ECE 445: Senior Design

WIRELESS MAGNET PICKUP WITH EFFECTS: DESIGN DOCUMENT

Team 19: Dylan Ouart, Wilson Ngai

TA: Daniel Frei

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1 Introduction

1.1 Objective

Acoustic guitars are an ancient instrument. They have been around for nearly 4000 years, and there are theories that suspect it was developed based on the lute or ancient Greek kithara (1). Despite being such an old instrument, they continue to be widely used today. As time moved on, people began to want louder guitars, and began to explore electric amplification. The first electric guitar was made around 1931 by George Beauchamp and Adolph Rickenbacker (2). This brings us to the modern age. The problem is that many acoustic guitars are not built with the capability to transmit their signal to an amplifier to make it louder. The ones that do have this capability are generally more expensive than ones that do not. For example, a Fender CD-60S is priced at 199.99 dollars, but essentially the same model with a pickup, the CD-60SCE, is priced at 299.99 dollars (3). Vintage acoustic guitars also do not have this capability. It also is desirable to put effects on the sound of the guitar. This can be done with various pedals or one multi-effect pedal. These pedals can also be relatively expensive, with prices ranging from around 50 to about 1500 dollars (4).

Our goal is to create a cost efficient wireless pickup that does not damage the body of the guitar while at the same time being able to create guitar sound effects. We will use a magnetic pickup which will then send the audio signals to the effects module and from there will be sent to the RF transmitter and then be sent to the receiver into the amp.

1.2 Background

There are 4 basic types of pickups used in an acoustic guitar: undersaddle, magnetic, contact, and microphones or blended systems. Many of these systems require modifications to the guitar itself. This is undesirable if someone does not wish drill holes, cut holes, etc. in their guitar (5). There is a product that solves this solution but it costs about 200 dollars (6). This product, however, does not incorporate effects. There are other products out there are simply a pickup. From personal experience these pickups do not work very well due to the quiet output of the amplifier. The amplifier had to be turned up extremely loud before there was noticeable difference in volume.

Our pickup should be as affordable as possible. Ideally the product would be less than 100

dollars. This will make it a economical option for somebody who wishes electrify their acoustic guitar but does not want to spend the money on an integrated system. It will also greatly reduce the cost of adding effects to the sound of the guitar.

1.3 High Level Requirements

1.System must be as affordable as possible. This should be ideally less than 100 dollars.

2.Sound output should be a clear sounding signal with little to no noticeable distortion in the sound.

3. The device should be able to be easily installed and removed from any acoustic guitar sound hole without damaging the guitar.

2 Design

Our device will consist of 4 sections: the power supply, magnetic pickup, signal manipulation, and RF circuits. The power supply will provide the necessary voltages to bias the pre-amplification module and power any IC chips needed for the effects and transmission circuit. The magnetic pickup will sense the signal from the guitar strings and send it to the pre-amplification stage to increase the voltage. The control unit will house the pre-amplification stage, the effects, and the user interface so the user can choose the desired effect. The RF circuits will transmit and receive the information from the pickup. The high level block diagram is depicted in Figure 1.

The physical design of the device must be small enough to fit into the sound hole of an acoustic guitar. The diameter of the sound hole is approximately 4 inches. The strings sit approximately 0.5 inches above the face of the guitar. Since the device will be placed into the sound hole it can have a depth of about 1 inch. This should give us an appropriate volume to fit all necessary components into the casing. The pickup is placed toward the top of the device so the rest of the electrical components can be placed in the bottom. The Thickness of the device is to be approximately 1 inch with the curved section of the top view having a diameter of 4 inches. The cutout for the pickup will need to be a rectangular shape measuring 2.5 inches wide by 0.625 inches. A sketch of the physical design is shown in Figure 2.



