How to make a Humbucker Pickup

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Abstract

The primary goal of this experiment is to learn how to wind a humbucking pickup that would sound like a Gibson P.A.F. humbucker and to analyze its real and imaginary electromagnetic characteristics. After winding and assembling two humbucking pickups from a kit, I have learned the unerlying difficulty in replicating not only the sound of an authentic P.A.F. pickup but also the immense complexity of the physics involved in pickups in general. That being said, the experiment was a success in that both completed humbuckers were functional and had a desirable sound, albeit not the same sound as the originally planned P.A.F.'s. There seems to be an equal amount of science and art in the creation of a good sounding pickup, and replication of any one pickup (sound and physics wise) is very difficult due to the human factor involved during the winding and assembly stages (i.e. nobody's perfect!).

1 Theory of a Humbucker

The primary goal of a humbucker pickup is to cancel out the hum that comes from alternating current while still producing a desirable sound from an electric guitar. The hum from alternating current is produced by equipment a guitar is plugged into (amplifiers, effects pedals, etc). This hum cancelling effect, or buck, is produced through the connection of two oppositely wound single coils in series. The magnetic field of the humbucker feels the vibration of the guitar strings, which produces an EMF in the pickup and leads to the production of sound. Seeing as the primary topic of this paper is the physical characteristics of the humbucker itself, I will skip the really gory stuff and point the reader to Professor Errede's talk on how pickups work should they desire a better explanation. [2]
As shown in Figure 1, a humbucker consists of two coils, or inductors, connected in series. The coils consist of 42 gauge enameled wire (.0025") wound around a bobbin. Since the wire and inductors are not perfect, each inductor has an internal capacitance and resistance associated with it. We can calculate the complex impedance, voltage, current, and power as functions of frequency using the inductance, capacitance, and the related resistances by driving a current through the pickup.
The method we take for resonance measurement is to measure the complex voltage $\tilde{V}$ and complex current $\tilde{I}$ induced in the pickup and locate the resonance maximum peak.
It is important to note that our equipment measures RMS voltage and current, which are

$$\tilde{V}_{rms} = \frac{1}{\sqrt{2}}\tilde{V} \tag{1}$$

$$\tilde{I}_{rms} = \frac{1}{\sqrt{2}}\tilde{I} \tag{2}$$

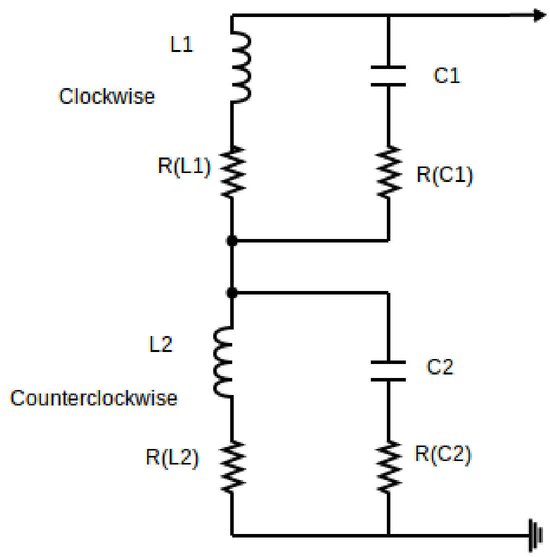

Figure 1: The simple RLC circuit diagram of a humbucker pickup. This isn't a perfect model, but it is very good for our purposes.

