MUSICAL INSTRUMENT: ELECTRONICALLY RESONATED METAL

Venkata Geetha Bijjam

Rachel Pashea

Final Report for ECE 445, Senior Design, Fall 2012

TA: Igor Fedorov

12 December 2012

Project No. 12

Abstract

We designed and developed an instrument that produces sound when the user initiates vibrations on a steel rod. These mechanical vibrations are converted into a voltage signal by a pickup like those used for electric guitars. This voltage signal is then amplified. The vibrations are reinforced and sustained by a driver coil, an electromagnet that produces a time-varying magnetic field which will alternately attract and repel the steel rod. When the user slides the rod, the pitch will change.

The basic design has been shown to be functional, but it operates inconsistently. In this paper we will explore reasons for its inconsistency and recommend solutions as well as additional features, such as a means of controlling volume and applying effects to the instrument's sound.

Contents

1. Introduction

1.1 Purpose

Over the past century or so, many electronic musical instruments have been developed, including the theremin, Ondes Martenot, Hammond organ, and Continuum Fingerboard. Each of these has its own distinct sound that it can contribute to a piece of music. Our objective was to add a new instrument to this ever-growing list, one that is unique and simple to play. The component of this instrument that provides the sound is the steel rod. A rod clamped at one end and free at the other produces overtones that are not harmonic multiples of the fundamental frequency, thus giving this instrument a somewhat dissonant sound. Another interesting feature of this instrument is that it is continuous rather than discrete like a piano, meaning that frequencies between those of the notes on the even-tempered scale can be played.

1.2 Objectives

Our musical instrument is unique in a way that we have to vibrate the entire metal rod using a powerful driver coil. On the market, there are guitars that use a similar mechanism, but they vibrate the strings with a less powerful driver coil. Our instrument uses magnetic pickup because it is easier to interface with the rest of our project and is a popular choice to use in electric guitars. The features of this instrument are the following:

- A high output current amplifier
- A pickup and a driver coil which can sustain vibrations in the rod

1.3 Specifications

The model for our musical instrument consists of a steel rod made of ferrous material which is electronically resonated using a driver coil via electromagnetic induction. In the initial setup, the rod lies between the rollers. The rollers are attached to chassis such that the rod is held place at the midpoint of the rod.

The user of this musical instrument places the instrument on a sturdy surface and positions the instrument in front of him or her such that the rod is aligned parallel to the ground and vibrating end of the rod is pointing to the right for a right hand player or to the left for a left hand player. The user starts off by exciting the rod with his or her non playing hand and extends the rod to the desired length. The arm motion while pulling the rod in and out to the desired length looks similar to a violin player extending and retracting the bow while playing different notes on the violin. The difference in the arm motion compared to a violin is that the user does not lift the arm or the elbow while playing this instrument.

The pickup coil is held near the extendable end of the rod and it converts the mechanical vibrations in the rod into voltage signal. The voltage output from the pickup coil feeds into a pre amplifier which amplifies the small signal coming from the pickup coil and outputs it to the power amplifier. The power amplifier will then further amplify the voltage signal and output current to the driver coil. The driver coil uses the current from the power amplifier to initiate the vibrations in the rod via electromagnetic induction similar to a solenoid. The vibrations in the rod are sustained using this setup because the driver coil vibrates the rod as long as the pickup coil converts the vibrations in the rod into voltage signals. The speakers are connected to the output of the pickup coil and the user will be able to hear sound at different frequencies through the speakers. If the pickup coil does not output any voltage signal, then the speakers would not produce any sound and similarly, the driver coil will see the 0A current at its input and will stop vibrating the rod.

1.4 Subprojects

The design is split into several subprojects, and a description of each follows.

1.4.1 Rod

The rod is made of steel, and is about 90 cm in length and 4 mm in diameter. When vibrating, it provides fundamental frequencies of 20 Hz to 78 Hz, corresponding to a low bass range of a little less than two octaves.

1.4.2 Pickup Coil

The pickup coil is placed underneath vibrating end of the rod. It senses the mechanical vibrations of the rod and converts them into proportional voltage signals, which it then outputs to the pre-amplifier.

1.4.3 Pre-amplifier

The pre-amplifier receives the voltage signal from the pickup as its input, and it outputs an amplified version of this signal. The gain varies between 1.5V/V and 2V/V based on room temperature.

1.4.4 Power amplifier

The power amplifier receives the voltage signal from the pre-amplifier as its input and amplifies the current in the input signal. It is capable of producing 7 A of current and delivering 68 W of power.

1.4.5 Driver Coil

The driver coil is an electromagnet, consisting of about 200 turns of copper wire wrapped around an iron core. It gets a voltage and current input from the power amplifier. Because the current signal is time-varying, the driver coil will produce a magnetic field that is also time-varying. When placed underneath the rod, the rod will alternately be attracted to and repelled away from the coil's magnetic field, causing the rod's vibrations to be sustained.

1.4.6 Power Supply

An external power supply will consist of a 9V battery for the pre-amplifier and two 12V batteries for the power amplifier. In our demo, we used bench power supply, although we eventually plan to use batteries instead.

1.4.7 Speaker

Because the sound of the vibrations in the rod is very quiet, the pickup coil is connected to the speaker.

1.4.8 Summary of the Modifications to the Original Design

We made several changes over the course of the semester to improve our design. The foremost of these changes was removing the microcontroller and the button from our original circuit design because the microcontroller would not function as controller, but merely as a switch. It was removed and replaced by a PID controller. Midway through the semester, we considered designing our own power supply but abandoned this idea because our number one priority was to get the basic circuit working. We also modified our amplifier design from an op-amp to a JFET and a high power amplifier IC chip. Although our design works, the behavior of the instrument is rather inconsistent because of overheating of the power amplifier IC chip.

2 Design

2.1 Rod

2.1.1 Design Procedure

It was necessary to choose a rod that could produce an adequate pitch range of about two octaves. It must be made of a magnetic material, and steel was chosen because it was readily available and not expensive. Other metals of which musical instruments are commonly made would produce their own unique sounds, but some, like titanium, are costly, and others, such as brass and nickel silver, are not magnetic. The natural frequencies produced depends on the vibrating length, the material of which the rod is made, and the radius of the rod. According to [1], the frequencies propagating on the rod at a certain length L are given by equation 2.1

$$f = (1.194^2, 2.988^2, 5^2, 7^2, \ldots)\frac{\pi\kappa c}{8L^2} \tag{2.1}$$

where κ is the radius of the rod divided by 2, c is the speed of sound in steel (5050 m/s), and the numbers separated by commas correspond to the overtones. For example, if it is desired to calculate the fundamental frequency at a certain length L, then 1.194^2 would be used; if the first overtone is to be calculated, then 2.988^2 should be used instead. This equation was derived by applying boundary conditions (bounded at one end and free at the other) to the solution of the equation of motion of a rod and using numerical techniques to solve for the frequencies. A couple of different rods were tested to see what their frequency ranges were. The first had a range of 40 Hz to 138 Hz, but because the rod needed to fit and slide easily between the rollers provided by the machine shop, a rod with a smaller diameter was used instead, thus lowering the frequency range of the rod.

