# Investigation of the Electromagnetic Properties of Electric Guitar Pickups

Dan Carson
University of Illinois at Urbana-Champaign
Physics Senior Thesis Fall 2009

## Abstract

The goal of the project described in this thesis is to gain a deeper understanding of the detailed physics operative in electric guitar pickups in order to be able to build pickups with a more versatile set of tonal qualities. Using phase sensitive lock-in amplifier techniques, the complex impedance of several different guitar pickups was measured over the frequency range of human hearing. The impedance data was fit to a lumped 4-parameter circuit model of the electric guitar pickup. Extracting the frequency dependant parameters of this model (i.e., inductance, capacitance, and AC resistances) from the fit provided valuable insight into the electromagnetic properties of pickups. The methods outlined in this thesis have been successful in analyzing the circuit properties of a wide variety of different pickups, and should be instrumental in carrying out deeper investigations of the physics of pickups in the future.

## Introduction/Motivation

Electric guitar pickups are crucial pieces of hardware, because they convert the vibrations of guitar strings into an electrical signal which is sent to an amplifier. The electromagnetic properties of pickups have a profound impact on the tonal qualities of an electric guitar. A deeper understanding the physics of electric guitar pickups is essential in order to obtain a better understanding of how to construct pickups with desirable tonal qualities.

A model of an electric guitar pickup that agrees with the totality of the pickup data is extremely important, giving us valuable insight into the details of the various electromagnetic phenomena that occur in pickups. An electric guitar pickup is essentially a very thin wire wrapped in thousands of loops (turns) around six magnetic poles, one for each string (Figure 1). However, it is difficult to analyze a pickup because the non-negligible capacitive effect of neighboring turns of wire, the effect of the presence of a magnetic field, and several other complicated second-order effects. A circuit model of the electric guitar pickup that attempts to lump all of these effects into just 4 parameters (Figure 2) has been developed. [Withee]. This 4-parameter RL-RC model agrees well with the data collected for a wide variety of guitar pickups. A Matlab-based least-squares fitting program was developed in order to obtain the frequency dependence of these 4 parameters for any pickup for which complex impedance data was taken.

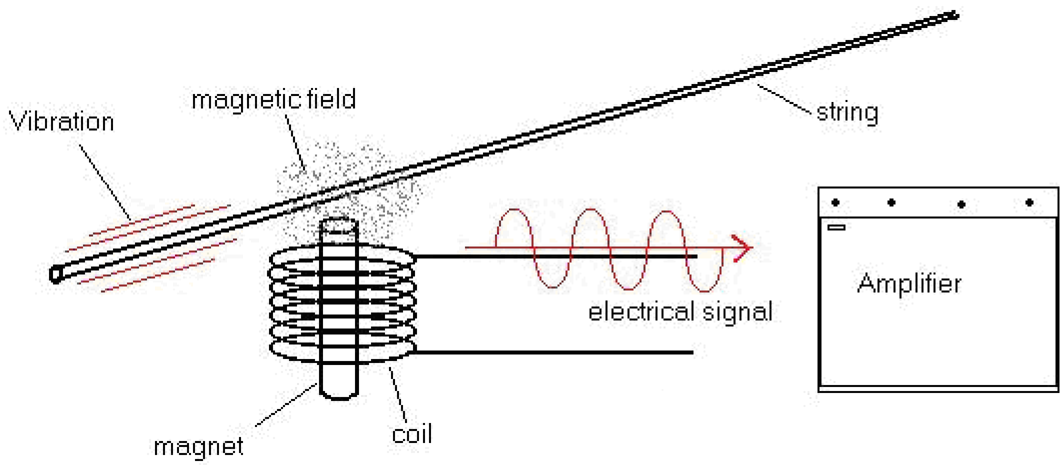


**Figure 1**. The vibrating metal string couples to the magnetic field and creates an emf (electro-motive force) in the pickup coil. Image courtesy of guitar-4u.com.