We can then use these measured quantities to calculate the RMS complex power $\tilde{\mathrm{P}}$ and complex impedance $\tilde{\mathrm{Z}}$ as functions of frequency through the following formulas.

$$\tilde{P}_{rms}(\omega) = \frac{1}{2}\tilde{V}_{rms}(\omega) \cdot \tilde{I}^{\star}_{rms}(\omega) \tag{3}$$

$$\tilde{Z}(\omega) = \frac{\tilde{V}_{rms}(\omega)}{\tilde{I}_{rms}(\omega)} = \frac{\tilde{V}_{rms}(\omega)\tilde{I}^{\star}_{rms}(\omega)}{|\tilde{I}_{rms}(\omega)|^2} = \frac{\tilde{P}_{rms}}{|\tilde{I}_{rms}(\omega)|^2} \tag{4}$$

This leads directly to the relation

$$\tilde{P}_{rms}(\omega) = |\tilde{I}_{rms}(\omega)|^2\tilde{Z}(\omega) \tag{5}$$

Since these quantities are complex, there must be a phase angle. The phase angle can be introduced through

$$\tilde{P}_{rms}(\omega) = |\tilde{P}_{rms}(\omega)|e^{i\Phi_p(\omega)} = |\tilde{P}_{rms}(\omega)|e^{i(\Phi_V(\omega)-\Phi_I(\omega))} \tag{6}$$

and

$$\tilde{Z}(\omega) = |\tilde{Z}(\omega)|e^{i\Phi_z(\omega)} = |\tilde{Z}(\omega)|e^{i(\Phi_V(\omega)-\Phi_I(\omega))} \tag{7}$$

Thus, we can now see that

$$\Phi_P(\omega) = \Phi_Z(\omega) \tag{8}$$

2 Humbucker Assembly

The assembly of the humbucker is the most intricate part of this project. The parts used in these pickup assemblies are as follows:

Part	Quantity
Nickel Silver Baseplate	1
Unwound Plastic Bobbin (Slug)	1
Unwound Plastic Bobbin (Adjustable)	1
Slug Pole Pieces	6
Adjustable Pole Pieces	6
Mounting Screws	4
Braided Pushback Wire (1 ft.)	1
Bar Magnet (Alnico 2 or 5)	1
Metal Pole Piece Spacer	1
Plastic Shim	1
#42 Enamel Coated Wire Spool	1
Bobbin Tape Roll	1
Outer Pickup Tape Roll	1
Paraffin Wax	1

The first step is to wind the bobbins. It is important to make sure to wind the bobbins in opposite directions. The setup used for winding pickups is shown below in Figure 2. The bobbins are attached

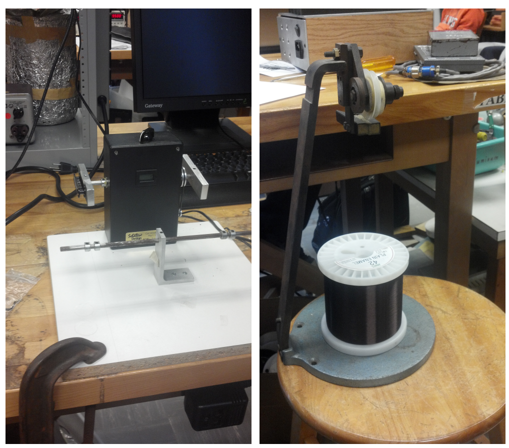

Figure 2: Winding machine and wire spool used to wind pickup bobbins. Bobbins are attached to the two metal bars on the black box, which rotate around at an adjustable speed controlled by a knob on the top.

on opposite sides of the winding machine from eachother to ensure opposite winding sense and are wound to approximately 5,000 winds of wire around each. It is important that both bobbins have the same number of winds and are wound with reasonable tension (I used the friction of my finger coupled with leverage) to get maximal humbucking. Next, the magnetic pole pieces should be inserted into their respective bobbins. After the bobbins are fully assembled and taped, they are mounted on the mounting plate and the start of the adjustable pole bobbin (APB) is connected to the end of the slug pole bobbin (SPB) so that they are connected in series. The remaining winding ends from the bobbins are then connected. The end of the wind on the APB goes to the ground (outer layer of pushback cable) and the start of the SPB goes to the lead (inner layer of pushback cable). Once the bobbins are connected, the Alnico magnet is placed between the bobbins and the mounting plate, carefully keeping track of magnetic pole orientation. The spacers are then placed to ensure magnetic coupling of the Alnico magnet with the pole pieces and to help organize the wiring. It is important to connect the outer layer of the pushback cable to the baseplate in order to establish a good ground connection for the pickup.