2.1.2 Design Details

Initially, we obtained a steel rod from the machine shop that was about 0.5 cm in diameter. The lowest fundamental it could produce was calculated to be around 40 Hz using the equation above, and the highest fundamental it could produce was calculated to be 138 Hz at a length of 16 cm. The shortest length was determined by noting that as the length was decreased, the rod became less flexible, and the vibrations died out quickly. At any length shorter than 16 cm, it was just too difficult to initiate vibrations. This range of 43.5 Hz to 138 Hz, about three notes shy of a full two octaves. However, the rod needed to be thinner in order to fit between the rollers that the machine shop designed, thus lowering the frequencies. When positioning the driver coil and pickup underneath the rod, it was discovered that the shortest length the rod can go is 19 cm; otherwise, if it were shorter, the driver coil and pickup would not be underneath the rod. The rod was also much longer than the original rod, and its range of fundamental frequencies was calculated to be 3.5 Hz to 78 Hz. Although 3.5 Hz is below the audio range, the overtones at this length can still be heard. The range of audible fundamental frequencies is 20 Hz to 78 Hz, and this range is approximately two octaves. It also should be noted that this instrument is a low bass instrument.

2.2 Pickup Coil

2.2.1 Design Procedure

The pickup coil consists of an electroacoustic transducer which converts the sound due to the mechanical vibrations produced by the rod into voltage signals. The input for the pickup is the sound waves from the vibrating rod. The pickup coil is made of permanent magnets with wire wrapped finely around it. The output of the magnetic pickup coil is the voltage signal that will feed into the pre-amplifier. We used a standard guitar pickup because it is more reliable than winding our own pickup coil. Some of the disadvantages of winding our own pickup coil are the following: the wires might break if not wound carefully, and it is a very tedious job. The design alternatives include using either a electret microphone or a piezo film transducer. The disadvantage of the electret microphone and a piezo film transducer is that they are very sensitive to noise so our instrument might not function as intended.

2.2.2 Design Details

We used a standard magnetic guitar pick up in our design. A photograph of the pickup coil is shown in figure 2.2.

2.3 Pre-amplifier

2.3.1 Design Procedure

The pre-amp amplifies the voltage output from the magnetic pickup coil. The gain of the amplifier should be enough to amplify the signal from the pickup coil into a range of few volts peak to peak signal. One of the design alternatives we considered is to use op-amps in a non-inverting configuration for the pre-amplifier from [2]. The midband gain of the op-amp will be set by two resistors R1 and R2, and it is derived from

$$Vout = Vin\left(1 + \frac{R2}{R1}\right) \tag{2.2}$$

If we want a larger gain, we will need R2/R1 to be a very large value. The disadvantage of the op-amps is that the power supply to the op-amp IC chip used will clip the output voltage if the output voltage exceeds the power supply voltage. This means that the gain is limited by the power supply. We found that JFETs are more versatile in our design because there is less clipping at the output.

The pre-amplifier is designed using a JFET in a common source amplifier configuration with source degeneration as seen in figure 2.3(a). The midband gain of this amplifier is given by

$$Am = -gm\frac{Rd||Rl}{1 + gmRs} \tag{2.3}$$

where Rd is the drain resistor, Rl is the load resistor, gm is the transconductance parameter, and Rs is the source resistance. We can observe in equation 2.3 that if Rs is 0 then Am will be significantly smaller which means that if we want to increase gain, we have to use a resistor in the source.

2.3.2 Design Details

The transconductance of MPF102 as seen in figure 2.3(b) is given as a range of 2000uS and 7500 uS in [4]. The gm of the pre-amplifier is arbitrarily to chosen to be 5000uS in our design of the amplifier. Referring to [3], the coupling capacitor before the output pin of the pre-amplifier blocks DC from feeding into the power amplifier. If the power amplifier gets DC input signal then it will not function efficiently so we used a DC blocking capacitor at the output of the pre-amplifier. The gate capacitance of the common source amplifier should should be really big in order to provide large input impedance to the circuit. An order of Mega ohms is chosen and this RG provides gate bias VG for the circuit. Generally, the common source amplifiers are designed to operate in the saturation region. The drain current, ID, is given as

$$I_D = \frac{1}{2} k_n V_{ov}^2 \tag{2.4}$$

and in our design, we picked ID = 0.5 mA where

$$V_{ov} = V_{GS} - V_T \tag{2.5}$$

In equation 2.5, VGS is the gate source voltage difference and VT is the threshold voltage of the transistor. In equation 2.4, kn is the conduction parameter which is proportional to the device length and the width. The source and the body of the transistor are tied together so we can neglect the body effect that might affect VT parameter otherwise. Using the gain expression in equation 2.3, the resistor and the capacitor values for the pre-amplifier are chosen to give the preferred midband gain greater than 1.1 V/V.

2.4 Power Amplifier

2.4.1 Design Procedure

The main component of the power amplifier is the LM3886 amplifier chip. This is a high-performance audio amplifier that can deliver 68 W of power to a 4 Ω load. In our original design, we had a voltage amplifier, but it would not have produced enough current to drive the driver coil. The LM3886 chip can produce 7A of current, and it is inexpensive compared to other high-output current amplifiers such as OPA 512.

2.4.2 Design Details

The LM3886 has a supply voltage $|V^{+} + V^{-}|$ range of 20V to 84 V. We decided to use +12 V and -12 V from the wall for V^{+} and V^{-}, respectively, to give $|V^{+} + V^{-}| = 24$.

The schematic of the power amplifier is shown in figure 2.4 in section 2.8. The purpose of the 5.1 kΩ resistor is to provide current to the MUTE pin, which requires at least 0.5 mA for the output of the amplifier to *not* be muted. According to the data sheet, the mute resistance is calculated using the equation $R_m \leq (|V^{-}| - 2.6V)/0.5m$ mA. The value of $|V^{-}|$ is 12 V, so R_m must be ≤ 18.8 kΩ, so a 5.1 kΩ resistor works here.

The input resistance R_i and the feedback resistance R_f set the gain of the amplifier. The expression for the amplifier gain was calculated as

$$\frac{V_0}{V_{in}} = 1 - \left(\frac{1}{\frac{1}{j\omega C_3} + Ri}\right)\left(\frac{R_f \frac{1}{j\omega c_f}}{R_f + \frac{1}{j\omega c_f}}\right) \tag{2.6}$$

The feedback capacitor C_f, in parallel with the feedback resistance R_f, sets the gain to 1 at high frequencies. The purpose of C_1 and C_2 is to reduce external electromagnetic switching noise from fluorescent lamps, according to [5]. This reduces noise in the output. A gain of approximately -14 V/V in the midband was chosen.

