple with no air blown through it. Then the fipple was connected to a tank of compressed nitrogen and a manometer with surgical rubber tubing while still attached to the reflectometer. With as little as just 2 Torr blowing pressure, the magnitude of the reflection coefficient varies considerably from its value when no air is blown through it. Figure 3 shows the reflection coefficient when 2 Torr is applied to the fipple.

With the fully assembled recorder attached to the compressed nitrogen, several of the tone holes were covered with masking tape in order to finger the note G, which is 784 Hertz. It was found that a low-pitched tone, approximately 480 Hertz, could be played with as little as 0.4 Torr. After increasing the pressure it was found that at 1.4 Torr the recorder started playing G = 784 Hz and that this tone was played at all of the higher pressures tested.

After placing the fipple back onto the reflectometer a sine wave of frequency 800 Hz was produced on the speaker. The air pressure delivered to the fipple was varied in 0.1 Torr increments while measuring the reflection coefficient. The complex reflection coefficient for a range of pressures between 0 and 5 Torr is plotted in figure 4. The pink data points show the pressures where the low tone had been heard on the assembled recorder. The blue triangles mark the pressures were the pitch G had been heard. It can be seen that the rate of change of the reflection coefficient changes at the pressure where the recorder had stopped playing the low tone and began playing the tone G. This indicates that the production of the low-pitched tone preceding the actual fingered tone G is due to some property of the air jet or the fipple and not the other half of the recorder.

Conclusions and Future Work

The reflectometer has been shown to work satisfactorily on objects of known reflectance such as the open and close-ended tubes. It has also been found to be capable of measuring the acoustic properties of the recorder's air jet. This reflectometer has shown that its design and construction work well for acoustic measurements and the experience with this machine has shown ways in which it can be improved upon.

In future work the circuits containing the electret microphones will be of an improved design that will allow for the measurement of a wider dynamic range with less distortion. The small tweeter used in the present instrument could not be driven at high powers without distorting the signals. This will be replaced with a loud speaker capable of producing much higher sound pressure levels while also having a flatter response. These changes will allow the reflectometer to study the air jet of a recorder at sound pressure levels similar to those present inside a recorder during the performance of music. This will provide more insight into how to air jet behaves when a musician plays their instrument.

References

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2. Coltman, J.W., Jet Behavior in the Flute, J. Acoustic Society of America, Vol. 92, No 1, July 1992.

3. Smith, Fritz and Wolfe, A New Technique for the Rapid Measurement of the Acoustic Impedance of Wind Instruments, Seventh International Congress on Sound and Vibration, July 2000.

