Physics of Music

Final Report

Nella Granback

Professor Steve Errede

May 12, 2011

Abstract

Throughout the spring semester I completed two separate projects. First, I recorded a few notes from my flute and tested the audio for harmonics. In addition, I investigated the difference in present harmonics when playing with the key caps in or out. After acquiring a separate head joint for my flute, I was also able to test various notes for resonances using pressure and particle velocity microphones. As a separate project, I built a guitar FX pedal from a kit. Upon completion, I did some simple testing on the pedal at two different configurations of the potentiometers. The test was to give it a sine wave input signal and note the form of the output signal, and the present harmonics.

Get To Know The Flute

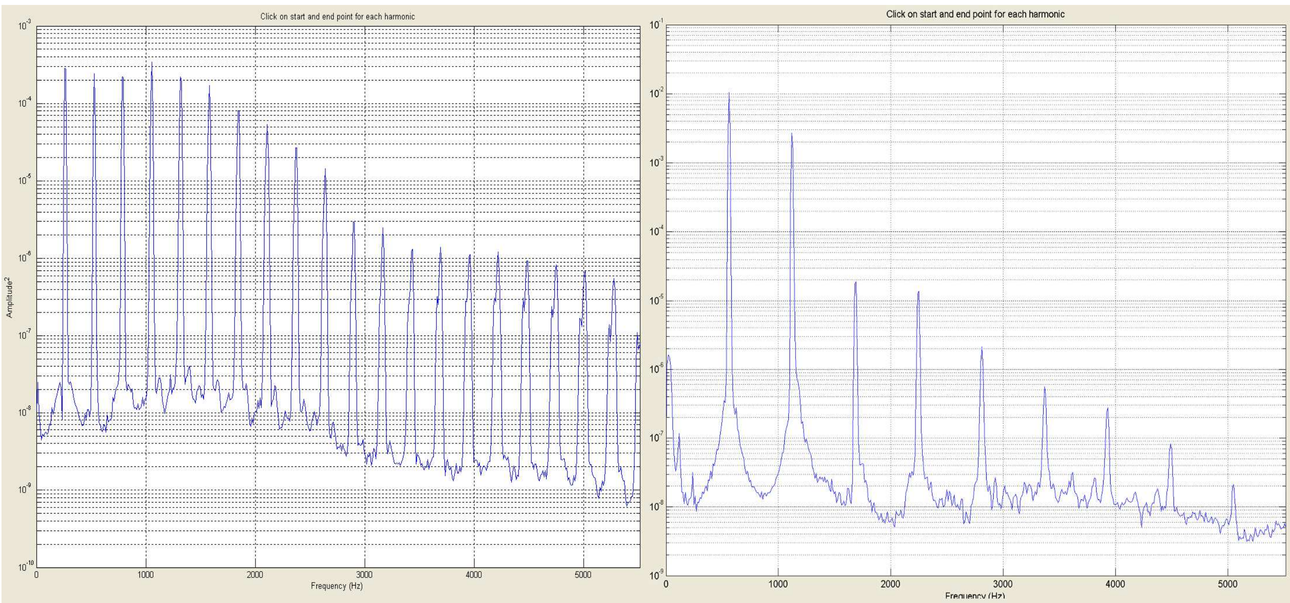
The flute is constructed of three pieces: the foot joint, the body, and the head joint. The foot joint and body hold the keys, which sometimes (in higher level flutes) have open holes that must be covered completely by the player's fingers. They can also be covered by plastic key caps while learning to play with open hole keys. The head joint holds the lip plate, the raised area on which the player's lower lip rests while playing. The flute is unlike any other band instrument in the way it is played. Much like blowing across the lip of a glass bottle, the player blows a stream of air over the hole in the lip plate in order to produce a note. Varying the speed and focus of this air stream allows the player to play notes in the upper octaves, which are simply the various harmonics of the lower fundamental notes. While the higher notes have their own fingerings in order to be easier to play, they can also be reached using the fingering of the lowest note and changing only one's embouchure (the use of one's lip muscles to control air flow). The flute used in this project was my Yamaha 361-H. It features open hole keys and a solid silver head joint. The silver head joint is meant to improve tone; this is a step above entry level flutes, which have nickel-silver plated head joints. Both types have nickel-silver plated body and foot joints.