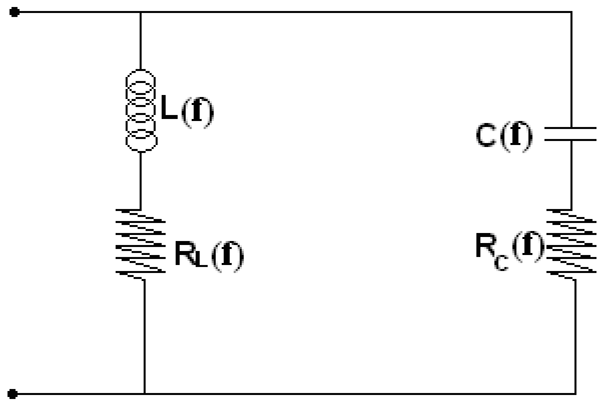


**Figure 2.** The lumped parameter model of an electric guitar pickup, consisting of a resistor and inductor in parallel with a resistor and capacitor.

A direct relation exists between the differential equation that describes the response of the guitar pickup circuit to an applied AC current (in terms of the 4 parameters in the model) and the differential equation that describes the motion of the domain walls in the magnetic materials in the guitar pickup [Craik]. Properly understanding the frequency dependence of the 4 lumped parameters in the guitar pickup model allows us to understand the frequency dependence of the magnetic properties of the pickup. Thus, the somewhat crude 4-parameter model described in this thesis will offer valuable insight into the magnetic dissipation and absorption processes within electric guitar pickups.

An improved understanding of the electronic properties of electric guitar pickups should enable us to design and build electric guitars with a wider, more versatile set of tonal qualities. In the rest of this thesis, I describe the procedures used to obtain complex impedance data for electric guitar pickups, the methods used to analyze the data and fit the data to our 4-parameter model, and the conclusions we were able to make based on our analysis of the data.

## Experimental Procedure

A personal computer (PC) based data acquisition system (DAQ) was used to gather complex impedance data for electric guitar pickups over the $5 < f < 20005$ Hz frequency range. The PC controls an Agilent function generator, setting the sine wave amplitude to 1.0 volt at a given frequency $f$ and increasing the frequency in 10 Hz steps. The low impedance 50 Ω output of the function generator (a nearly constant/ideal voltage source) is converted to a high impedance, nearly constant current source (to emulate the excitation of the pickup due to a vibrating guitar string) using a 1.5 MΩ resistor. The pickup DAQ setup is shown in Figure 3.