The load of this circuit is the driver coil connected in series with a 5 Ω resistor. Because the resistance of the coil is small, the resistor is there to increase the load resistance over the minimum load resistance that is expected by the chip (4 Ω). Otherwise, the chip will burn out trying to output more current than it can handle.

2.5 Driver Coil

2.5.1 Design Procedure

The driver coil's function is to produce a time-varying magnetic field that will cause the rod to vibrate. Its inputs are a time-varying current and voltage. While just wrapping wire into a coil and passing a current through it will produce a magnetic field, the magnetic field will be stronger if the wire is wrapped around a ferromagnetic core, such as iron. In our design we used a cylinder of iron with a diameter 0.5 inches as the core. Figure 2.5 is an illustration of the driver coil, showing the magnetic field lines it produces.

The important parameters to be determined are the number of turns of wire around the driver coil and the amount of current that it receives from the power amplifier. These are related by the equation

$$N = \frac{Bl}{i \cdot \mu_0 \mu_{iron}} \tag{2.7}$$

where N is the number of turns of wire, B is the magnitude of the magnetic field, i is the magnitude of the input current, l is the vertical length of the coil, μ_0 is the permeability of free space, and μ_{iron} is the permeability of the iron core, and the values for these are $\mu_0 = 4\pi \times 10^{-7}$ H/m, and $\mu_{iron} = 125$.. Increasing the number of turns will increase the magnetic field. Increasing the current i through the wire will also increase the magnetic field, and this can be done by decreasing the resistance of the wire. The resistance of the wire is given by $R = \rho L/A$, where ρ is the resistivity of the wire, L is the length, and A is the cross-sectional area. Thicker wires have less resistance than thinner ones, so a lower gauge corresponds to a thicker wire, leading to less resistance and more current.

According to [6], the magnetic field will saturate at a certain value, no matter how much current is input into the coil. This value can be around 1.6 T. Knowing this, and that a typical value of the current from the power amplifier is 7 A according to its data sheet, we used equation 2.7 to get an estimation of how many turns of wire were required. Initially, we believed that the wire would be wrapped around the full length of the iron core (11 cm), but the wire stayed in place better if it was wrapped around only a 4 cm section of the core. The initial estimate of the number of turns was calculated as follows.

$$N = \frac{(1.6T)(0.11m)}{(7A)(125)(4\pi\times10^{-7}H/m)} = 145 \text{ turns}$$

(2.8)

The inductance of the driver coil is given by

$$L = \frac{\mu_{iron}\mu_o N^2}{l}$$

(2.9)

where the additional variable, A, is the cross-sectional area of the coil.

2.5.2 Design Details

Using the initial estimate of 145 turns as a starting point, several driver coils were built, with varying wire gauges and number of turns. They were tested first by applying a DC voltage, then by applying an AC voltage from a function generator. The results of these tests are shown in tables 2.1 through 2.4 in section 2.8. The driver coil with gauge 20 wire and N = 200 provided the most power. Its resistance was measured to be 0.93 Ω, and its inductance was calculated as follows by using equation 2.9:

$$L = \frac{(125)(4\pi\times10^{-7}H/m)(200^2)(\pi(0.25in\times0.0254m/in)^2)}{0.04\ m} = 0.0199 \text{ H}$$

(2.10)

2.6 Power Supply

The power supply consists of batteries. The pre-amplifier requires a 9V power supply while the power amplifier requires a +12V and -12V power supply. In our demo, we used an alternate power supply design, mainly the bench power supplies because we could not get a hold of these large batteries for the demo. Another alternative is to design our own power supply using transformers, low pass filters, and a zener diode that caps the voltage. Because of time limitations we did not design our own power supply. Since we did not design the power supply, the design details are not included.

2.7 Speaker

Any 4 ohms speaker can be connected to the output of the pickup coil in order to hear the sound produced when the rod is vibrating. The pickup coil can drive a 4 ohms load. We did not design the speaker as we used an off the shelf component in our project. The positive terminal of the speaker will receive its input from the positive lead of the pickup coil. The negative terminal of the speaker will be connected to the ground. The alternate design to using the speakers is to not use the speakers at all. If our instrument works consistently then the rod will vibrate with powerful oscillations and will produce audible sound that can be heard without any external speakers. Since we did not design the speakers, the design details are not included.

2.8 Figures and Tables

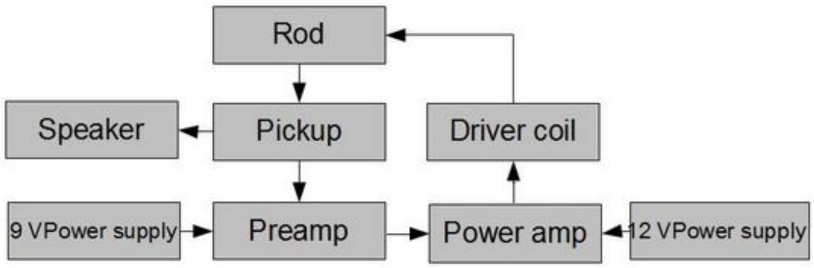
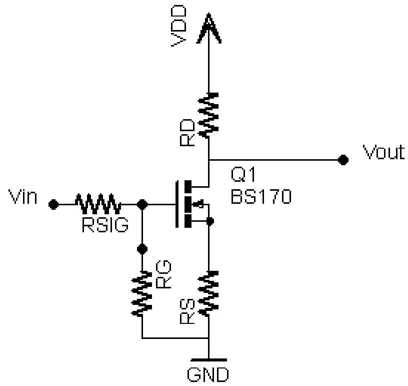
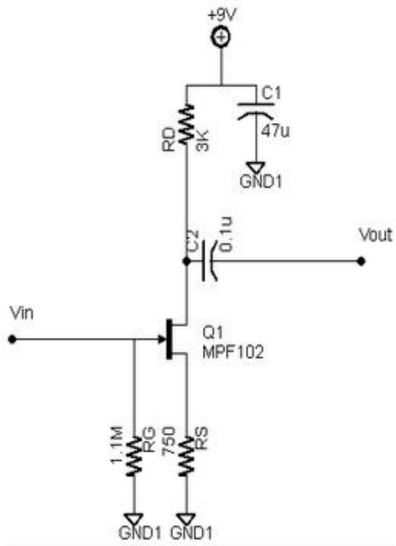


Fig. 2.1. High-level block diagram





(a) **(b)**

Fig. 2.2 **Fig. 2.3**

Fig. 2.2. Photograph of the pickup

Fig. 2.3. (a)General Circuit of the Common Source Amp with Source Degeneration Resistor (b) Schematic of the pre-amplifier