Audio Testing

My first step was to make audio recordings of a few notes from my flute. I chose to record B4 (the lowest playable note, with all keys closed), Db5 (the highest fundamental note, with all keys open) and G5 (a middle range note). By running the WAV files through a matlab program, I used the graph of amplitude vs. frequency to identify the first few playable harmonics. From there I acquired several graphs illustrating values such as the amplitudes, frequencies, and relative phases of the harmonics.

When looking at the graph of amplitude vs. frequency, there is an obvious difference between a flute and a different instrument, such as, for example, a trumpet. For a note on the trumpet, the amplitudes of the harmonics decrease very gradually. For quite a few, the amplitudes are almost even with the fundamental. This makes sense, seeing as a trumpet, having only 3 valves, is played mainly by utilizing different harmonics. On the flute, however, the amplitudes begin to die off immediately. On average, the amplitude of the third harmonic is already almost two orders of magnitude lower than the fundamental, and the fourth harmonic is another order of magnitude below that. In this way, the flute can be related again to blowing across a glass bottle, for which the harmonics fall away so quickly that it can almost be considered a pure sine wave signal.

Below, a side by side comparison of graphs from a Trumpet (left) and Flute (right). Trumpet graph was taken from Greg Frazier's data.



Side Note: One interesting feature of the amplitude vs. frequency graph is only seen when looking at the graph of E natural in the second octave, the first harmonic of low E (<u>not</u> the graph shown above). This is the only note I tested that was not the first octave, meaning it was not a fundamental. A difference can be seen in the graph of frequencies – they are what I like to call "ghost peaks"! These are small peaks between the main harmonics, with a difference of about three or four orders of magnitude. Unfortunately, though I was intrigued, I had neither enough data to pursue this topic further, nor enough time to experiment further.

Experimenting With Key Caps

Throughout my career as a flautist, many people have voiced their opinions, such as band directors, peers, and private teachers. The general consensus was that this higher-level feature improved tone. I never understood the reasoning behind this claim, and wanted to investigate for myself. I decided that the best measure of a “better tone” would be a greater presence of harmonics. I recorded two versions of the same note, E5, on my flute: one with all key caps in, and one with all key caps out so the holes were open. It should be noted that even with all holes open, I chose a note with a fingering such that all those keys are still covered by my fingers. The only difference in the second recording is that, instead of reverberating against plastic, the air inside the flute is hitting my finger tips.

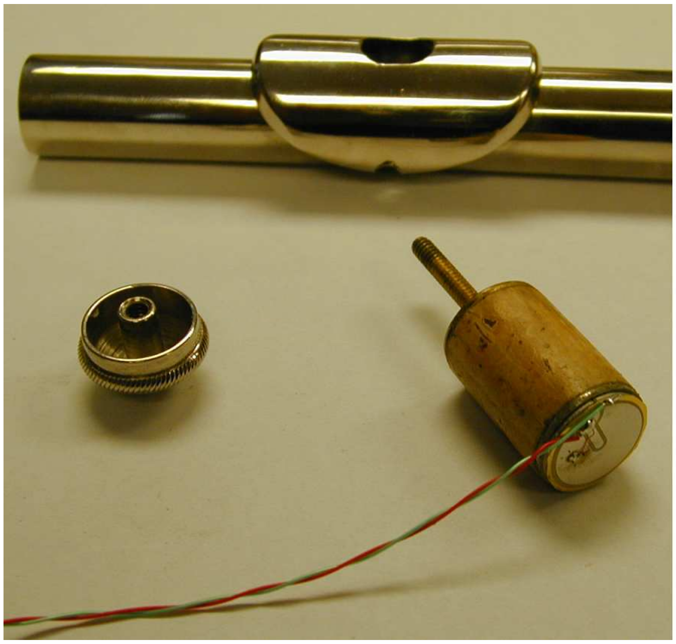
When comparing the graphs of amplitude vs. frequency, I was very disappointed to see almost no difference between the two recordings. In fact, any difference that I could find was so small that I would attribute it simply to the fact that I cannot play two identical notes. Due to these highly disappointing results, I am forced to conclude that open hole keys do not improve tone, by my definition of the word. Though I have no experimental data to back up these claims, I would guess their function is to allow minute tuning adjustments by skilled players, or, as some sources say, to allow for more robust sound in the lower register.

