

# Building and using an inexpensive impedance head<sup>1</sup>

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## **Inexpensive impedance head for classroom use**

The input impedance is defined as  $Z_{in}(f) = p / u$ , where  $p$  is the pressure amplitude response to the applied excitation volume velocity  $u$ , which is oscillating at frequency  $f$ . To measure the input impedance of tubes and musical wind instruments easily and inexpensively in the classroom and for demonstrations, consider an adaptation of a design introduced by Benade and Ibbi for an impedance head<sup>2,3</sup> that uses low cost components yet is suitable for research work.

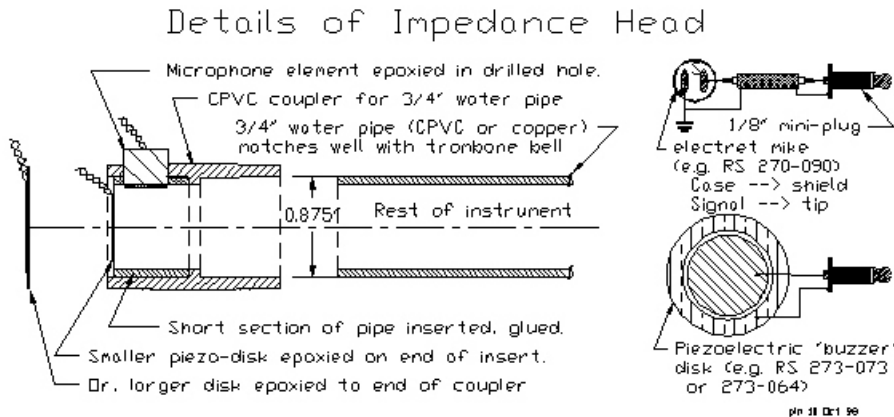
As a sound source, this design uses a piezoelectric “buzzer” disk, which has a high acoustical impedance and is therefore not strongly affected by the air column’s own resonances. Buzzers with housings such as Radio Shack 273-073 or 273-064 are easy to find and have leads attached, but they must be disassembled in order to remove the brass disk with the piezoelectric element. Or, the disk itself can be obtained from electronics supply houses such as Mouser or Digi-Key.

The piezodisk displacement is proportional to the voltage applied between the brass disk and the silvered top of the electrode; the disk’s center moves approximately  $10^{-7}$  meters/volt.<sup>4</sup> The disk’s useful operating frequency range is from DC up to a little below its first resonance frequency, which is often between 2 kHz and 6 kHz and may have a Q between 10 and 100. Below this frequency, the velocity amplitude of the disk is proportional to frequency for a given voltage amplitude, and this needs to be compensated by a -6dB/octave equalization either in the applied voltage or in the measured response. The piezodisk can be driven directly from the output of any audio device, including either the “line out” or the “speaker out” of a computer sound card. Because it also has high electrical impedance, it won’t draw very much current, but voltages of more than 30V should be avoided in order to avoid re-polarizing the crystal and changing its sensitivity<sup>5</sup>.

To measure the pressure response, use an electret microphone element, which has flat frequency response and can be powered by low voltages. A suitable one will have two terminals, such as the RS 270-090. Most computers and sound cards with microphone inputs have built-in facility for powering a microphone; there are a few different schemes for implementing this, but the most common one simply has the signal and power delivered on the tip of the 1/8" mini-plug.<sup>6</sup> Both the AC-coupling on the sound card input and an internal leak around the sides of the electret diaphragm reduce the response at very low frequencies, below about 10 Hz.

The piezodisk and microphone are inexpensive enough to allow custom-building of impedance heads for a wide variety of instruments, or to allow a class to build several impedance heads that they can use in their own measurements on common water pipe. A good general-purpose head can be built from a coupler for 3/4" CPVC plumbing pipe (technically, this is called 3/4" CTS, for Copper Tubing Size), as detailed in Figure 1. Cut off a short piece of 3/4" tubing about 0.1"

less than half the length of the coupler, and use the appropriate solvent pipe cement to glue this in place so that it is just below flush with the end of the coupler. When this is dry, a hole may be drilled to fit the microphone<sup>7</sup>. A 5-minute epoxy may be used to attach the piezodisk and the microphone, but be sure not to get any epoxy on the felt that covers the small microphone aperture.