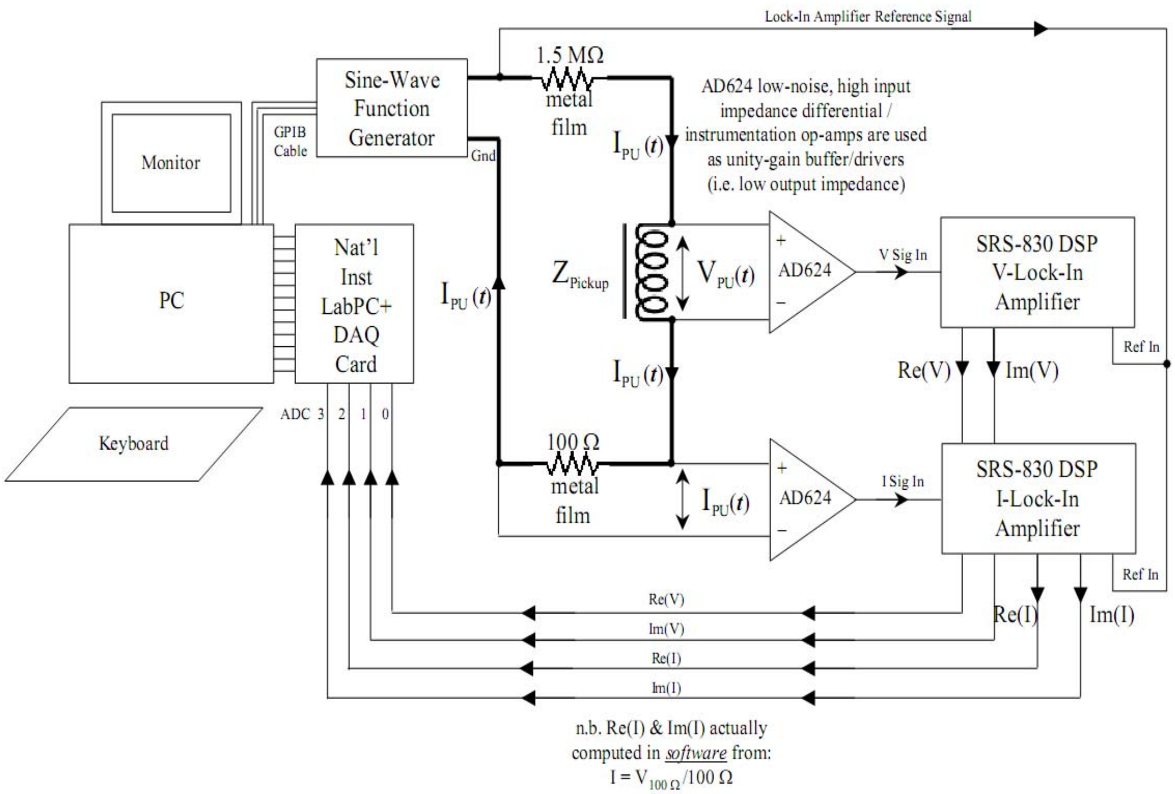


**Figure 3.** Pickup DAQ setup used to gather complex impedance data for electric guitar pickups. Image courtesy of S. Errede. [errede pic]

At each frequency, the complex voltage amplitude $\tilde{V}(f)$ was measured across the pickup and the complex current amplitude $\tilde{I}(f) \equiv \tilde{V}_{100\Omega}(f)/100\Omega$ was measured across a 100 Ω metal film resistor in series with the electric guitar pickup. Low noise, unity-gain FET-input AD624 instrumentation op-amps were used to buffer the complex voltage and current signals. The low output impedance of the AD624 instrumentation op-amps minimized frequency-dependent, capacitive AC signal loss effects in transporting these signals on coax cables from the electric guitar pickup to the (10 M Ω input impedance) of the SRS-830 lock-in amplifier inputs. At each frequency of the sine-wave function generator, measurements of the complex voltage and current were made using two SRS-830 lock-in amplifiers and 12-bit analog-to-digital converters (ADC). The PC recorded the data associated with the real and imaginary components of the voltage and current, allowing the complex impedance and complex power to be calculated over the entire range of frequencies for which these measurements were made.

The 4-parameter model of an electric guitar pickup allows for frequency dependant resistance in both the inductive and capacitive branch. The impedance of the inductive branch is described by $\tilde{Z}_L(\omega) = R_L(\omega) + i\chi_L(\omega)$ where the angular frequency $\omega = 2\pi f$ and the impedance of the capacitive branch is described by $\tilde{Z}_C(\omega) = R_C(\omega) - i\chi_C(\omega)$, with the reactances given by $\chi_C(\omega) = 1/\omega C(\omega)$ and $\chi_L(\omega) = \omega L(\omega)$. This is a lumped parameter model; that is for each branch, anything that manifests as a dissipative impedance is lumped together with R and anything that manifests as a reactive impedance is lumped into χ. Included in $R_L$ is the DC ($f = 0$) resistance of the pickup (which is constant, not a parameter), i.e., $R_L(\omega) = R_{DC} + \Delta R_L(\omega)$. Since the inductive and capacitive branches are in parallel, the total complex impedance of the pickup is $\tilde{Z}_{PU} = (1/\tilde{Z}_L + 1/\tilde{Z}_C)^{-1} = R_{PU} + i\chi_{PU}$. The total resistance and total reactance of the pickup are given in terms of the model's 4 parameters ($L$, $C$, $R_L$, and $R_C$):

$$R_{PU} = \frac{(R_C{}^2 + \chi_C{}^2)R_L + (R_L{}^2 + \chi_L{}^2)R_C}{(R_L + R_C)^2 + (\chi_L - \chi_C)^2} \text{ and } \chi_{PU} = \frac{(R_C{}^2 + \chi_C{}^2)\chi_L - (R_L{}^2 + \chi_L{}^2)\chi_C}{(R_L + R_C)^2 + (\chi_L - \chi_C)^2}.$$

This result is derived by applying the complex form of Ohm's law $\tilde{V}(\omega) = \tilde{I}(\omega)\tilde{Z}(\omega)$ and Kirchoff's voltage law $\sum_{loop} V = 0$ to the 4-parameter model of an electric guitar pickup. [Withee].