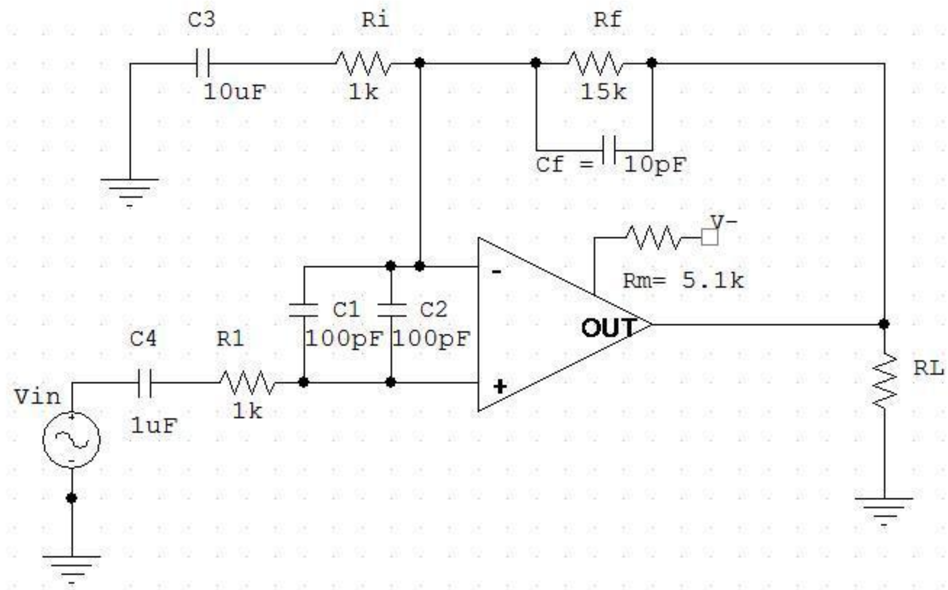


Fig. 2.4. Power amplifier schematic.

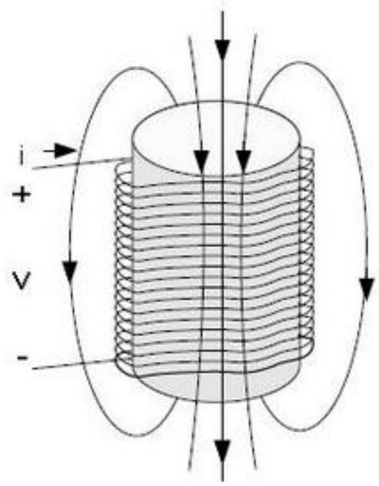


Fig. 2.5. Illustration of the driver coil.

Table 2.1 N = 200, gauge 30 wire

Voltage (V)	Current (A)	Calculated B field (T)	Calculated Power (W)
1.000	0.288	0.226	0.297
1.500	0.431	0.3385	0.665
2.000	0.573	0.45	1.175
2.500	0.708	0.556	1.194
*3.000	0.844	0.663	2.55
3.609	0.996	0.782	3.55
4.008	1.092	0.857	4.267
4.508	1.217	0.956	5.3
5.007	1.337	1.05	6.399

*At this point, the B field is strong enough to lift a small rod off a table. The coil was also hot.

Table 2.2 N = 80, gauge 20 wire

Voltage (V)	Current (A)	Calculated B field (T)	Calculated Power (W)
1.001	1.29	0.405	1.248
1.501	2.60	0.816	5.07
2.001	3.56	1.118	9.5
2.501	4.8	1.508	17.28

Table 2.3 N = 200, gauge 20 wire

Voltage (V)	Current (A)	Calculated B field (T)	Calculated Power (W)
0.997	1.268	0.996	1.495
1.997	2.513	1.9737	5.873
2.998	3.759	2.95	13.14
3.870	4.997	3.92	23.22

Table 2.4 N = 400, gauge 30 wire

Voltage (V)	Current (A)	Calculated B field (T)	Power (W)
0.997	0.108	0.1696	0.1143
1.997	0.229	0.3597	0.5139
2.998	0.363	0.5702	1.29
3.998	0.480	0.7539	2.258
4.997	0.600	0.942	3.528
5.997	0.726	1.14	5.165

3. Design Verification

3.1 Testing

Please refer to the Appendix for the detailed Requirements and Verifications procedure for our subcircuits. The speaker and the power supplies we used are from the off the shelf components so we did have a formal testing procedure. However, we know that both are working. We were able to hear sound from the speaker when we placed the pickup coil under the rod, connected the output of the pickup coil to the speakers, and vibrated the unclamped end of the rod using a hand. The power supply supplies the power to the amplifier and we know that our amplifiers work so using proof by contrapositive we can say that if each of the amplifiers work then their respective power supply works also.

3.1.1 Rod

To verify the theoretical frequency range of the rod, a pickup coil was hooked up to an oscilloscope and placed underneath of the rod. The rod was struck manually and its vibrating frequency was displayed on the oscilloscope. This test was repeated at several lengths, and the measured frequencies matched the theoretical ones almost exactly. The oscilloscope traces from these tests are shown in section 3.3. These tests also have the benefit of demonstrating that the pickup coil is outputting the correct frequencies.

3.1.2 Pickup Coil

To verify that the pickup coil works, the same procedure as in section 3.1.1 can be used and the results can be seen in section 3.3. Since the purpose of the pickup coil is to convert the vibrations in the rod into voltage signals, if the pickup coil does not work then the tests in 3.1.1 will not show correct frequencies.

3.1.3 Pre-amplifier

The pre-amplifier can be verified if it is working or not by sending an input sinusoid of 1V p-p from a function generator and observe the output waveform on oscilloscope and ensure that the signal is being amplified. Since gm parameter of the JFET used in the design of the pre-amplifier does not have a specific value and may be any value between 2000 uS and 7500 uS, the actual gain of the pre-amplifier might be anywhere between 1 V/V and 3.5 V/V. The graphs in in section 3.3 show that the signal is being amplified from the pre-amplifier.

3.1.4 Power Amplifier

The power amplifier needs to be able to produce an output signal that is the input voltage signal multiplied by the gain. Different values of the gain were tested by changing resistor R_f in figure 2.4 from section 2.8. Figure 3.3 shows that for a gain of 6.25 V/V, a 1 V peak-to-peak sine wave is amplified to 6.25 V peak-to-peak, with no voltage clipping when the offset is increased, and little noise. A frequency sweep was done on the function generator, and the gain was consistently 6.25 V/V for all audio frequencies, with no distortion until the offset voltage was increased to 3 V.

3.1.5 Driver Coil

The driver coil's main function to to vibrate the rod at the same frequency as the input frequency. The driver coil, driven by a function generator, was held up to the end of the rod. A pickup was also placed underneath the rod, and the oscilloscope displayed the signal from the pickup. The frequency of this signal was measured and compared to the input from the function generator. This test was repeated for several different frequencies, and the driver coil passed every test. An oscilloscope waveform from these tests is shown in figure 3.4.