Figure 1: High Level Block Diagram of Device

2.1 Power Module

The device is going to be powered with a 9 volt battery. The battery will be followed by a voltage regulator that will regulate the voltage to 8 volts. This is done to ensure that any variations in the battery voltage can be handled. We will be using an LF80C voltage regulator to regulate the voltage to this value. Values of typical 9 volt batteries can range from 8.4-9.6 volts. The schematic for the voltage regulator for both the full device and the FM-Receiver can be found in Figure 3. Figure 11 shows the requirements and verifications of this module.

2.2 Magnetic Pickup

The magnetic pickup is the heart of this device. Its purpose is to sense the vibrations of the guitar and convert them into a voltage signal. The magnets in the coil, Neodymium in our case, magnetize the strings above the pickup. When a string is plucked, the change in the magnetic field induces a voltage in the coil of wire wrapped around the magnets. This voltage is then sent to the pre-amplification module to be increased in magnitude. Figure 12 shows the requirements and verifications of this module.



Figure 2: Sketch of the Physical Design of Enclosure

2.3 Signal Manipulation

The signal manipulation block of the device consists of 4 modules. These modules are preamplification, a low-pass filter, a switch, and an effects module. The pre-amplification module will be used to increase the magnitude of the voltage signal coming from the pickup. This will help to prevent the signal being diminished too greatly when being sent through other lossy modules. The low-pass filter will smooth out the signal from the pickup and pre-amplification modules. This filter will need to pass all frequencies from the guitar and block high frequency noise. The switch is a simple component that will be able to choose between the different effects available. The effects module will consist of a few different effects that can be applied to the signal.

The pre-amplification module will be a 3 stage amplifier consisting of two common-source and a common drain amplifier. This will amplify the voltage signal. The common-source amplifier works very well for high resistance loads. However, when the load resistance is low, the gain from the amplifier drops off significantly. For this reason, the common-drain amplifier is cascaded to keep the load resistance of the common-source amplifier near infinite. The common-drain amplifier's gain does not depend on its load resistance, so the load can have a small resistance value and the gain is preserved. A simulation was ran on this module as well. The input to the module can be seen in Figure 6 and the output is shown in Figure 8. Figure 12 shows the requirements and verifications of this module.

The low-pass filter will be a single order RC filter. The highest frequency of a guitar is 1318.52 Hz, so signals at much higher frequencies than this need to be attenuated. This will filter out the high frequency noise the circuit may have. The schematic of the pre-amplification and RC low-pass filter can be found in Figure 4.

The switch will be a 4-way toggle switch. The options of the switch will be no effect, octave up, octave down, or distortion.

2.4 Effects

The three effects implemented will be distortion, octave up and octave down. The distortion sound effect is produced by clipping the amplitude to make the sound gritty and distorted. This is known as hard clipping.

The octave up effect is produced by taking the input signal and putting it through a full-wave rectifier. The amplitude of the output should remain the same as the input. The audio sound should sound higher but the same note.

The octave down effect is produced by taking the input signal and putting it through a half-wave rectifier. This in turn will halve the frequency.

2.5 RF Circuits

The RF circuits will consist of and FM transmitter and receiver. The transmitter will send the signal to the receiver where it will then be able to be heard through a guitar amplifier. FM is being used because it has a higher quality than AM transmission. Since the signal is an audio signal the highest quality is essential so the end signal is a clear as possible. RF was also chosen because of its speed. Since the device will be used in real time, it is essential that it is fast so that no delay is noticed in the output.

The receiver circuit we chose was a quadrature demodulation circuit. This detects the incoming signal and passes it to an AND gate. Then, the waveform is shifted by 90 degrees and is sent to the other pin of the AND gate. The output signal is then passed through an integration circuit then a low-pass filter. The same low pass filter can be used as the pre-amplification process since the audio signal will not be of any higher frequencies. The schematic for the FM receiver is shown in Figure 5. A simulation of the integrator circuit was performed. The input used was pulse waveform, and it can be seen in Figure 9. The expected output would be a triangle wave, and the output is shown in Figure 10. Figure 14 shows the requirements and verifications of this module.