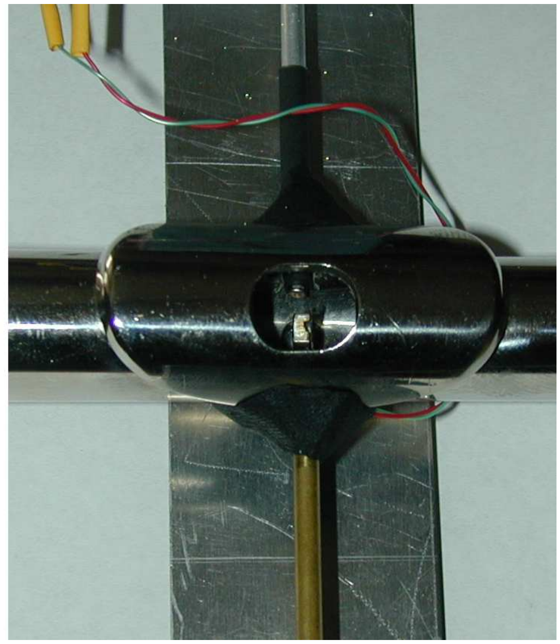
Testing For Resonances

One thing keeping me from more in depth testing was lack of hardware. To test for resonances, we would eventually need to drill holes in the head joint in accommodate the microphones – something I was not willing to do to my own beloved flute! Professor Errede decided to buy a nickel-silver plated Selmer brand head joint for this purpose. It was much cheaper than other head joints, which we soon realized was because it had been previously dented or mistreated. Many weeks were spent reshaping, measuring, and sanding the end until it finally fit in my flute. Next, I was faced with the problem of how to excite the flute via piezoelectric transducer. Since the flute is played differently than other instruments, previously tested methods could not be easily applied. Our first thought involved keeping the transducer inside the small plastic case that it comes in, acting like a makeshift Helmholtz Resonator. The opening could be aimed across the lip plate of the flute, like the player's own air stream.

After running a test using this set up, we could see by the results that this method was not an effective way to excite the flute. The next idea was to align the transducer with the column of air inside the flute. To do this, we unscrewed the very top of the head joint and removed the cork. This is a feature meant for major tuning adjustments – the cork can be moved in or out to completely change the length of the flute, in a case where the flute is majorly out of tune. We attached the piezoelectric transducer to the end of the cork, and reinserted it into the head joint. Comparing test results with what was expected, this method proved to be an acceptable way of exciting the flute.

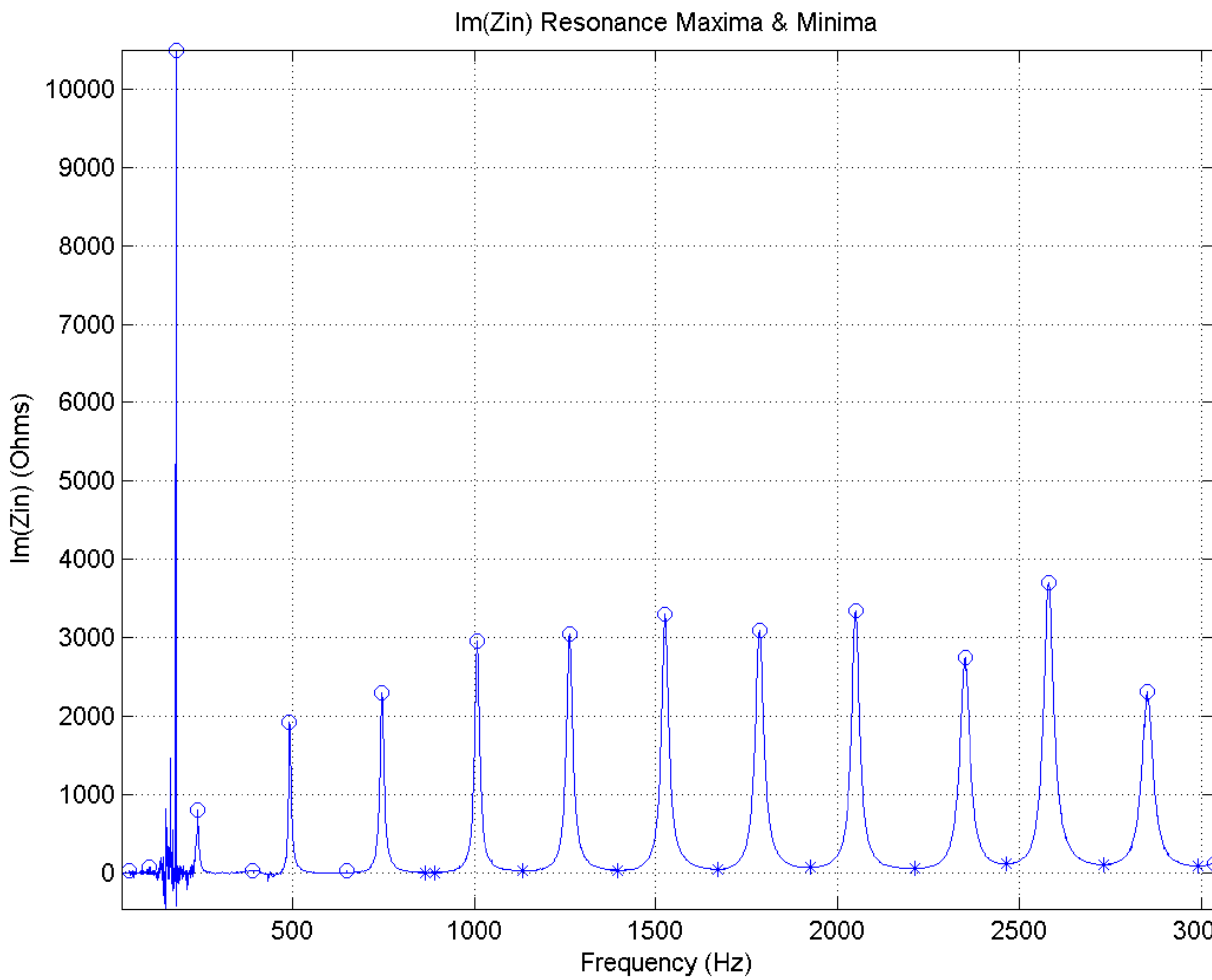
Left – the removed cord with the piezoelectric trasducer attached to its end
Right – the head joint with both microphones inserted: pressure on top, particle velocity on bottom