3.2 Tolerance Analysis

The tolerance of the power amplifier in not distorting the input signal is tested.

The testing procedure for the tolerance analysis is as follows:

1. Connect the input signal from the signal generator to the input of the power amplifier

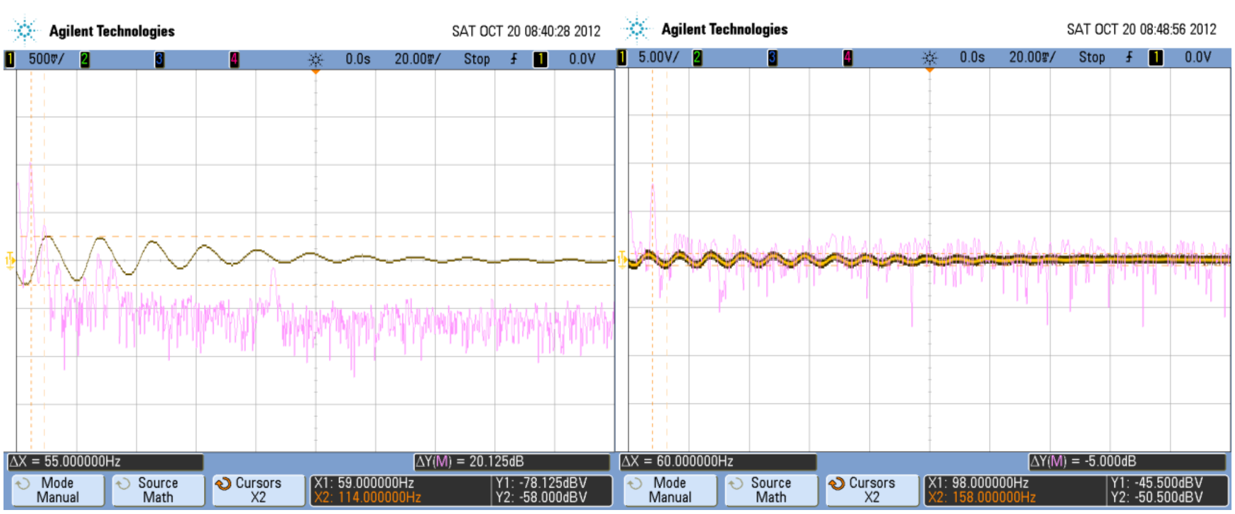
2. The input signal should be varied from 1V to 20 V peak to peak sinusoid at frequencies 20 Hz to 20 kHz.

3. Observe the output on the oscilloscope.

4. Write down above what voltages the output waveform is clipped.

We observed that the tolerance about 3 V + or - 0.1 V of DC offset at the input before the output signal becomes distorted. We also found that the power amplifier can also amplify over the full range of audio frequencies, ~20 Hz to ~20 kHz.

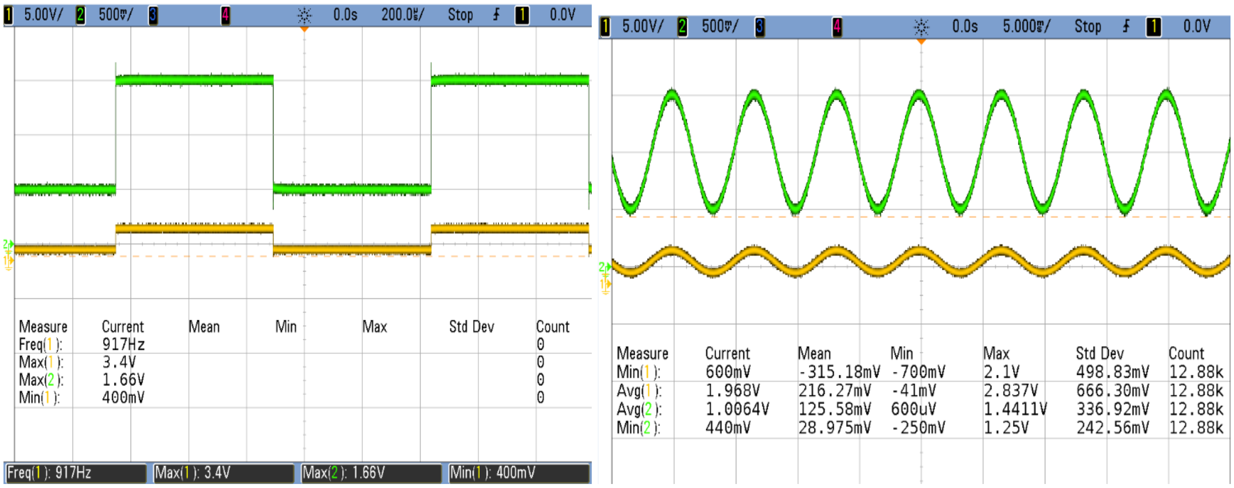
3.3 Figures and Tables



(a) **(b)**

Fig. 3.1. Testing the rod and pickup. In (a), the calculated theoretical fundamental frequency at this length of 24.3 cm is 59.85 Hz, and the pickup measured 59.00 Hz, which corresponds to the peak of

the FFT (purple).In (b), the theoretical frequency at this length of 19 cm is 97.89 Hz, and the pickup measured 98.00 Hz.

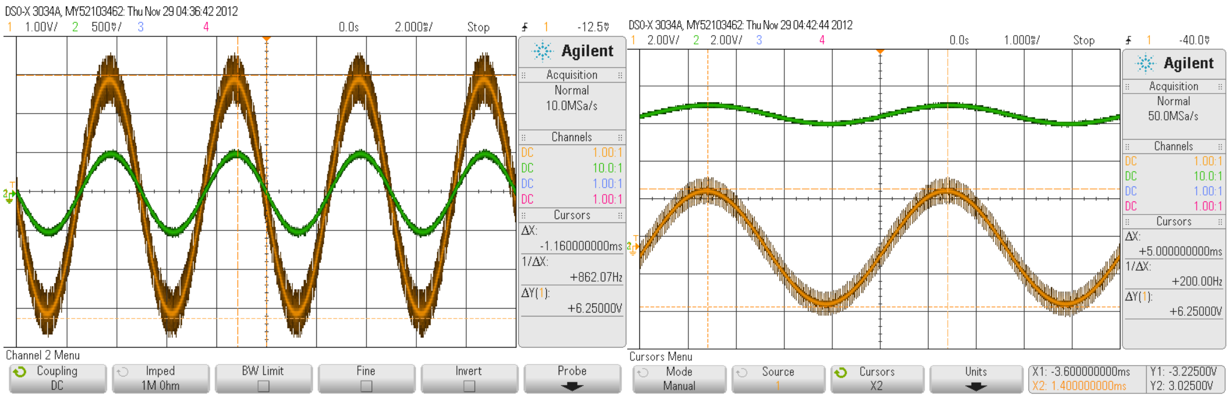


(a) **(b)**

Fig. 3.2. (a)Testing the output of the pre-amplifier using an input Square wave of 917 Hz. The midband gain given by the ratio of Vout (Green) to Vin (Yellow) is roughly 2 V/V. (b) Testing the output of the pre-amplifier using an input sine wave. The midband gain given by the ratio of Vout (Green) to Vin (Yellow) is roughly 2 V/V.