+9V +9V C1 C1 C1 C1 C2 C2C2

2.6 Schematics

Figure 3: Voltage Regulator



Figure 4: Pre-Amplification Module



Figure 5: FM Receiver



Figure 6: Distortion Schematic



Figure 7: Octave Up Schematic



Figure 8: Octave Down Schematic



Figure 9: Transmitter Schematic



Figure 10: Sketch of physical design of the pickup

2.7 Simulations

Simulations of many of the circuits required for the project have been performed using ltspice. This helped to refine some of the theoretical design choices and fine tune the performance of the modules.



Figure 11: An input of 150 mV was used to test the pre-amplification circuit.



Figure 12: The output of the pre-amplification module.



Figure 13: A pulse wave was used to simulate the integrator circuit.



Figure 14: The output of the simulated integrator circuit.



Figure 15: Distortion Simulation



Figure 16: Octave Up Simulation



Figure 17: Octave Down Simulation

3 Calculations

3.1 Magnetic Pickup

The pickup is essentially a coil of wires wrapped around a group of magnets. The wire used is very thin so it will not be able to tolerate much current. We are striving to have the pickup have a dc coil resistance of at least $4k\Omega$ in order to ensure that the current stays small in the coil. The resistance of the wire per unit length then needs to be calculated. The resistivity of copper, ρ , is $1.7x10^{-8}$ Ω/m . The cross sectional area, A, of 44 AWG magnet wire is .0022 in. This is found in Equation 1. Also using Equation 1 the minimum length of wire needed was found to be approximately 2000 ft.

$$\frac{R}{l} = \frac{\rho}{A} = 2.0461 \frac{\Omega}{ft} \tag{1}$$

3.2 **Pre-Amplification**

It is necessary for the signal coming from the pickup to be pre-amplified before entering the effects or the FM transmitter. This is so the signal is not too greatly affected by losses in these modules. The gain of a common source amplifier depends on the load resistance so a common drain amplifier needs to be cascaded after it. A MOSFET need to be biased in saturation mode in order for amplification to occur. For biasing the gate voltage was selected to be 3.5 V. This is done using a voltage divider to determine the necessary resistances. R_2 was chosen to be 500k Ω . Using Equation $3 R_1$ was found to be 785.7 k Ω . These resistor values need to be large so little current flows through them. The overdrive voltage was then calculated using the threshold voltage and Equation 3 of the 2N7002 transistor which is 2.1 V. The overdrive voltage was found to be 0.4 V. Once this value is known, the only other condition required to meet is that the drain to source voltage needs to remain higher than the overdrive voltage. To meet these requirements V_{DS} was chosen to be 1 V. Now that the FET is biased, the drain current can be calculated. Using Equation 4 this was found to be 64 mA. Then using Ohm's law, R_D was found to be 110 Ω and R_S was 15.625 Ω . Once the resistances are know the gain of the amplifier can be found using Equation 5. This was found to be 5.867. The same configuration was used for the common drain amplifier, and its gain was calculated to be 0.833 using Equation 6. After simulating the circuit, it was seen that R_S of the common drain amplifier needed to be larger to preserve the gain of the entire amplifier. The final parameters are found in Table 1.

$$V_G = V_{cc} \frac{R_2}{R_1 + R_2} \tag{2}$$

$$V_{ov} = V_{GS} - V_{th} \tag{3}$$

$$I_D = \frac{V_{ov}gfs}{2} \tag{4}$$

$$A_{v} = \frac{-g_{fs}(R_{D}||R_{L})}{1 + g_{fs}R_{S}}$$
(5)

$$A_v = \frac{g_{fs} R_S}{1 + g_{fs} R_S} \tag{6}$$

3.3 RC Low-Pass Filter

The low-pass filter will need a cutoff frequency of 1500 Hz. Choosing the resistance to be 10 k Ω allows a suitable capacitor to be calculated using Equation 7. The capacitor was found to be 10.61 pF. The performance of the amplifier for various frequencies was calculated using Equation