The Matlab least squares fitting program that we developed uses16 constraint equations for the complex voltage, current, impedance and power, including their real and imaginary components, their magnitude and phase. The least squares fitting program works by finding the values of the 4 parameters ($L$, $C$, $R_L$, and $R_C$) which minimize the sum of the squares of the difference between the measured and calculated values of these 16 quantities (Table 1) at each of the 2000 data points. The constraint equations are obtained from the complex form of Ohm's Law, $\tilde{V} = \tilde{I}\tilde{Z}$ and the complex power expressions $\tilde{P} = \tilde{V}\tilde{I}^*$, $\tilde{P} = |\tilde{I}|^2 \tilde{Z}$ and $\tilde{P} = |\tilde{V}|^2 / \tilde{Z}^*$.

Strictly speaking, only 4 independent constraint equations are necessary to extract the values of the 4 unknown quantities in a least squares fit. In addition, since the only *directly* measured quantities are $V_{real}$, $V_{imaginary}$, $I_{real}$, and $I_{imaginary}$ (all other measured quantities are expressed in terms of these), 12 of the constraint equations are redundant. However, using this redundant information in the constraint equations serves to suppress the adverse effects that noise in the complex voltage and current data has on the least squares fitting. Due to the inherently non-linear nature of the constraint equations used in the least-squares fit, using only 4 equations, the program is prone to converging to false minima when there is too much noise in the complex current and complex voltage data, and thus outputting bad/spurious values for the fit parameters. There are many sources of electromagnetic noise in our laboratory. Magnetic field noise from outside traffic (i.e., cars and busses driving close to the lab) manifests itself primarily as ~ 1/f noise in the complex current data. 50 Hz and 60 Hz AC power noise (and higher harmonics) from electrical equipment have a small, but noticeable effect on the complex voltage data. Even the earth's Schumann resonances are a source of noise! [errede, schum res]. The effect of voltage and current noise were suppressed using waveform-acquisition of 10K ADC samples/frequency point and signal-averaging techniques. Using redundant constraints in the form of products $X \bullet Y$ and ratios $X/Y$ minimizes the impact of noise in the raw voltage/current data, because the effect of noise on the different constraints has a cancelling effect when summed over all 16 equations. (This became apparent after observing dramatic improvements in the least square fitting program after adding progressively more redundant constraint equations).

**Table 1.** Calculated and measured quantities used in the least squares fitting.

| Quantity | Calculated Value | Measured Value |
|---|---|---|
| $V_{real}$ | $I_{re,meas}R_{PU} - I_{im,meas}\chi_{PU}$ | directly measured |
| $V_{imaginary}$ | $I_{re,meas}\chi_{PU} + I_{im,meas}R_{PU}$ | directly measured |
| $V_{magnitude}$ | $\sqrt{V_{re,calc}{}^2 + V_{im,calc}{}^2}$ | $\sqrt{V_{re,meas}{}^2 + V_{im,meas}{}^2}$ |
| $V_{phase}$ | $V_{im,calc} / V_{re,calc}$ | $V_{im,meas} / V_{re,meas}$ |
| $I_{real}$ | $(V_{re,meas}R_{PU} + V_{im,meas}\chi_{PU}) / (Z_{mag,calc}{}^2)$ | directly measured |
| $I_{imaginary}$ | $(V_{im,meas}R_{PU} - V_{re,meas}\chi_{PU}) / (Z_{mag,calc}{}^2)$ | directly measured |
| $I_{magnitude}$ | $\sqrt{I_{re,calc}{}^2 + I_{re,calc}{}^2}$ | $\sqrt{I_{re,meas}{}^2 + I_{im,meas}{}^2}$ |
| $I_{phase}$ | $I_{im,calc} / I_{re,calc}$ | $I_{im,meas} / I_{re,meas}$ |
| $Z_{real}$ | directly calculated, $R_{pu}$ | $(V_{re,meas}I_{re,meas} + V_{im,meas}I_{im,meas}) / (I_{mag,meas}{}^2)$ |
| $Z_{imaginary}$ | directly calculated, $\chi_{pu}$ | $(V_{im,meas}I_{re,meas} - V_{re,meas}I_{im,meas}) / (I_{mag,meas}{}^2)$ |
| $Z_{magnitude}$ | $\sqrt{R_{PU}{}^2 + \chi_{PU}{}^2}$ | $\sqrt{Z_{re,meas}{}^2 + Z_{im,meas}{}^2}$ |
| $Z_{phase}$ | $\chi_{PU} / R_{PU}$ | $Z_{im,meas} / Z_{re,meas}$ |
| $P_{real}$ | $(\mathrm{I}_{mag,calc}{}^2) * (R_{PU})$ | $V_{re,meas}I_{re,meas} + V_{im,meas}I_{im,meas}$ |
| $P_{imaginary}$ | $(\mathrm{I}_{mag,calc}{}^2) * (\chi_{PU})$ | $V_{im,meas}I_{re,meas} - V_{re,meas}I_{im,meas}$ |
| $P_{magnitude}$ | $\sqrt{P_{re,calc}{}^2 + P_{im,calc}{}^2}$ | $\sqrt{P_{re,meas}{}^2 + P_{im,meas}{}^2}$ |
| $P_{phase}$ | $P_{im,calc} / P_{re,calc}$ | $P_{im,meas} / P_{re,meas}$ |