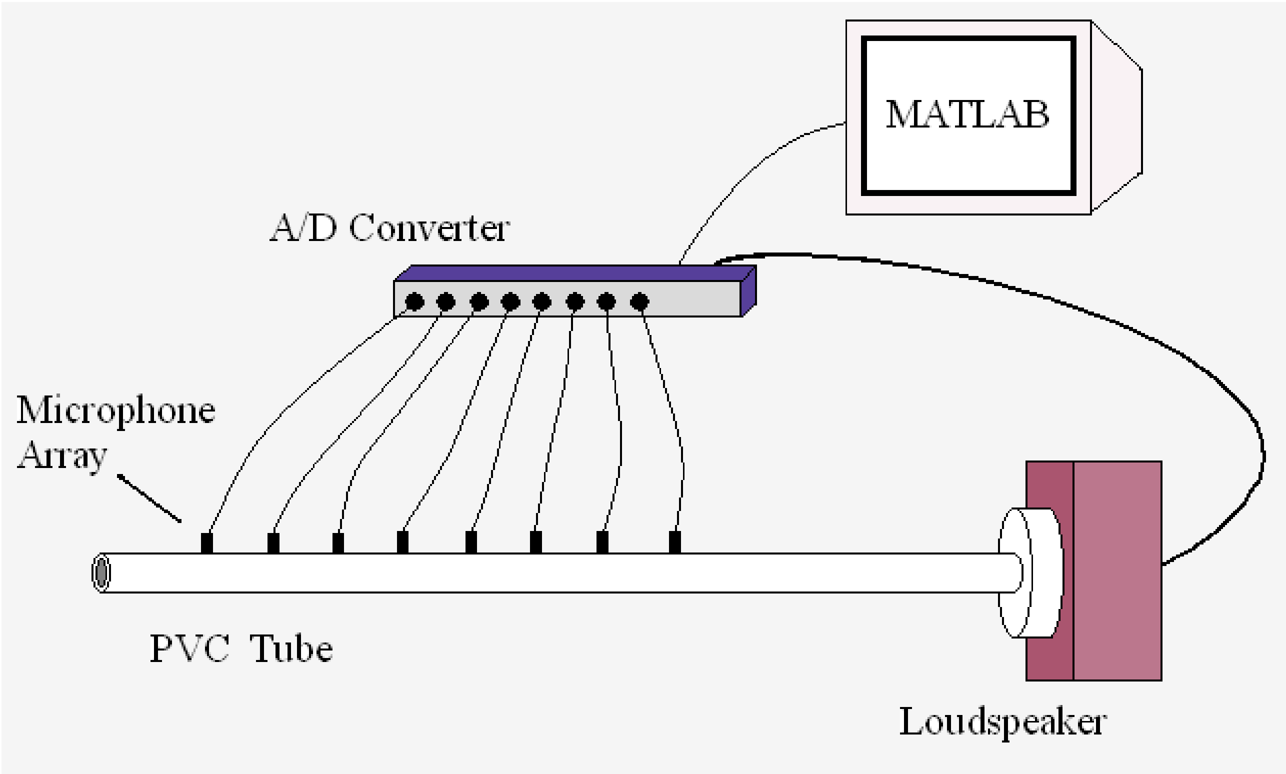
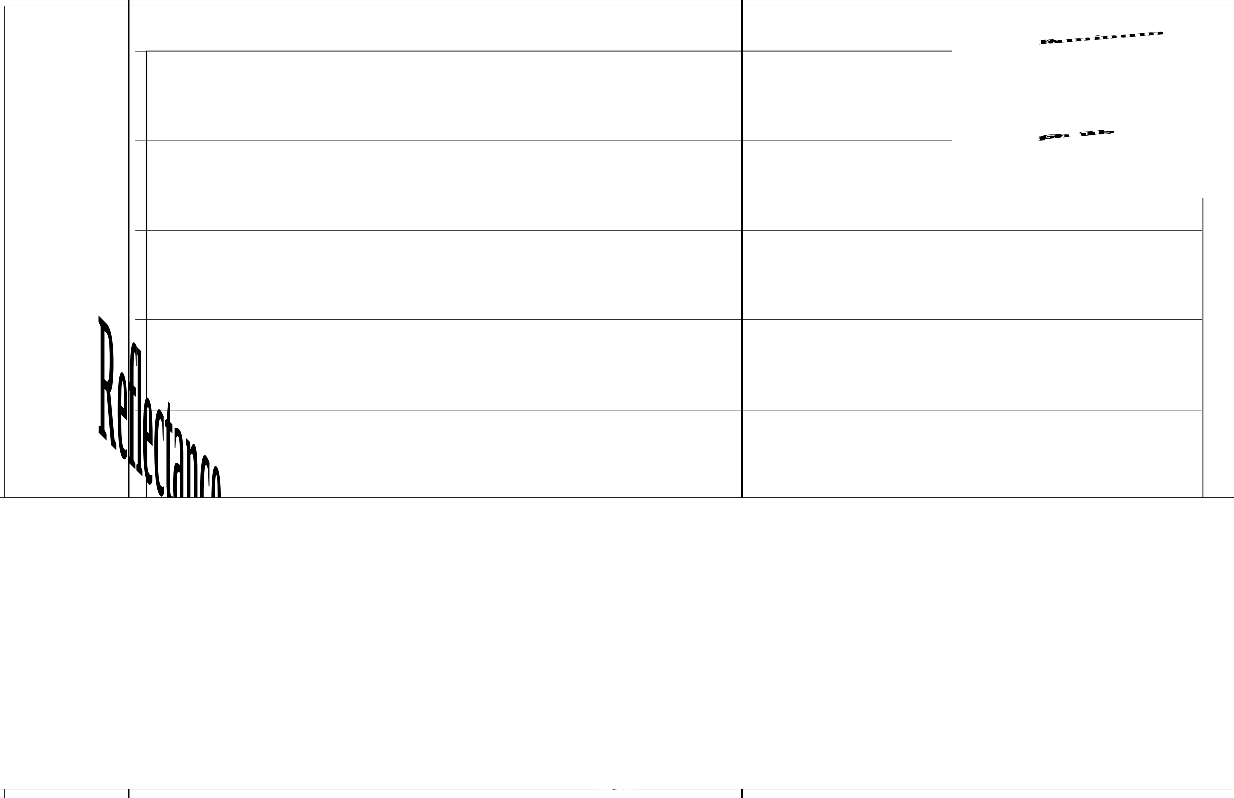