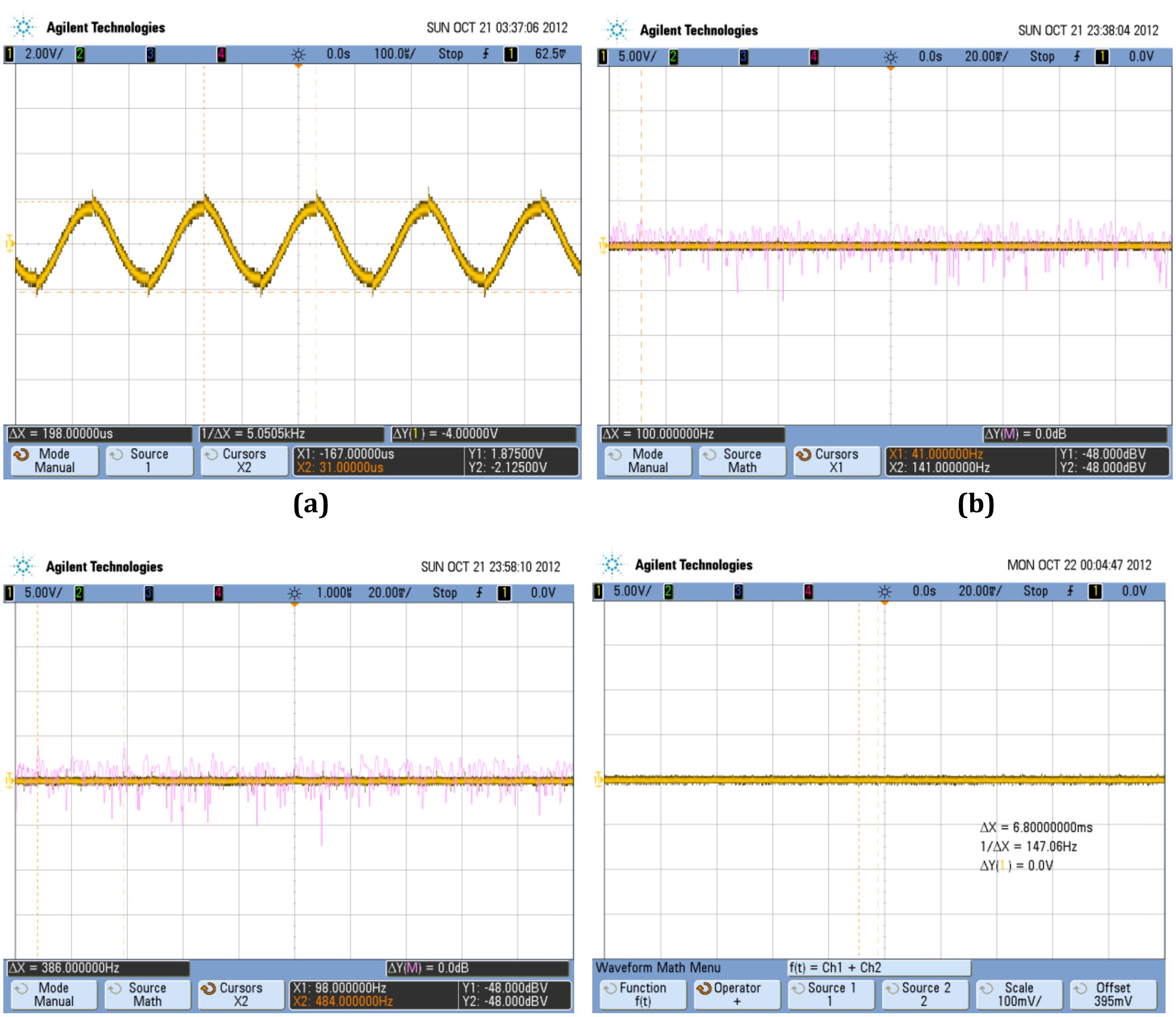
Table 3.1 Midband Gain of pre-amplifier at different room temperatures

Room Temperature by Location	**Midband gain of the pre-amplifier**
Very Warm(>25 degree Celsius)	1.5 V/V
~25 degree Celsius	2.5 V/V
Chilly (<25 degree Celsius)	3.3 V/V



(a) **(b)**

Fig. 3.3. Testing the power amplifier (a) with a gain set to 6.25 and offset 0 V, and (b) with a gain set to 6.25 and a voltage offset of 2 V.



(c) **(d)**

Fig. 3.4. Testing the driver coil. The input frequencies are 5.02 kHz, 40.0 Hz, 98.0 Hz, and 145 Hz for (a), (b), (c), and (d), respectively. The frequencies measured by the oscilloscope are 5.0505 kHz, 41.0 Hz, 98.0 Hz, and 147.06 Hz for (a), (b), (c), and (d), respectively.

4. Costs

4.1 Parts Cost

As seen in table 4.1, the cost for the parts $146.31 when we include the bulk manufacturing costs for our instrument.

4.2 Labor Costs

As seen in table 4.2, the labor cost for Rachel Pashea is $17,500 and the labor cost for Venkata Bijjam is $17,500. Based on our ideal salary of 40/hr, the total labor cost is $35,000.

4.3 Additional Costs

As seen in table 4.3, we estimate that the electronics and the machine shop spent around five hours on making the rod and the rollers for our instrument. At a cost of $10/hr, the additional cost incurred for these five hours is $50.

4.4 Total Cost

By adding the costs in tables 4.1, 4.2, and 4.3, the total cost incurred for our project is $35,196.31. To break even, we have to sell 704 units of our instruments at a cost of $50 before we even get marginal returns on our product.