## Experimental Results

The impedance curves for different pickups, while varying in their peak/resonance locations and resonance widths and heights, all shared several common features (shown in Figure 4) which indicate that the current 4-parameter model of the electric guitar pickup is correct. First, all pickups clearly have the general shape of a resonance curve, indicating that there really is both a capacitance and inductance in each of the pickups. At 0 Hz, all pickups were found to have non-zero impedance, corresponding to the non-zero DC resistance of each pickup. The DC resistance of the pickups was not treated as a free parameter in the pickup model, but rather as a constant (which was measured using a digital ohmmeter) and then written into the least squares fitting code for each pickup. The 5 Hz lock-in measurements of the DC resistance agreed well with measurements of the DC resistance taken with a digital ohmmeter. The small discrepancies in these measurements were most likely due to small ambient temperature variations which affect the resistivity of the copper wire used in the pickups. Another feature that all pickup impedance curves shared was that they leveled off to an ~ constant non-zero value at high frequencies, but never approached zero. This is the origin of the $R_C$ term in the 4-parameter pickup model. Since the voltage due to a pure capacitance goes to zero at high frequencies (i.e., $\chi_c(\omega) = 1/\omega C \to 0$ as $\omega \to \infty$), and since the parallel capacitive and inductive branches must have equal voltages, there <u>must</u> be some dissipation in the capacitive branch giving rise to this voltage at high frequencies, namely $R_C$. All of these common features of the impedance curves further support the current 4-parameter model of the electric guitar pickup.