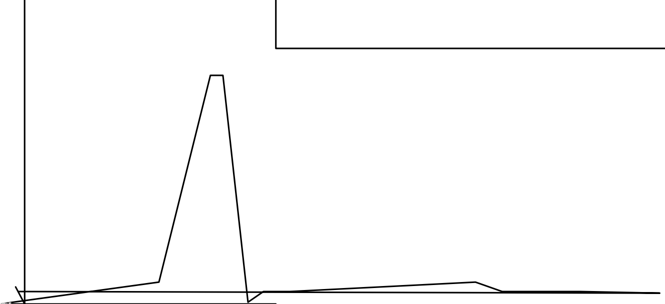
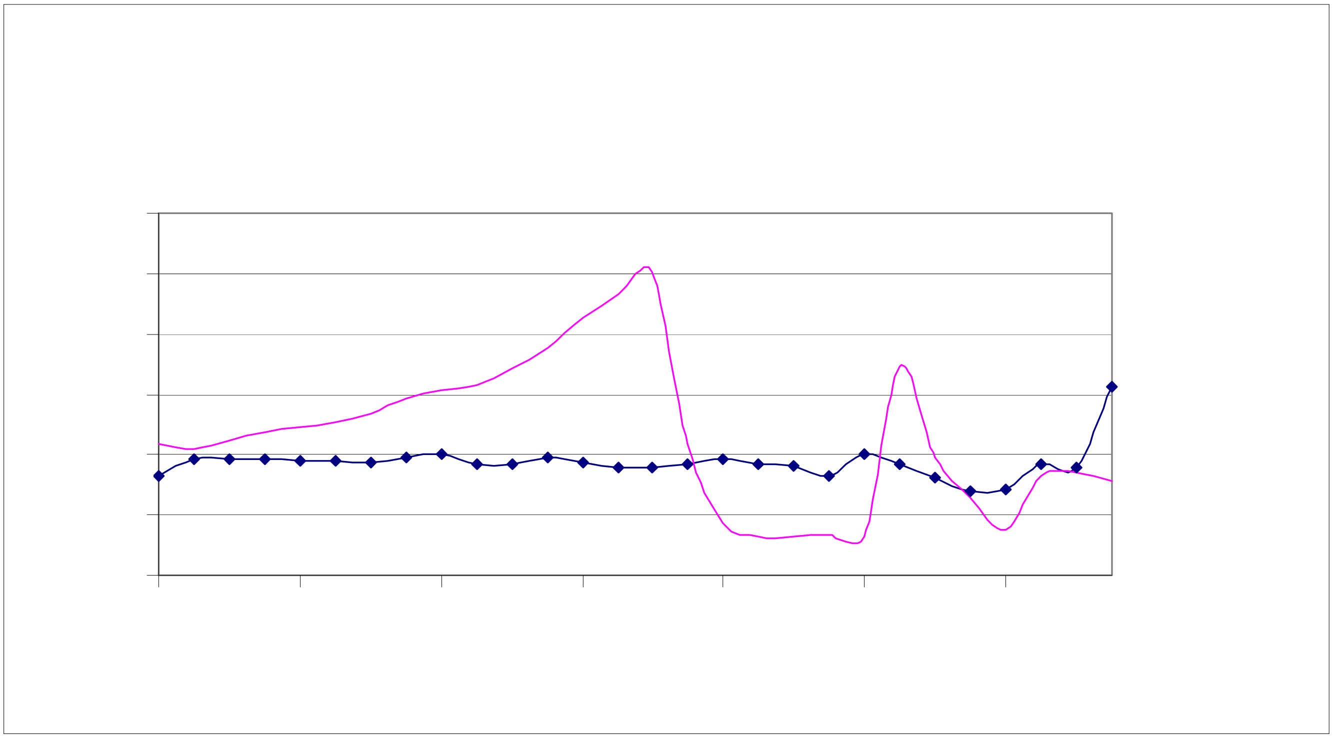