4.5 Figures and Tables

Table 4.1 Parts Costs				
Part	**Manufacturer**	**Unit Cost ($)**	**Bulk Purchase Quantity**	**Actual Cost ($)**
10 Yards Gauge 20 wire	Belden	$4.99	1	$4.99
0.5” diameter iron core	Machine Shop	$10.00	1	$10.00

LM3886 chips	National Semiconductor	$5.95	6	$35.70
Circuit board	Vectorbord	$19.96	1	$19.96
Heat sink	Aavid Thermalloy	$0.38	2	$0.74
MPF102 FET	RadioShack	$0.97	1	$0.97
¼ W Resistor Pack	Futureluc	$2.95	1	$2.95
C100UC 0.1 uF capacitor	Futureluc	$0.10	100	$10.00
0.46 uF capacitor	Futureluc	$0.10	100	$1.00
Pickup Coil	Seymour Duncan	$60.00	1	$60.00
Total				**$146.31**

Table 4.2 Labor Costs			
Name	**Hourly Rate**	**Total Hours Invested**	**Total = Hourly Rate x 2.5 x Total Hours**
Venkata Bijjam	$40.00	175	$17,500.00
Rachel Pashea	$40.00	175	$17,500.00
Total			**$35,000.00**

Table 4.3 Additional Costs			
Outside Resources	Hourly Rate	Total Hours Invested	Total = Hourly Rate x 2.5 x Total Hours
Machine Shop	$10.00	5	$50.00
Total			$50.00

5. Conclusion

5.1 Accomplishments

We started this project with little knowledge of amplifiers or the mechanical components of the instrument. It was a very abstract concept which became clearer as the semester progressed. We feel very accomplished in our progress and the design of the instrument even though the instrument did not work consistently during the demo. One of the greatest accomplishments we feel is that the whole instrument worked the day before the demo.

5.2 Uncertainties

Due to problems arising from the inconsistencies of the power amplifier IC chip, we are uncertain how long the rod can vibrate before the power amplifier chip overheats. additional impulse to the rod. We are however certain that the rod can vibrate continuously for 15 minutes before the power amplifier chip gets overheated. This could be because of the high gain of the power amplifier. The maximum output signal of the pickup is about 1 V. If the gain of the pre-amplifier is 2.5 V/V and the gain of the power amplifier is 14 V/V, that is an output voltage of 35 V peak-to-peak. Considering that the resistance of the load is about 6 Ω, this gives an output current of 5.83 A, and a power dissipation of about 200 W, which exceeds the amount of power that the chip can provide. The next step is to reduce the gain of the power amplifier so that it doesn't produce quite so much power.

5.3 Ethical considerations

In table 7.2, the IEEE code of ethics from [7] are listed the left column and in the right column, we listed how we adhered to each item of the code during this project. Along with adhering to IEEE code of ethics, we put our utmost priority in making sure the safety of the users of this instrument because we have a very high output current amplifier in our design. To avoid injury to the users, the manufacturing of this instrument would have warning labels and also have a secured chassis so that the amplifier parts and the driver coil wire are not exposed out of the chassis.

5.4 Future work

In the future, we hope to add various effects to this instrument. These effects would include filters that the user would be able to turn on or off as he or she wishes. For example, the lower harmonics could be filtered out to emphasize the higher ones. These filters would allow the user to play notes that are beyond the range of the fundamental frequencies of the instrument. We also plan to add a mechanism that would allow the driver coil to move with the rod so that it will always be directly beneath the rod's free end. And, as our original design review specified, we would like for the user to be able to initiate and sustain the vibrations by pressing a button and holding it down, instead of just exciting the rod with a finger. The button would also be instrumental in halting the vibrations, because when it is released the vibrations will cease; currently the way to stop the vibrations just involves sliding the rod out of range of the driver coil. In addition to that, we would like to have a controlled feedback system implemented using PD controller so that the user can control the sound and the intensity of the vibrations in the rod to their preferred level. The PD controller amplifies the difference between the input signal and the reference signal and tries to bring the system to the reference level with minimum time delay. The P term controls the proportional gain and amplifies the error proportionally. The D term computes the rate of change of error or the difference. The I term is absent from the PD equation because past error values do not contribute as much as the P and D terms to the working of our instrument.

6. References

[1]L. Kinsler, A. Frey, A. Coppens, and J. Sanders, *Fundamentals of Acoustics*, 4th ed., Hoboken: John Wiley & Sons, 2000, pp. 68-87.

[2] A. Sedra and K. Smith. *Microelectronic Circuits*, 6th ed., Oxford: Oxford University Press, 2010, p. 53-108.

[3] Mike Martell. *Design Guidelines for JFET Audio Preamplifier Circuits* [Online]. Available: www.rason.org/Projects/jfetamp/jfetamp.htm

[4] *MPF102 - N-Channel RF Amplifier.* [Online]. Available: http://www.fairchildsemi.com/ds/MP/MPF102.pdf

[5] *Saturation (magnetic)*. [Online]. Available: http://en.wikipedia.org/wiki/Saturation_(magnetic)

[6] *LM3886 - Overture TM Audio Power Amplifier Series High-Performance 68W Audio Power Amplifier w/Mute - National Semiconductor.* [Online]. Available: http://www.alldatasheet.com/datasheet-pdf/pdf/8892/NSC/LM3886.html

[7] *IEEE Code of Ethics*[Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html

7. Appendix A Additional Tables

7.1 Requirement and Verification Table

Table 7.1 System Requirements and Verifications		
Rod Requirement	Rod should have vibration frequencies within the range of 40-200 Hz	
Sub Requirements	**Verification/Testing**	**Verification Status**
1. The rod should be magnetic	1.Hold a magnet near the rod. 2.If the magnet attracts to the rod, then this test is passed. 3. Else, the test fails.	Y. Rod is made of steel.
2. The diameter of the rod should be less than 1”.	1. Measure the rod’s diameter using a ruler 2. If the diameter of the rod is less than 1” then this test is passed 3. Else, the test is failed.	Y. We can verify this visually.
3.There should be minimum vibrations (less than 1V) at the other end of the rod where the vibrations are not initiated.	1. Visually, make sure that there are rollers holding the rod in place. 2. Measure using a multimeter a). Clamp the rod to the table. b). Place the pickup coil underneath the rod near the non-vibrating end and connect the pickup’s positive lead to the	Y. The output is 300 mV.

	positive terminal on the multimeter c). The input to the pickup will be the voltages that are sensed when the rod is excited on the other end of the rod where the pickup coil is not placed. d) Pluck the rod with the finger to initiate vibrations in the rod. e).If the output voltage of the pickup coil measured on the multimeter is greater than 1 V, then the rod fails this test. f) Else, the rod passes this test.	
4. Frequency range of the rod is within 20 Hz to 100 Hz	The range of frequencies will depend on the type of metal, length, and thickness of the rod. 1. Clamp the rod to the table. 2. Place the pickup coil underneath the rod near the vibrating end and connect the pickup to the oscilloscope's channel 1. 3. The input to the pickup will be the voltages that are sensed when the rod is excited by hitting it on one end with a finger. 4.The fundamental frequency and overtones can be determined by using the FFT function on the oscilloscope for the output voltages from the pickup coil.	N. Machine shop used a rod of a smaller diameter than the rod we initially tested (the rod we initially tested fulfilled these requirements). The fundamental frequencies in the audio range of this rod are between 20 Hz to 70 Hz (corresponds to E three octaves below middle C to D two octaves below middle C.) However, for fundamental frequencies below

	5. The lowest frequency occurs when the rod is at its longest length, and the highest frequency will occur when the rod is the shortest it can be while still being able to freely vibrate. 6. By measuring the frequencies we can verify that the rod will vibrate within the desired range of 40 to 200 Hz. 7. If the measured frequencies do not fall in the desired range of 40-200 Hz then the rod fails this test. 8. Else, the the rod passes this test.	the audio range, higher overtones may be heard.