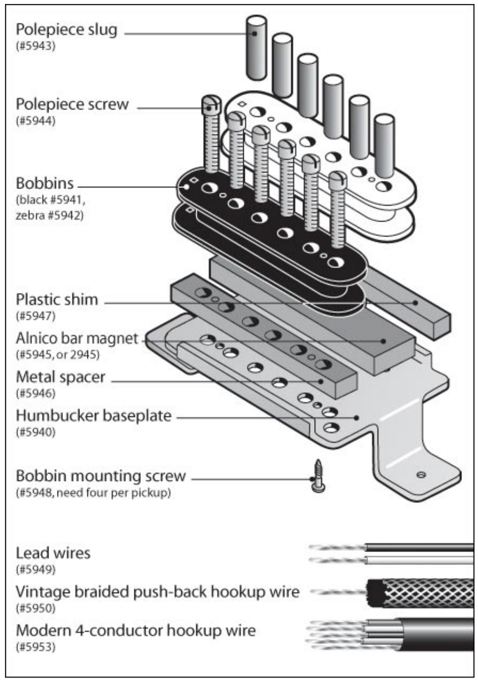

Figure 3: Diagram showing basic pickup assembly and what is included in the pickup kit used in this experiment.[1]

The pickup is now ready to be potted. The pickup must be dipped in melted paraffin wax and the air bubbles must be allowed to fully diffuse from the pickup in order for the potting to take full effect. This process takes approximately 20 minutes per pickup, and great care should be taken around the melted wax as it is very hot! If the pickup is not potted, the pickup could go microphonic when the guitar is being played. Unless you really enjoy feedback, pot your pickups!

3 Measurements and Final Results

The equipment used to measure the physical characteristics of these pickups is as follows:

- Digital Multimeter - Quickly measures the DC resistance of the pickups and ensures that there is an actual functioning circuit.
- Hall Probe - Measures magnetic field strength at pole pieces on completed pickup.
- HP 4262A LCR Meter - Measures the inductance and dissipation of the pickup at various frequencies.
- HP 3563A Dynamic Signal Analyzer with DAQ Software - Measures and calculates the impedance, voltage, and current of the pickup as a function of frequency.

Below is a table showing all relevant quantities for both pickups, most of which are measured using the HP 3563A Dynamic Signal Analyzer with DAQ software.

	Humbucker 1 (Zebra)	Humbucker 2 (Black)
Clockwise Coil Winds	5051	5025
Counterclockwise Coil Winds	5022	5025
Unpotted f_{res}	10.055 kHz	7.895 kHz
Potted f_{res}	6.895 kHz	7.315 kHz
Unpotted Q_{res}	2.793	1.733
Potted Q_{res}	.9426	1.713
Unpotted Z_{res}	339.141 kΩ	276.252 kΩ
Potted Z_{res}	119.938 kΩ	265.117 kΩ
Unpotted V_{res}	194.3 mV_{rms}	161.5 mV_{rms}
Potted V_{res}	75.2 mV_{rms}	155.5 mV_{rms}
R_{DC}	7.45 kΩ	7.61 kΩ

Note the small changes before and after potting for almost all of the quantities for Humbucker 2 and the large changes for Humbucker 1. Humbucker 2 behaves much more like a professionally made pickup than Humbucker 1 does, and that is because there is some unidentifiable major flaw in the construction of Humbucker 1. The current theory behind the major misbehaviors of Humbucker 1 is that the magnetic coupling of the humbucker is somehow behaving incorrectly and causing these very strange measurements to occur. That being said, Humbucker 1 still sounds great in the guitar by a matter of dumb luck, so I will not modify it any further.