Table 1: Pre-amplifier Parameters		
Parameter	Value	
R_1	785.7 $k\Omega$	
R_2	$500 \ k\Omega$	
I_D	64 mA	
V_{ov}	$0.4 \mathrm{V}$	
A_{v1}	5.867	
A_{v2}	0.8333	

8 and the results are displayed in Table 2. If more attenuation in the filter is need, another can be cascaded after the first to improve performance.

$$f_c = \frac{1}{2\pi RC} \tag{7}$$

$$\frac{v_{out}}{v_{in}} = \frac{X_c}{(X_c^2 + R^2)^{.5}}$$
(8)

Table	2:1	Low-Pass	Filte	r P	erformance
		[TT]			, •

Frequency [Hz]	Attenuation
200	0.99
700	0.91
1200	0.78
1500	0.71
2000	0.60
3000	0.45
5000	0.29

3.4 FM Receiver/Transmitter

A quadrature demodulation circuit was chosen as the FM receiver. It will run on the same type of power module as the main device. The basic circuit was found while doing research, and the following formulas were also found here (8). The center frequency of our carrier wave was chosen to be 2.45 GHz as this falls in the ISM frequency range. Using Equations 9 through 12, the RLC components can be calculated and chosen to shift the incoming signal by 90 degrees. Q was chosen to be 5 and L to be 5 μ H. This allowed R to be calculated to be 384.85 k Ω . Then using Equation 9 a relation between C_1 and C_2 was found. C_2 could then be calculated by using Equation 10. Lastly using the relation between them C_1 was calculated. C_1 was found to be 0.11 μ F, and C_2 was found to be 2.21 μ F.

A simple FM transmitter will be used for this circuit. A simple LC Tank circuit will be used as a tuner to adjust the output frequency. The chosen frequency would be 2.45Hz. Given this, we can calculate the LC relationship.

$$f = \frac{1}{2\pi\sqrt{LC}}\tag{9}$$

$$\frac{v_2}{v_1} = \frac{C_2 L s^2}{(C_1 + C_2) L s^2 + \frac{L}{R} s + 1}$$
(10)

$$\omega_n = 2\pi f_c = \frac{1}{(L(C_1 + C_2)^{.5})} \tag{11}$$

$$Q = \frac{R}{\omega_n L} \tag{12}$$

$$a = 2Q \frac{\Delta \omega_n}{\omega_n} \tag{13}$$

3.5 Tolerance Analysis

The pre-amplification module is essential to the device working. If the transistors become biased the wrong way the module will no longer behave how it is expected to. The gain will fail and the output signal will no longer be the signal from the guitar. It is important to figure out how much this can tolerate so the transistors are not thrown out of saturation mode. In order for a transistor to be in saturation the difference between the drain and source voltage must be greater than the overdrive voltage. For this design this value must remaining higher than 0.4 V. From the design of the amplifier it can easily be seen that V_{DS} must not go swing more than 0.6 V.

Another way this module could fail is if the transistors do not turn on. This could occur if the gain is too large and V_{GS} swings below the threshold voltage. If this were to occur the transistor would turn off and no current would flow through the drain and source. Since the gate voltage is set at 3.5 V, and the source voltage is set at 1 V, the voltage swing can easily be calculated using the threshold voltage. The threshold voltage of the transistor used is 2.1 V. This means the Gate must not fall below 3.1 V or else the transistor risks turning off blocking current flow.

4 Cost and Schedule

4.1 Cost

The cost can be found in Table 3.

4.2 Schedule

The schedule can be found in Table 4.

5 Requirements and Verifications

Requirements	Verifications
 Must be able to power the system at full load for 2 hours 	 Power up the system and send a signal through it for 2 hours
 Output must stay at 8 V +/- 5% Must be able to supply handle loads of up to 1 A. 	 Probe the output voltage of the power module and check the deviation from 8 V Set voltage to rated voltage. Attach the circuit to load the power Supply. Probe the current to make sure it does not exceed 1 A.