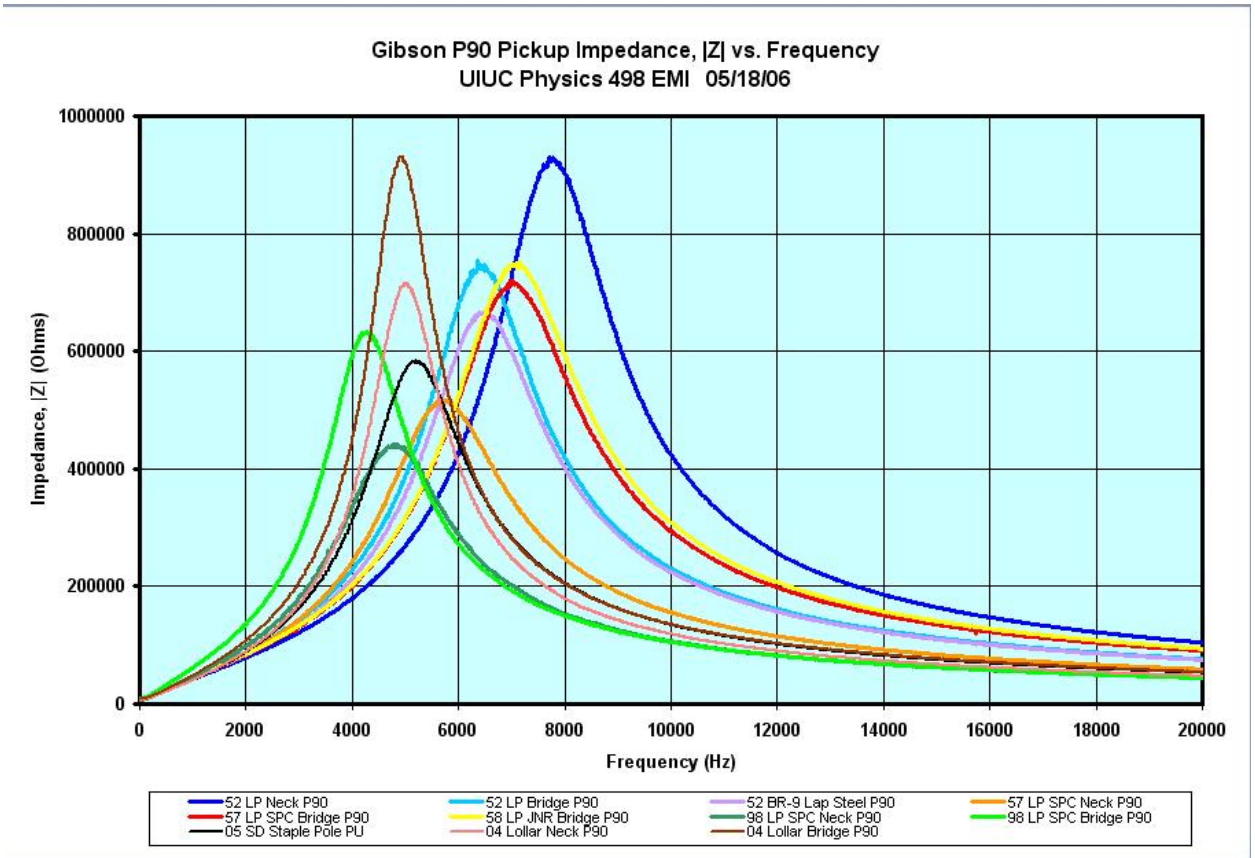


**Figure 4.** Overlay of magnitude of complex impedance $|Z(f)|$ vs. frequency for various types of P-90 guitar pickups, illustrating the typical features of pickup resonance curves.

Gibson P-90 style pickups are great-sounding single-coil electric guitar pickups, and because of their unique design, they are easy to (non-destructively) take apart, and are thus ideal for studying the effect(s) of the various pickup components on the pickup's electromagnetic properties. The electromagnetic properties of a P-90 pickup as a bare coil, a coil with magnetically permeable materials (a soft iron pole piece and screws), a coil with magnetically permeable materials and AlNiCo magnets, or as a complete pickup with a nickel plated brass base-plate and plastic cover can thus be investigated. Complex impedance data was taken for several different P-90 pickups in each of these 4 configurations. The least squares fit results for a 1952 Gibson BR-9 Lap Steel P-90 pickup are shown in figure 5.