Figure 1 Layout of the reflectometer.


Reflectance





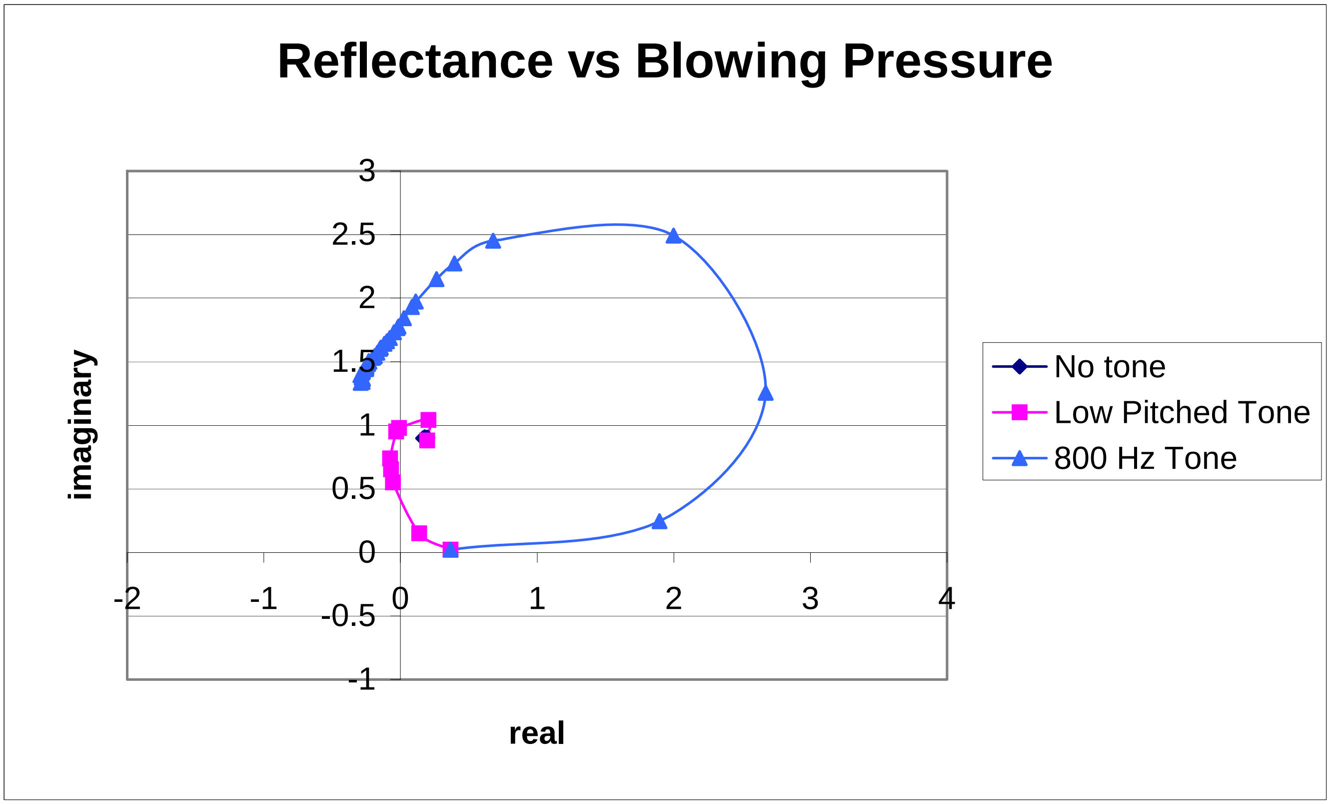


Figure 4 The complex reflection coefficient of a tenor recorder mouthpiece at 800 Hertz. The purple diamond at approx (0,1) is the reflection coefficient at 0 Torr blowing pressure. The data was collected at 0.1 Torr intervals.