Figure 18: Requirements and Verifications of Power module - 15 Points

Requirements	Verifications
1. Must be able to output a voltage signal with the same from upper of the pate on	1. Place the pickup under a string
the string being played	Using a tuner measure the frequency of the string to be plucked
Voltage output must be 150 mV or	
greater for frequencies up to 1320 Hz.	Pluck the string and probe the output voltage of the pickup
	Display this voltage on the oscilloscope and measure the frequency of the Signal
	Probe the output voltage of the pickup when a string is plucked
	Measure the amplitude of this voltage to check if <u>150mV</u> or greater

Figure 19: Requirements and Verifications of the pickup - 15 Points

Requirements	Verifications
 Must have an overall gain of 5 or greater 	 Probe the input test voltage of 150mV and display on the oscilloscope
 Output voltage must be in phase with the input voltage 	Probe the output voltage and display the ac coupled signal on the oscilloscope
	Measure the amplitudes of input and output voltage then check the output amplitude is at least 5 times greater than the input voltage
	 Probe the input and output voltage as in step 1
	Measure the phase difference between the two waves

Figure 20: Requirements and Verifications of the Pre-Amplification module - 20 Points

Requirements	Verifications
 Able to sense the incoming/outgoing signal from at least 50 feet away 	 Set the receiver 50 feet away from the transmitter
 Output audio should have the same frequency as signal entering the FM Transmitter 	Send a signal through the transmitter and check that the signal is output from the receiver
 Output signal should attenuate any high frequency noise, greater than 1500 Hz to 25% its endiated emplitude. 	 Probe the signal entering the transmitter and display on the oscilloscope
onginal amplitude	Probe the output signal of the receiver and display on the oscilloscope
	Measure the frequency difference between the two signals
	 Measure the signal in the receiver just it enters the filtering stage and display it on the oscilloscope
	Measure the output signal of the receiver and display it on the oscilloscope
	Measure the spikes in the high frequency noise and make sure the output is 25% the amplitude of the input

Figure 21: Requirements and Verifications of the FM transmitter and receiver - 30 Points (15 points for transmitter, 15 points for receiver)

Distortion

Requirements	Verifications
 <u>Ouput</u> distorted signal should maintain original frequency Signal should "hard clipped" Audio output should sound gritty and distorted 	 Measure the output frequency using an oscilloscope Observing the amplitude of the output signal should show an abrupt flattening which is consistent throughout (not gradual) Play guitar and listen for distortion

Octave Up

Requirements	Verifications
 Output amplitude must be the same amplitude as input signal Output voltage must not drop below 0V 	 Probe the input signal and output of the effect Compare the input voltages and output voltages using an oscilloscope Observe voltage waveform on an oscilloscope

Octave Down

Requirements	Verifications
1. Output amplitude must be the same amplitude as input signal	 Probe the input signal and output of the effect
 Output frequency should be half the input frequency 	voltages using an oscilloscopeProbe the input and output signal and measure the frequency. Compare.

Figure 22: Requirements and Verifications of the Effects - 20 Points (each worth 6.666 points individually)

Part Table 5: Cost	$\operatorname{Price}/\operatorname{Unit}(\$)$	Total(\$)
Various Resistors, Capacitors, Transistors, FETs, Inductors, etc.	15.00	15.00
Precision Op-Amp (OPA221) x3	9.34	28.02
Magcraft Neodymium Rod Magnets $(.125x.5) \times 6$	0.30	2.00
9V Battery x2	1.32	2.64
44 AWG Magnet Wire	3.00	3.00
SPDT Slide Switch x3	0.75	2.25
Total	\$52	.91