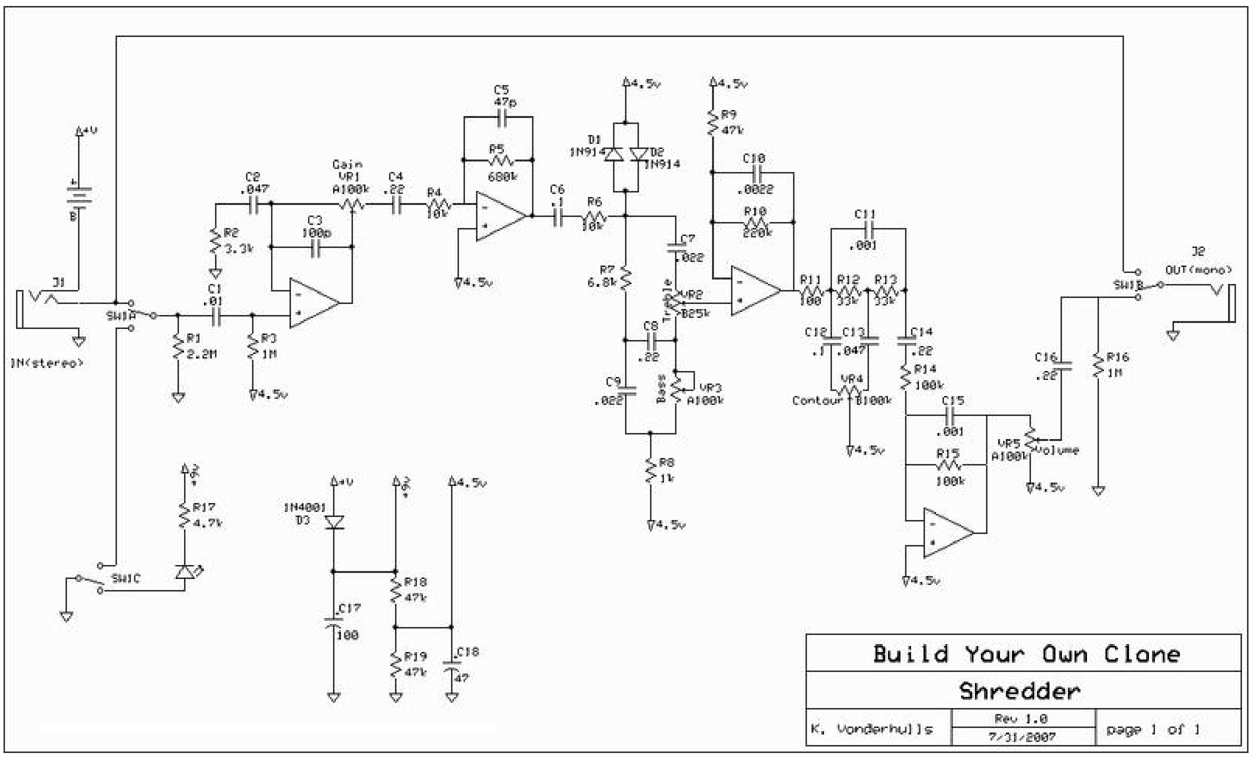
The body and foot joint were connected to the head joint, with a pressure level microphone and particle velocity microphone positioned inside the head joint as shown above, and one of each microphone positioned at the base of the foot joint, and the whole contraption was put in the foam insulated box. The goal was to do more testing on the three notes I looked at earlier: B4, G5, and Db5. For each test, the appropriate keys were taped down with plastic key caps in place. The testing consisted of sweeping through from 0 Hz to 3000 Hz, at intervals of 10 Hz, and looking for resonant frequencies within that range. With any luck, these frequencies would match up with the known frequencies of the specific note and its harmonics. Below is a picture of the set up, including four lock in amplifiers.