Driver Coil Requirement	The driver coil should be able to vibrate at the same range of frequencies as the rod.	
Sub Requirements	**Verification/Testing**	**Requirement Status**
1. Driver coil should produce a magnetic field.	1. Connect a battery to the driver coil. 2. Place small metal objects such as paper clips or staples on a surface and use the coil to attempt to pick them up. 3. If the objects are attracted to the coil, then the driver coil passes the test.	Y.
2. Driver coil should produce a time-varying magnetic field strong enough	1. Use a function generator to generate an input current to the	Y. However, this was very hard to observe because

to vibrate the rod.	driver coil. 2. Place the driver coil underneath the rod. 3. If the rod is observed to vibrate, the driver coil passes the test.	the output of the function generator is current limited. When this setup is used, the driver coil must be touching the rod to hear noise. The power amplifier (being driven by the function generator) outputs a maximum of 7 A peak to peak, so the driver coil is able to produce a stronger magnetic field than when it was connected to the function generator, and it is much more obvious that the rod is vibrating.
3. Driver coil should be able to sustain the rod's vibrations at the same frequency as the input current.	1. Use a function generator to generate a sinusoidal wave that has a frequency between 40 and 200 Hz. This will be the input of the driver coil. 2. The rod will be placed on a roller above the driver coil, and the coil will cause it to vibrate. As before, a pickup will be placed underneath the rod and connected to an oscilloscope. The frequency of the rod's vibration can be determined by using the FFT function.	Y. Again, it is easier to see these results when using the power amp to drive the coil. The power amp will be driven by the signal from the function generator.

	3. This should match the frequency of the input signal. Otherwise, this test has been failed.	
4. Driver coil should be able to sustain the rod's vibrations at frequencies between 40 and 200 Hz.	1. Repeat the test for requirement 3 above for several different frequency values within the specified range. 2. If the frequency measured on the oscilloscope does not match the frequency of the input signal for all of the frequencies tested, the driver coil does not pass the test.	Y.

Pickup Coil Requirement	The pickup coil should convert the mechanical vibrations of the rod into a voltage signal.	
Sub Requirements	**Verification/Testing**	**Requirement Status**
1. The output of the pickup coil circuit connected should not exceed 5V.	1. Using alligator clips, connect the positive lead of the pickup coil to the positive lead of the multimeter. 2. Connect the negative leads of the pickup coil and the multimeter together using alligator clips. 3. Place the pickup coil under the rod and excite the rod at different lengths of 2", 4", 6", and 8" using a finger. 4. The pickup coil passes this test	Y. Peak to peak amplitude is about 2V at all lengths..

	if the voltage read from the multimeter at those above lengths is less than or equal to 5V. 5. Otherwise the test gails	
2. The pickup coil should not be placed more than 6” from the rod.	1. Measure how far away the pickup coil is from the rod using a ruler. 2. If the length measured is greater than 6” then the test fails. 3. Else, the test passes.	Y. Pickup coil is placed at a distance of ~1”” from the rod.

Pre-amp Requirement	The pre-amp should be working properly: If all of the tests below are passed then the pre-amp circuit is working.	
Sub Requirements	**Verification/Testing**	**Requirement Status**
1. The pre-amp should have a gain more 1.1V/V.	1. The input of the pre-amp will be a sine wave of 1V peak to peak from a signal generator. 2. The output should be amplified. The gain is just output divided by input. 3. Else Test fails.	Y. Signal is amplified

Power Amplifier Requirement	The power amplifier should take the voltage output from the preamp as the input, and it will output the amplified current to the driver coil.	

Sub Requirements	Verification/Testing	Requirement Status
1. The frequency of the output signal should match the frequency of the input signal.	1. A sine wave of 1 V peak to peak from a function generator will be the amplifier input. The output will be displayed on an oscilloscope. 2. Use the oscilloscope to measure the frequency of the input signal (should match the frequency of the input according to the function generator) and output signal. Both frequencies should be equal. If not, the amplifier fails this test.	Y.
2. The amplitude of the output voltage should be the amplitude of the input signal multiplied by the value of the amplifier's gain.	1. A sine wave of +1V peak to peak from a function generator will be the amplifier input. 2. The theoretical gain is calculated to be **~15 V/V**. The output of the amplifier will be displayed on an oscilloscope. The peak to peak voltage of the waveform will be measured. This peak to peak voltage should be **~15**, since the input peak to peak voltage was 1 V. If the peak to peak voltage of the output signal is not **15**, then the amplifier has failed this test. 3. Otherwise, adjust the frequency at which the function generator is operating. The gain should still be **~15** at all frequencies. If this is true, the amplifier passes the test.	Y.
2. If there is a DC offset in the input signal, there should be no DC offset at the output.	1. Connect a function generator to the input of the amplifier, at 1 V peak to peak. Display the output of the amplifier on an oscilloscope. 2. Adjust the amount of DC offset on the function generator. The output waveform	Y

	should not change. If this is not the case, the test has failed. 3. Try several different values of DC offset. The output waveform should not be raised or lowered by the offset; it should be unaffected.	
3. There should be no voltage clipping at the output.	1. Connect a function generator to the input of the amplifier, and vary the input peak to peak voltage from 1 V to 15 V peak to peak. 2.Display the output of the amplifier on an oscilloscope. 3. The output waveform should not be clipped for this test to pass.	Y

7.2. Ethical Considerations Table

Table 7.2 Ethical Considerations from [7]

To accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment	Our project is intended to be used by the public when it is finished, so it is our responsibility to write clear instructions for using the instrument.
To be honest and realistic in stating claims or estimates based on available data	All of our statements and estimations are backed up by calculations; we did not make a claim without reason. Data is not fabricated.
To improve the understanding of technology; its appropriate application, and potential consequences	We will do our best to inform the public about the correct use of this instrument, predict the consequences of misuse, and develop a prototype that minimizes the negative consequences.
To maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of	Each of us is more knowledgeable in a certain area than the others, which is how we divided up our work, and yet we must all have an understanding of the project as a whole. This required us to communicate and teach each other to improve our knowledge.

pertinent limitations	
To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others	This is a team project, so each of us review the others' work, gave feedback, and gave each team member credit for her contributions.
To treat fairly all persons regardless of such factors as race, religion, gender, disability, age, or national origin	We treat everyone involved with this project with the same respect.
To avoid injuring others, their property, reputation, or employment by false or malicious action	We did not cause injury to others, their property, reputation, or employment during the course of the project.
To assist colleagues and coworkers in their professional development and to support them in following this code of ethics	We made sure that everyone working on this project adhered to this code of ethics, and we provided support and encouragement to one another to live up to Illinois engineering standards.