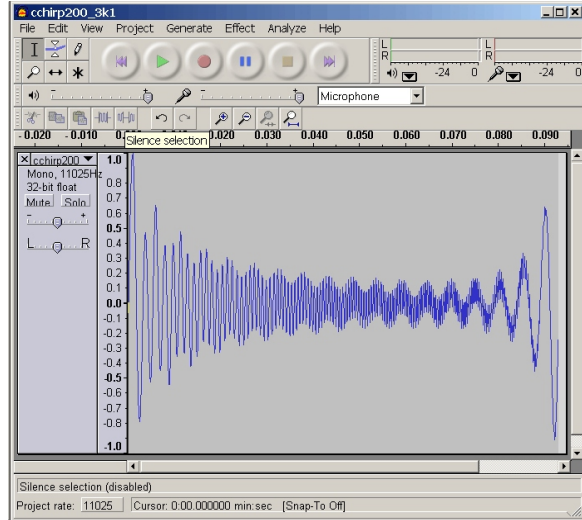
**Figure 1**

### Sound editing and analysis software

With the boom in computer multimedia, computers with sound recording and playback capabilities have become common, and software for editing waveforms and for spectral analysis have become common and inexpensive. Some of this inexpensive software is listed further below. For this demonstration, two tools called Audacity and WavPrism will be used.

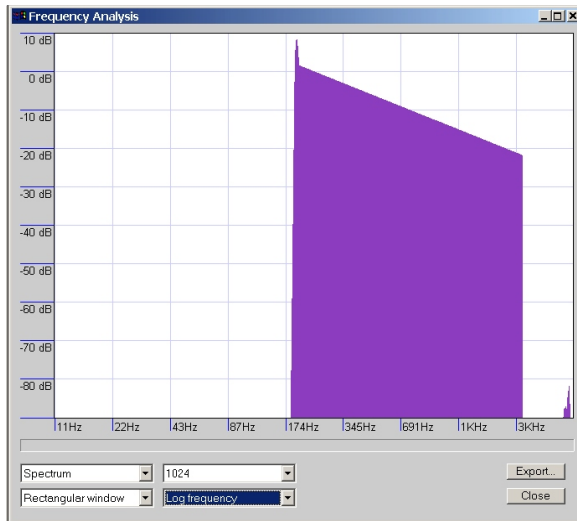
The general approach is to have the computer both provide the excitation signal to the piezodisk as well as to record the microphone response. To do this requires that the sound card be able to operate in "full-duplex mode", which is true of most recent models. If not, the excitation signal could be recorded onto a tape recorder and played back that way. Some programs have sound generation facilities, including the ability to generate swept tones. Though this would seem to be a good approach, it turns out not to be especially satisfying. Better is to use a "Schroeder chirp"<sup>8</sup>, which sounds like a swept sine, but in fact is composed by summing individual sinusoids that are running continuously. The phases have been adjusted in a way that effectively minimizes the ratio of (peak amplitude)/(RMS amplitude)<sup>9</sup>. Each sinusoid has a frequency at the center of its corresponding frequency bin when analyzed using an FFT, for example, with Audacity, or WavPrism<sup>10</sup>. Therefore, it is best to use a "rectangular" analysis window.

To start, Audacity should be opened, and then a chirp file loaded. For demonstrations or exploration, Audacity can be placed in Loop mode and the sound played continuously. Figure 2 shows an Audacity screen in which a chirp has been loaded. This particular chirp has been equalized by -6dB/octave in order to compensate for the piezodisk response, so the amplitude varies through each chirp. Equalization can be done in Audacity.



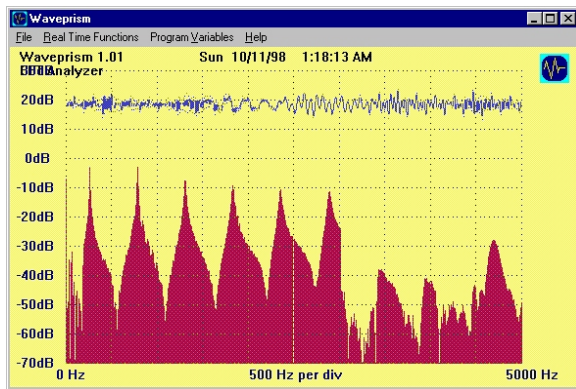
**Figure 2**

To monitor the response, go to the File | Preferences | Audio I/O menu and select Play other tracks while recording new one. When the Record button is pressed, a new track will be recorded and the chirp will play automatically. Or, for demonstrations, a real-time analyzer such as WavPrism may be started while Audacity is playing the chirp. Set the sampling frequencies of both input and output to be the same. Also, the same number of points should be used for the FFT analysis as are used in each cycle of the repeating chirp, and a “rectangular” window should be used, if available. Figure 3 is an Audacity spectrum screen for the same chirp as in Figure 2, with a log frequency scale, and showing the -6dB/octave equalization.