Looking at the graphs acquired through that test, we noted that the most interesting one was the graph of the imaginary part of impedance vs. frequency. This graph closely matched the known values of the tested note and its harmonics. High peaks in impedance are the only way a note is able to be produced from an instrument. In this graph, taken from the test of B4 (all keys taped down), we see that the first peak is at approximately 500 Hz. The known value for B4's frequency is 493.88 Hz. Similarly, each following peak corresponds very closely to the known values of B4's harmonics.



Building An FX Guitar Pedal

My second project was building a guitar pedal from a kit. My brother, who plays guitar, agreed that he would like to buy the kit and let me build it for him. He chose The Shredder pedal from Build Your Own Clone. This was my first experience with a soldering iron, and the first real circuit I have ever assembled. It was a great project and I thoroughly enjoyed it. The Shredder is modeled after the Marshall Shredmaster, and is described as “a full on 80's heavy metal distortion” – perfect for my brother’s taste in music! It has five knobs: volume, gain, treble, bass, and contour.



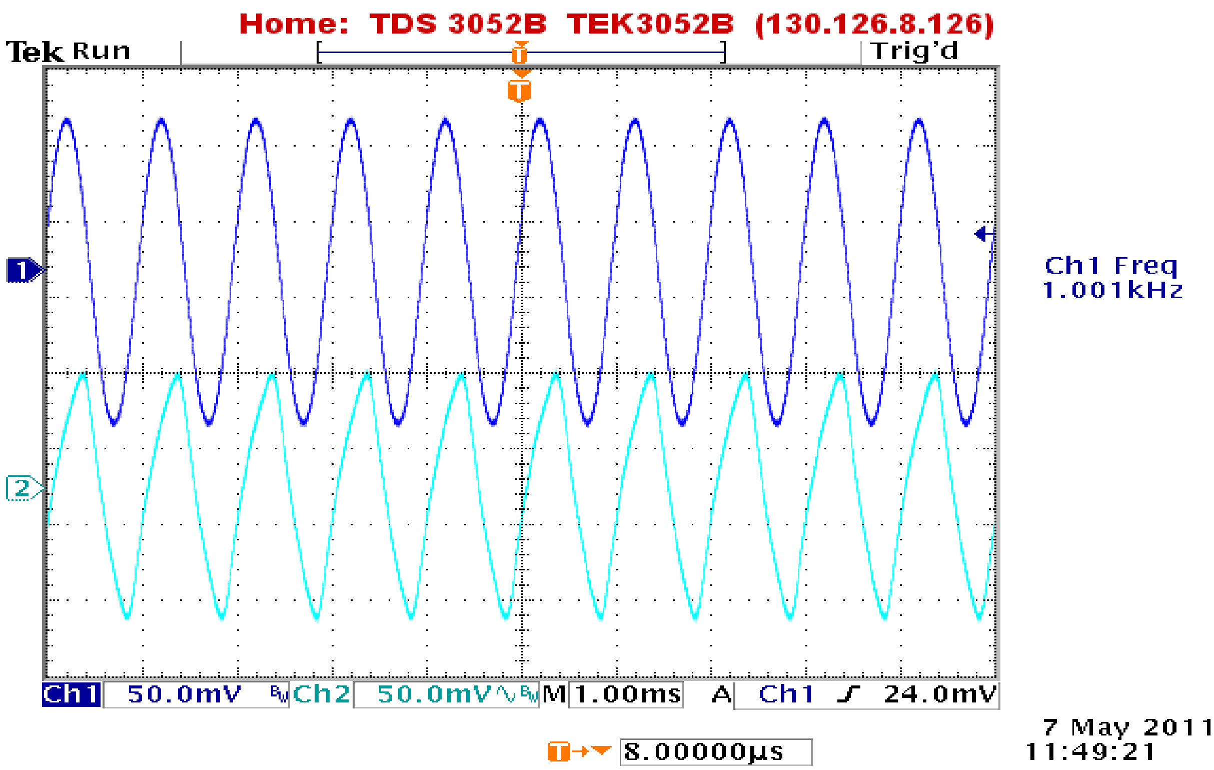
When I completed building the pedal, I asked a friend to test it out with his guitar. Thankfully, it worked just fine on the first try. After messing around for longer than necessary, it was time to do some more meaningful testing. We hooked it up to a function generator and fed it a 1kHz sine wave with amplitude of 100 mV, and spied on the output signal with an oscilloscope. When the pedal is off, the output is exactly the same as the input. (So, as advertised on the BYOC website, this pedal has true bypass.) Additionally, we hooked it in to a spectrum analyzer to monitor the presence of harmonics in the output.