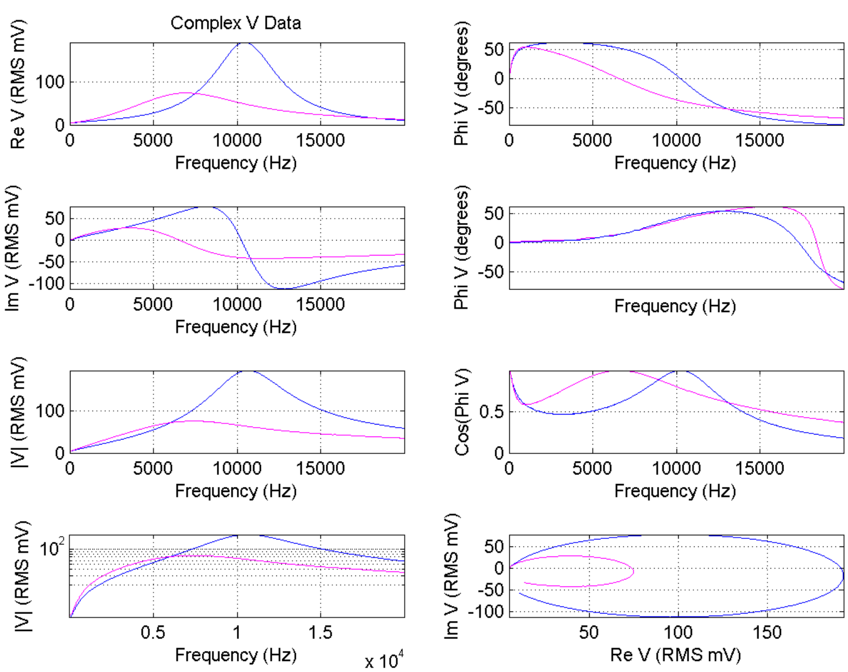

Figure 4: Comparison plots of Humbucker 1 (Zebra) voltage before and after potting.

As shown in Figures 4-7, Humbucker 1 has major differences between its unpotted (blue) and potted (purple) quantities, while Humbucker 2 doesn't really seem to change too much. Humbucker 2 maintains the same curve shapes throughout all measurements, while Humbucker 1 has a very notable drop in resonance magnitude and a greatly wider peak width after it is potted. As stated previously, a

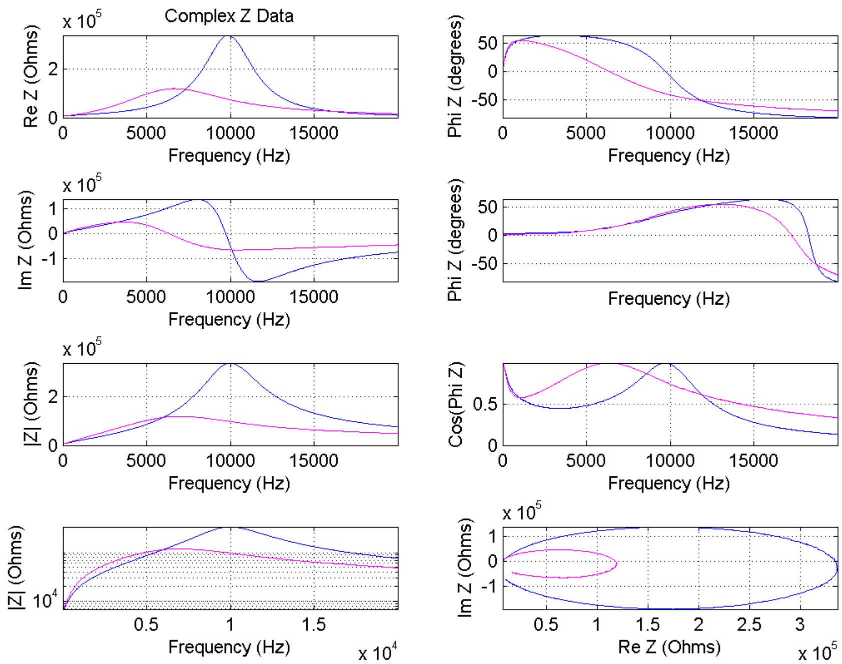

Figure 5: Comparison plots of Humbucker 1 (Zebra) impedance before and after potting.