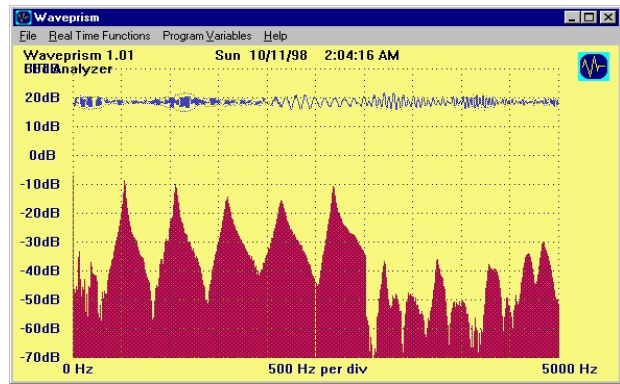


**Figure 3**

Figures 4 and 5 show the response of a tube attached to the impedance head, when the piezodisk is driven by the same chirp. In this case, the screens are from WavPrism, and the frequency scale is linear. The computer's mixer control should be used to control levels and to ensure that only the microphone signal is connected via the internal mixer to the input. Figure 4 illustrates the characteristic 1-3-5... sequence of the closed-open tube resonances, while in Figure 5 the resonances are in the sequence 2-4-6, equivalent to 1-2-3 an octave higher. Note that the spectrum is only driven between 100 and 3000 Hz; outside of this range, only noise is detected.



**Figure 4**



**Figure 5**

When a trombone bell is added to the end of the tube, all of the resonances move to lower frequencies, and become more closely spaced, because the tube is longer. This is shown in Figure 6. In fact, the waves penetrate poorly into the bell at low frequencies, but reach all the way down to the end at the “cutoff frequency” of about 1000 Hz. So, the resonances accordingly become more closely spaced at higher frequencies. These high frequency waves also penetrate beyond the bell, so they can’t reinforce the standing wave, and therefore the resonance peaks become weaker and die out at high frequencies.