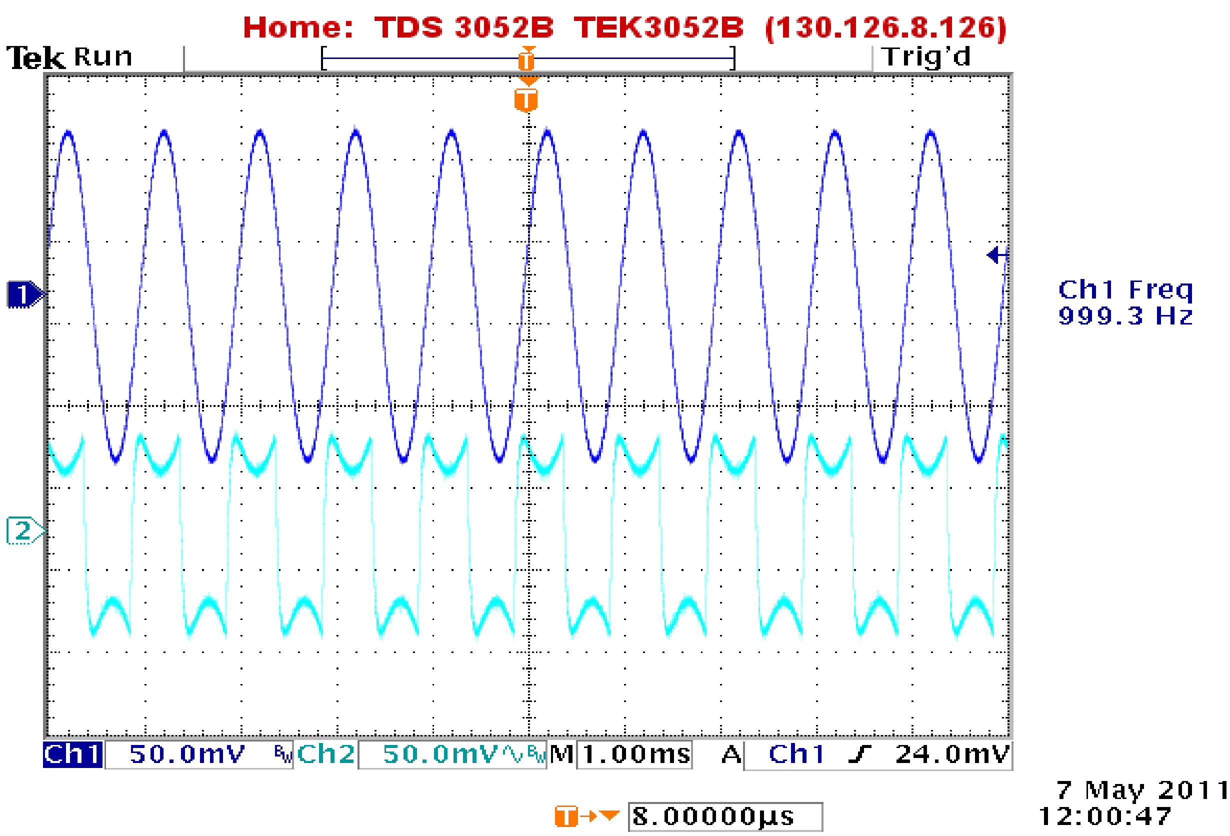
Note: *All graphs for the two tests can be found on the next two pages.*