Week	Dylan	Wilson
2/6	Design pickup and pre-amp stage	Design Effects
2/13	Finalize pre-amp work design LPF	Design FM Transmitter
2/20	First Draft schematics	First draft schematics
2/27	Build Pickup and Preamp	Build Effects
3/6	Debug pickup and Preamp	Debug Effects
3/13	Build RF	Build RF
3/20	PCB Design initial	Debug RF
3/27	PCB Revision	Physical Design Revision
4/3	Debug protoype	Debug Prototype
4/10	Build Final Product	Build Final Product
4/17	Test	Test
4/30	Prepare Final Presentation	Begin Final Report

6 Ethics and Safety

There are a few potential safety hazards that can occur in use with our project. If the pickup shorts there is a possibility of burning the circuits and with the battery in the pickup it may explode. Using a PCB in an enclosure will prevent the chances of a short happening. The 9-Volt battery could also become a hazard since the two positive and negative points are on the same side which means if they become shorted it could spark and cause a fire within the circuit and burn the guitar (and your hand). Using a 9 volt battery connector will prevent a short from happening. We will provide a casing for this battery to also prevent any chance of something piercing the battery. Using an abs enclosure which has a glass transition temperature of 221 degrees F. All safety concerns must be disclosed to the end user. We will address these safety concerns in accordance with 1 of the IEEE code of ethics which states "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" (7).

There is also the risk of our product to emit radio waves that are not under ISM. ISM stands for industrial, scientific and medical radio band. These frequencies are allocated for testing products while nearby frequencies are reserved for other specific uses. Using those reserved frequencies are considered illegal without proper licenses.

The dangers associated with the device should be relatively small. All necessary measures will be taken to ensure that injury will not occur when somebody is using the product. This aligns with 9 of the IEEE code of ethics which says "to avoid injuring others, their property,..." (7). The location of the pickup puts it in close proximity with the person who is playing the guitar, so extra precautions will be taken to ensure the safety of the user.

Designing a magnetic pickup from the ground up could prove difficult. The differences in signals it will output could vary greatly from those of a professionally designed pickup. It is important that data is not faked no matter what the output may look like. This follows 3 and 7 of the IEEE code of ethics (7). All data taken will be the real data no matter how noisy or bad it may be, if this problem occurs.

References

(1) Guy, 'A Brief History of the Guitar'. [Online]. Available:

http://www.guyguitars.com/eng/handbook/BriefHistory.html. [Accessed: 7-Feb-2017].

 $\left(2\right)$ Lemelson Center, "Invention," in Lemelson Center for the Study of Invention and

Innovation, 2014. [Online]. Available:

http://invention.si.edu/invention-electric-guitar/p/35-invention. Accessed: Feb. 07, 2017.

(3) Fender, "Dreadnought — Fender Acoustic Guitars.," in Fender. [Online]. Available:

http://shop.fender.com/en-US/acoustic-guitars/dreadnought. Accessed: Feb. 07, 2017.

(4) Guitar Center, "Multi Effects Pedals," in Guitar Center. [Online]. Available:

http://www.guitarcenter.com/Multi-Effects-Pedals.gc. Accessed: Feb. 07, 2017.

(5) Raitt, Donovan. "Choosing the Right Pickup For Your Acoustic Guitar." 03 Oct. 2014.

[Online]. Available: https://reverb.com/news/choosing-the-right-pickup-for-your-acoustic-gui

tar. [Accessed: 07-Feb-2017].

(6) GearTree.com, "Shadow SH-PMG-WA Panamag Wireless Acoustic Guitar System." GearTree.com
 —Instruments, Effects, Pro Audio Equipment!.[Online]. Available:

https://www.geartree.com/p/shadow-sh-pmg-wa-panamag-wireless-acoustic-guitar-system.

[Acessed: 25-Jan-2017].

(7) ieee.org. "IEEE IEEE Code of Ethics". 2016. [Online]. Available: http://www.ieee.org/about/corporate/go8.html. [Accessed: 8-Feb-2017]

(8) eetimes.com. "A Quadrature Demodulator Tutorial — EE Times". 6/4/2001. [Online].

Available: http://www.eetimes.com/document.asp?docid=1275839. [Accessed: 22-Feb-2017]