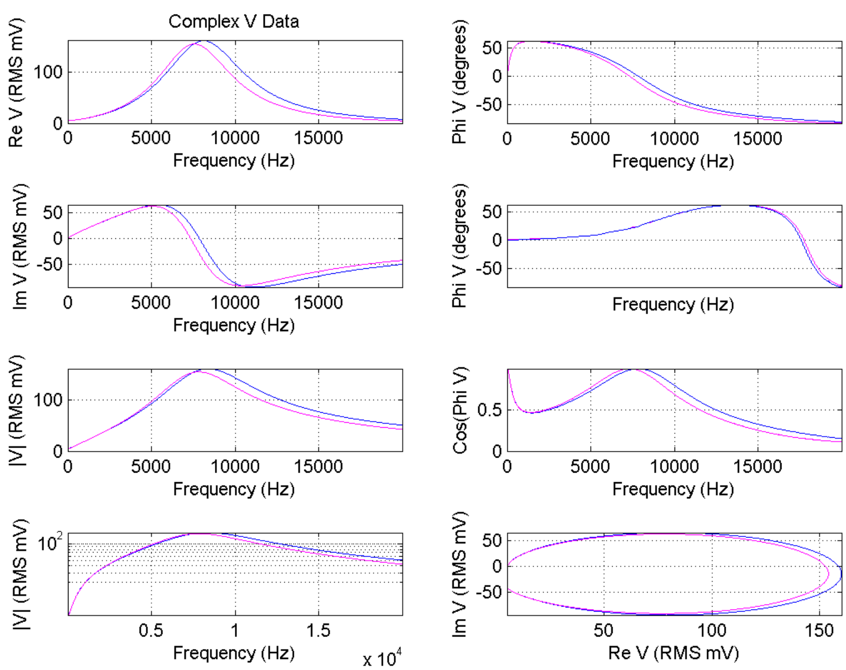

Figure 6: Comparison plots of Humbucker 2 (Black) voltage before and after potting.

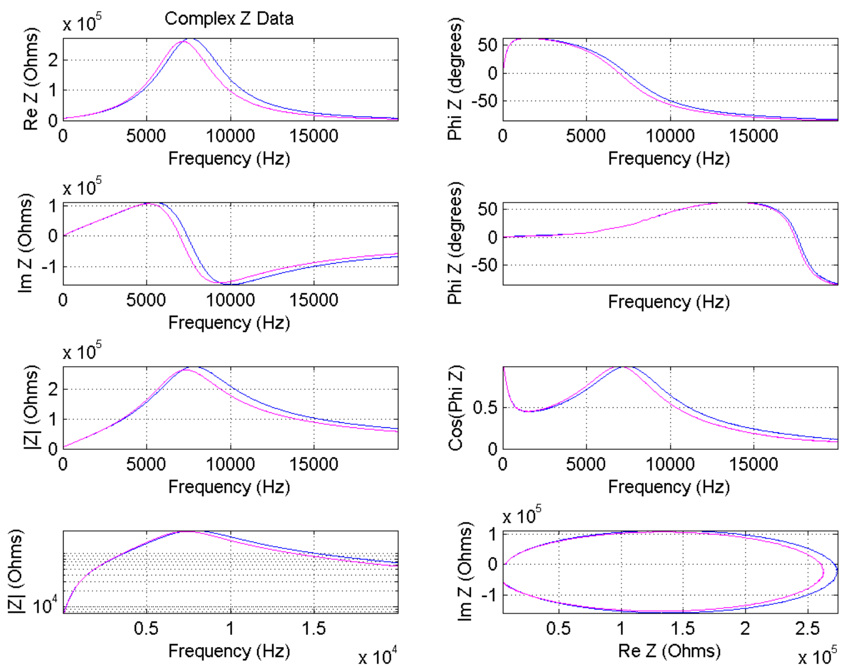

Figure 7: Comparison plots of Humbucker 2(Black) impedance before and after potting.

classic humbucker should exhibit the same behavior as Humbucker 2, but for some reason Humbucker 1 doesn't seem to fit that mold. Further analysis on Humbucker 1 may be undergone in the future.