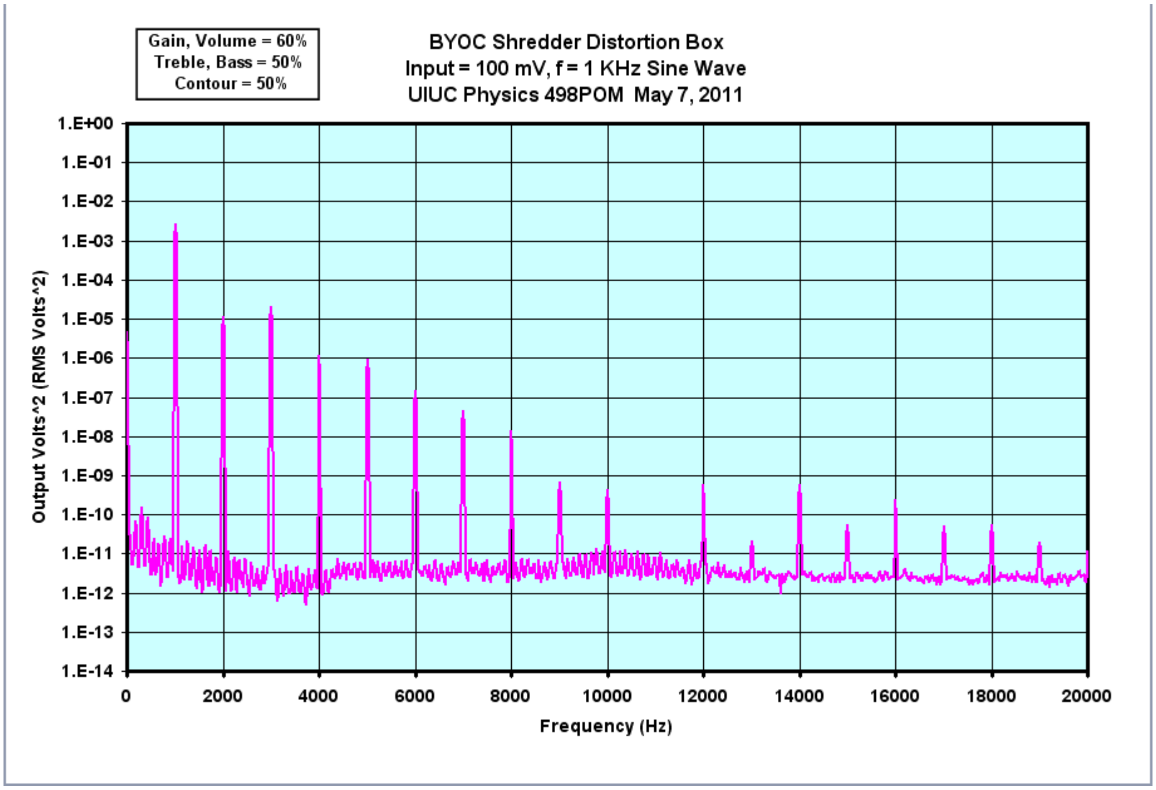
The first test was run with gain and volume set to 60%, and treble, bass, and contour set to 50%. Instead of a smooth sine wave, the output signal is more of a rounded saw tooth. There are a few harmonics present, but not many of them have very high amplitudes. The second test was run with gain and volume at 100%, treble and bass at 50%, and contour at 0%. With the settings so extreme, the results are much more drastic. While the first test's output still resembled the sine wave input, this test's output signal has become a sort of deformed square wave. The harmonics spectrum for this test is also very different. There are many more present, and as you move through the frequencies, the decrease in amplitude is very gradual.