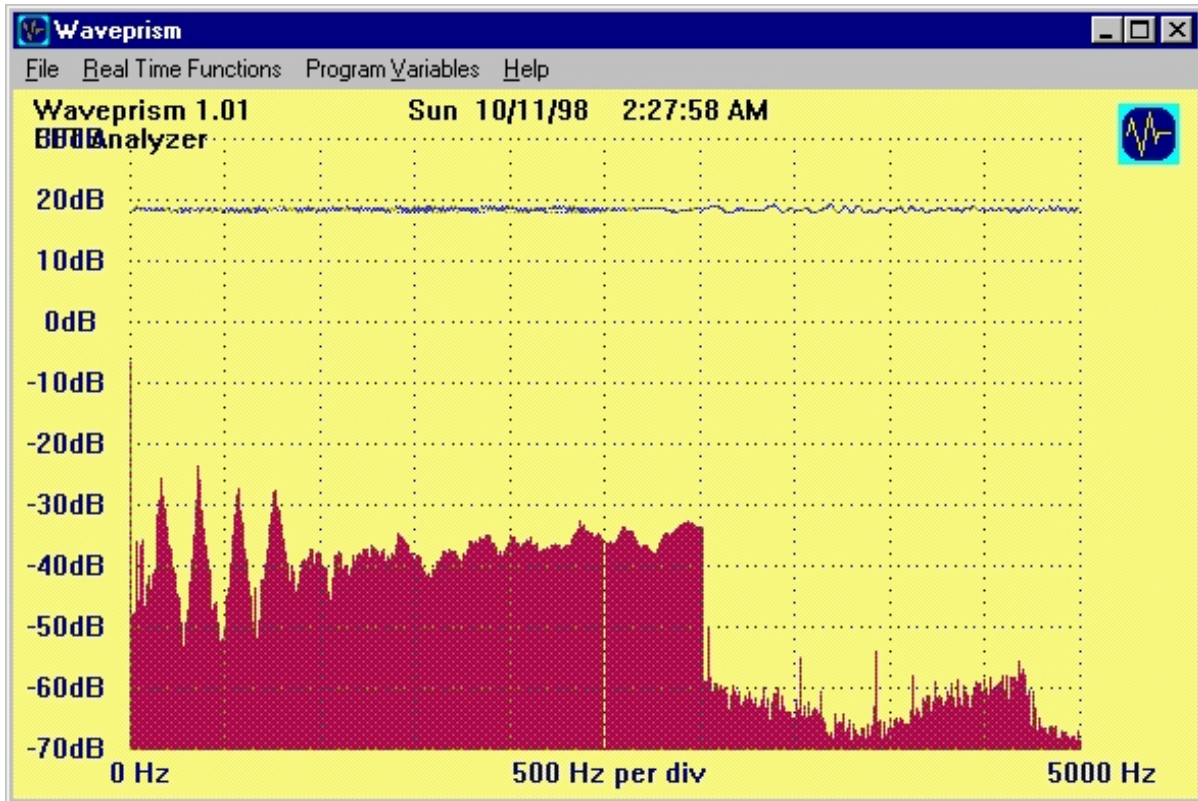


Figure 6

### **Some ideas for exploration!**

- ▶ The CPVC pipe is inexpensive and easily cut, and can be used with the impedance head in variations of traditional studies of tube resonances.
- ▶ The 3/4" tubing size is convenient because it fits well into the small end of a trombone bell (let your band director and instrument repairperson know that you have a pedagogical use for bells from trombones that have been otherwise disabled by damaged slides, etc.).
- ▶ Illustrate how the effective acoustic length of the brass instrument bell increases with frequency. Near the cutoff frequency of about 1000 Hz, the standing waves penetrate to the end of the bell and begin to leak out, so the resonance peaks are not as high!
- ▶ With slight reaming, this size impedance head will also replace a clarinet mouthpiece and barrel joint. Illustrate how the fingers change the effective length of the instrument air column by closing and opening holes. Show how the register hole spoils the low register resonance. Again show how the resonance peaks get small above the cutoff frequency of about 1500 Hz, for the same reason that high frequencies leak out the end.
- ▶ What happens if I dent my musical instrument? Attach a short pencil stub to a thin wire and recheck the resonance frequencies with this "volume perturber" placed at various places in the tube. Note that there is a slight change in each frequency, upwards or downwards depending on whether the perturber is at a pressure anti-node or at a velocity anti-node, respectively.
- ▶ Copper pipe will fit the same coupler; if closed at the far end, it can be immersed in cold or hot water to demonstrate the change of the speed of sound with temperature. If a valve is put at one end, and a leak hole at the other, the tube can be flushed with helium or other gas, the valve and hole closed, and the speed of sound in the gas measured.
- ▶ For advanced use, the frequency response of the piezodisk transducer can be calibrated, either by attaching a very well damped air column (a 20' pipe loosely filled with soft cotton twine) or by sealing the transducers into a small volume by plugging the end of the impedance head. It's enough to characterize the resonance by its frequency and its Q.

### **Inexpensive software tools for sound editing and analysis**

- ▶ Audacity - a recommended sound editor includes spectrum analysis. It is available for free download under the GNU General Public License from <http://audacity.sourceforge.net>, for MS-Windows, Linux, and Macintosh OS-X.

### **Real time spectrum analyzers**

For computers running MS-Windows

- ▶ WavPrism - (RRSP Labs, 4100 Chert Drive, Round Rock, TX, 78681, no longer available?)
- ▶ Spectrogram 5

For Macintosh computers:

- ▶ Armadillo

## Notes

1. This handout is a slightly edited version of one originally presented as paper 3aED3 *Air column resonance demonstrations* Uwe Hansen and P.L. Hoekje, at the 136<sup>th</sup> Meeting of the Acoustical Society of America (Norfolk)
2. M.I. Ibsi and A.H. Benade, "Impedance and impulse response measurements using low cost components," J. Acoust. Soc. Am. Suppl. 1 **63**, S63 (1982).
3. A.H. Benade and M.I. Ibsi, "Survey of impedance methods and a new piezo-disk-driven impedance head for air columns," J. Acoust. Soc. Am. **81**, 1152-1167 (1987).
4. As an optics demonstration, a small chip of a quality mirror can be waxed onto the disk and used as one arm of a Michelson interferometer and moved by applying a low frequency oscillating voltage.
5. Physically, however, these thin crystals will typically survive a few hundred volts.
6. Contact [phoekje@bw.edu](mailto:phoekje@bw.edu) for more information about other configurations or about 3-terminal microphones.
7. Be sure to use appropriate ventilation; if any sanding or filing is planned, a breathing filter also should be used, as CPVC dust does not decompose in the lungs.
8. M. Schroeder, "Synthesis of low-peak-factor signals and binary sequences with low autocorrelation," IEEE Trans. Inf. Theory **16**, 85-89 (1970).
9. A more general approach is described by Andrew Horner and James Beauchamp, "A genetic algorithm-based method for synthesis of low peak amplitude signals," J. Acoust. Soc. Am. **99**, 433-443 (1996).
10. Sound files containing equalized chirps may be obtained from the webpage <http://homepages.bw.edu/~phoekje/mahome.html>.