4 Connecting the Physics with the Sound

The biggest difficulty of fully understanding humbucker pickups is being able to connect the physics of the pickup with the sound it can produce once in the guitar. A very important physical quality of the pickup is the resonant frequency, as that will dictate the signal strength output by the pickup at various scale ranges on the guitar. As stated previously, this is strongly affected by the capacitance and inductance of the two bobbins in the pickup. The final resonant frequencies of the pickups produced for this experiment are 6.895 kHz for Humbucker 1 and 7.315 kHz for Humbucker 2. These resonant frequencies, along with the resonant widths of the voltage output, tell us where both of these pickups would be best placed on the guitar. Since Humbucker 1 has a very wide resonance peak and a lower resonant frequency, we decided to use it as the bridge pickup because the bridge pickup traditionally puts out mid to lower frequencies. This means that we placed Humbucker 2 in the neck position. Both humbuckers sound great in their designated positions and do their job of hum cancelling very well.
Another important quality that affects the sound of the pickup is how many winds of wire the bobbins have wrapped around them and how thick the wire being wound is. The more winds the bobbins have, the higher the output of the pickup will become. A high wind count also contributes to producing a "bassier" sound from the pickup. Likewise, if a pickup has fewer winds, the output will be much lower and the pickup will produce a more "trebly" sound. The pickups in wound for this experiment have approximately 5,000 winds per bobbin and use a thinner gauge wire, to the output is relatively low and the pickups do indeed favor a treble sound.
Though I wound both pickups with the initial plan of having them in phase when hooked into the

guitar, I made an error in connecting the leads in one of my pickups. The pickups are now connected in the guitar out-of-phase, and though it is not what I initially planned to do, I am pleased with the sound it produces. The out-of-phase pickup combination is not often found in Les Pauls, so it makes my guitar all the more unique and that much more fun to play!
There is an extreme measure of art to winding a pickup and a high learning curve as well. Innevitably one will wind better and better pickups as they gain experience from winding and assembling multiple pickups. Regretably I was only able to wind two, but I am very pleased with the results nonetheless.

5 Conclusions

Though the pickups do not sound like original Gibson P.A.F.'s, the experiment was still a success. The pickups have a clear sound and do their job very well. They cancel the alternating current hum and successfully produce a good tone out of the guitar that they were installed in. We were successfully able to take measurements of both pickups and learn their electromagnetic properties, and we saw some very strange behavior from Humbucker 1. The major difficulty in this experiment lies in the ability to reproduce exactly the same pickups because of the large amount of dependence winding a pickup has on the person doing the winding. The tension of the winds on the bobbins and even the winding pattern will affect the electromagnetic qualities of the pickup as well as the sound. That being said, music is about self expression and finding one's own "sound", the difficulty in producing identical pickups could arguably be considered a virtue of the process.

6 Acknowledgements

I would like to thank Thomas Satrom and Darby Hewitt for their assistance in the assembly of these humbucker pickups. Most importantly, I would like to thank Professor Steve Errede for providing not only multiple (some expensive) components for the assembly of the pickups, but also his vast knowledge base on pickups in general. This project has served as a huge learning experience on how humbucker pickups work and how deeply intricate the underlying physics of the guitar pickup really is (there's still so much to learn!). Hopefully I have been able to contribute some semblance of knowledge to the ongoing quest to fully understand humbucker pickups.

References

[1] Stewart-MacDonald Guitar Supplies: `http://www.stewmac.com/`

[2] Professor Steve Errede, "Electronic Transducers for Musical Instruments" `http://online.physics.uiuc.edu/courses/phys406/Lecture_Notes/Guitar_Pickup_Talk/Electronic_Transducers_for_Musical_Instruments.pdf`

[3] Professor Steve Errede, Various one on one discussion about pickups.