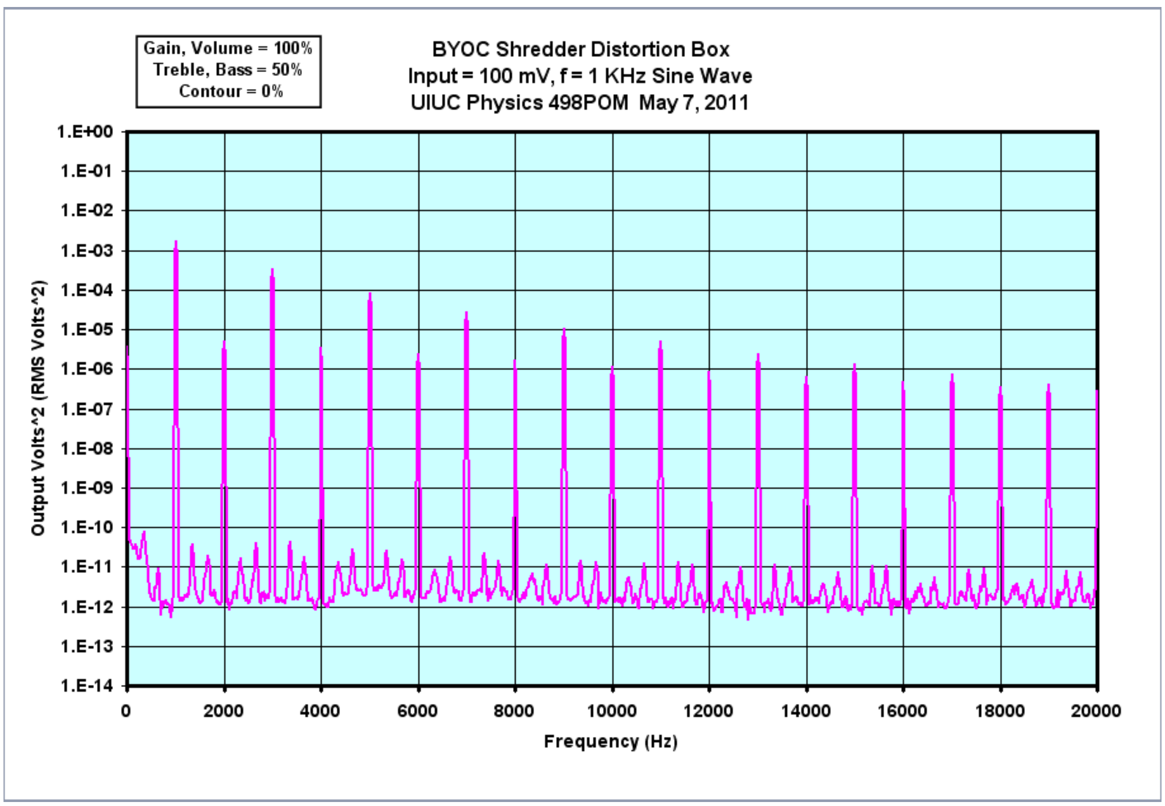
Conclusion

I originally took this class because I love music. I played the piano for 10 years, and I've been playing the flute for 10 years and counting. Now, in addition to just loving the music, I have a new appreciation for what is actually going on behind the scenes. The testing done on my flute has helped me to understand my instrument a little bit better. I have learned a lot about acoustical physics, but I've also gained a lot of hands on experience in the lab. I loved the chance to build something as real as the FX pedal. It was fantastic to start with a pile of components and turn it into a working machine by my own hands! Over all, I've had a great time in the class and I'm proud of what I've accomplished.


Home: TDS 3052B TEK3052B (130.126.8.126)
Tek Run
Trig'd
Ch1 Freq
1.001kHz
Ch1 50.0mV
Ch2 50.0mV
M 1.00ms
A Ch1 24.0mV
8.00000µs
7 May 2011
11:49:21


Home: TDS 3052B TEK3052B (130.126.8.126)
Tek Run
Trig'd
Ch1 Freq
999.3 Hz
Ch1 50.0mV
Ch2 50.0mV
M 1.00ms
A Ch1 24.0mV
8.00000µs
7 May 2011
12:00:47


Gain, Volume = 60%
Treble, Bass = 50%
Contour = 50%
BYOC Shredder Distortion Box
Input = 100 mV, f = 1 KHz Sine Wave
UIUC Physics 498POM May 7, 2011
Output Volts^2 (RMS Volts^2)
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
1.E-13
1.E-14
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Frequency (Hz)


Gain, Volume = 100%
Treble, Bass = 50%
Contour = 0%
BYOC Shredder Distortion Box
Input = 100 mV, f = 1 KHz Sine Wave
UIUC Physics 498POM May 7, 2011
Output Volts^2 (RMS Volts^2)
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
1.E-13
1.E-14
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Frequency (Hz)