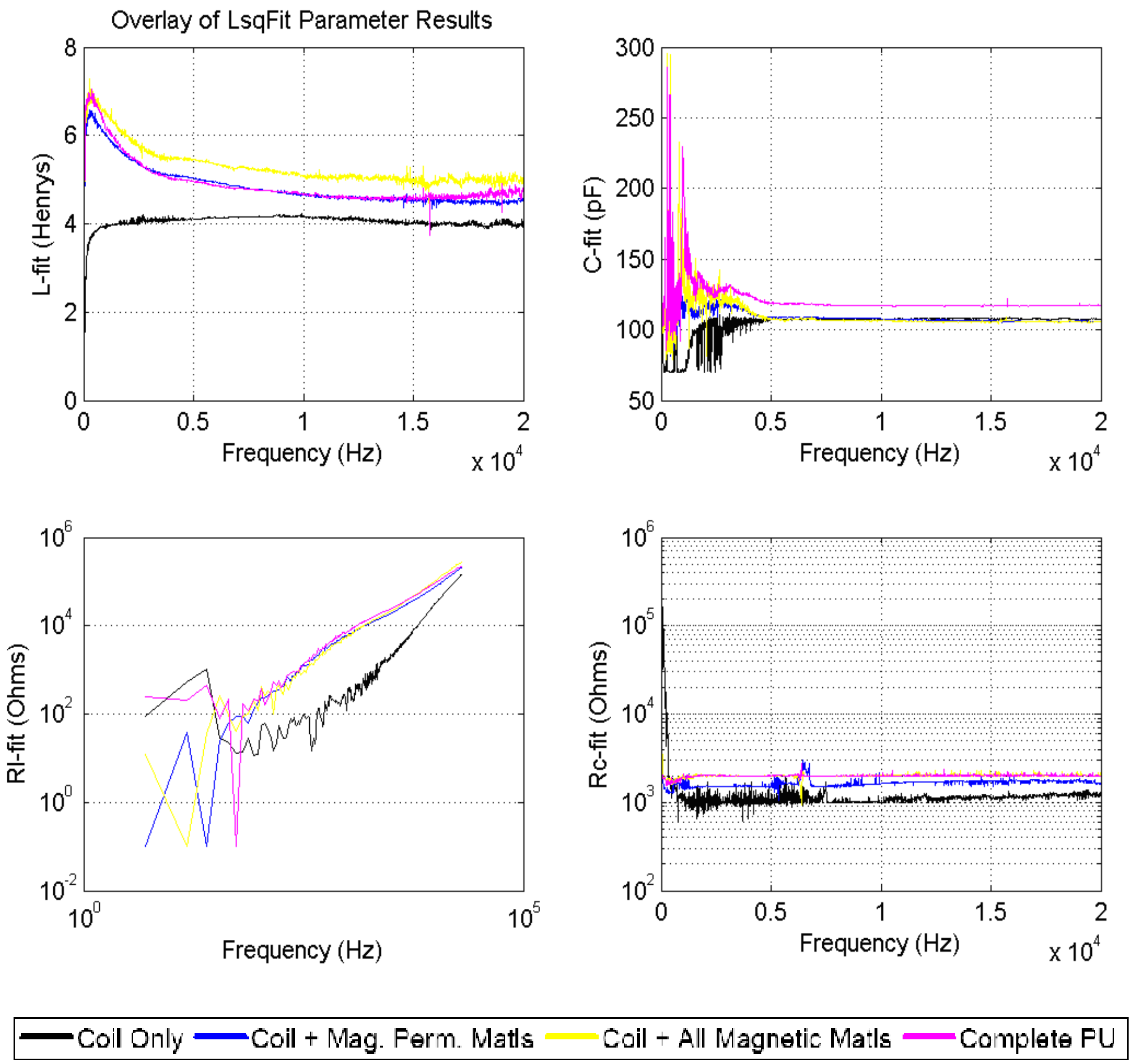


**Figure 5.** Overlay of the least squares fit results for $L$, $C$, $R_L$, and $R_C$ vs. frequency for a 1952 Gibson BR-9 Lap Steel P90 pickup for the 4 different pickup configurations. Note that the $L$ and $C$ plots are linear, the $R_L$ plot is log-log, and the $R_C$ plot is semi-log.

The results of the least squares fit show a great deal of interesting physics. The $R_L$ parameter follows a power law (as can be seen by the linear trend on the log-log plot of $R_L$ vs. frequency in figure 5). For the various single-coil pickups that we measured, this tends to be an approximate $f^2$ relation. $R_L$ also increases as more components are added to the pickup, but the majority of the increase in $R_L$ (from the bare coil values) comes from the addition of the magnetically permeable materials. This is a consequence of the magnetic dissipation that occurs in the magnetic permeable materials (i.e., the soft iron pole piece and screws). $R_C$ is nearly constant for all 4 of the pickup configurations and also increases with the addition of more pickup components. Adding the magnetically permeable materials and the AlNiCo magnets to the pickup increases the inductance (*L*) at low frequencies due to the frequency dependence of the magnetic permeability $\mu(\omega)$ of soft iron materials and AlNiCo magnets of the P-90 pickup. However, the addition of the nickel plated brass base-plate and plastic cover to complete the pickup has the overall effect of decreasing the pickup's inductance at high frequencies, due to the back-EMF effect(s) of induced eddy currents in the nickel plated brass base-plate of the P-90 pickup, as well as a slight frequency-independent increase in the capacitance of the pickup due to the dielectric properties of the plastic pickup cover.

All of the pickup data that we analyzed show several resonances (peaks) in the *C* data in the low frequency range, but <u>only</u> when magnetic permeable and/or permanent magnets were added to the bare coil of the pickup, as shown in the figure below:

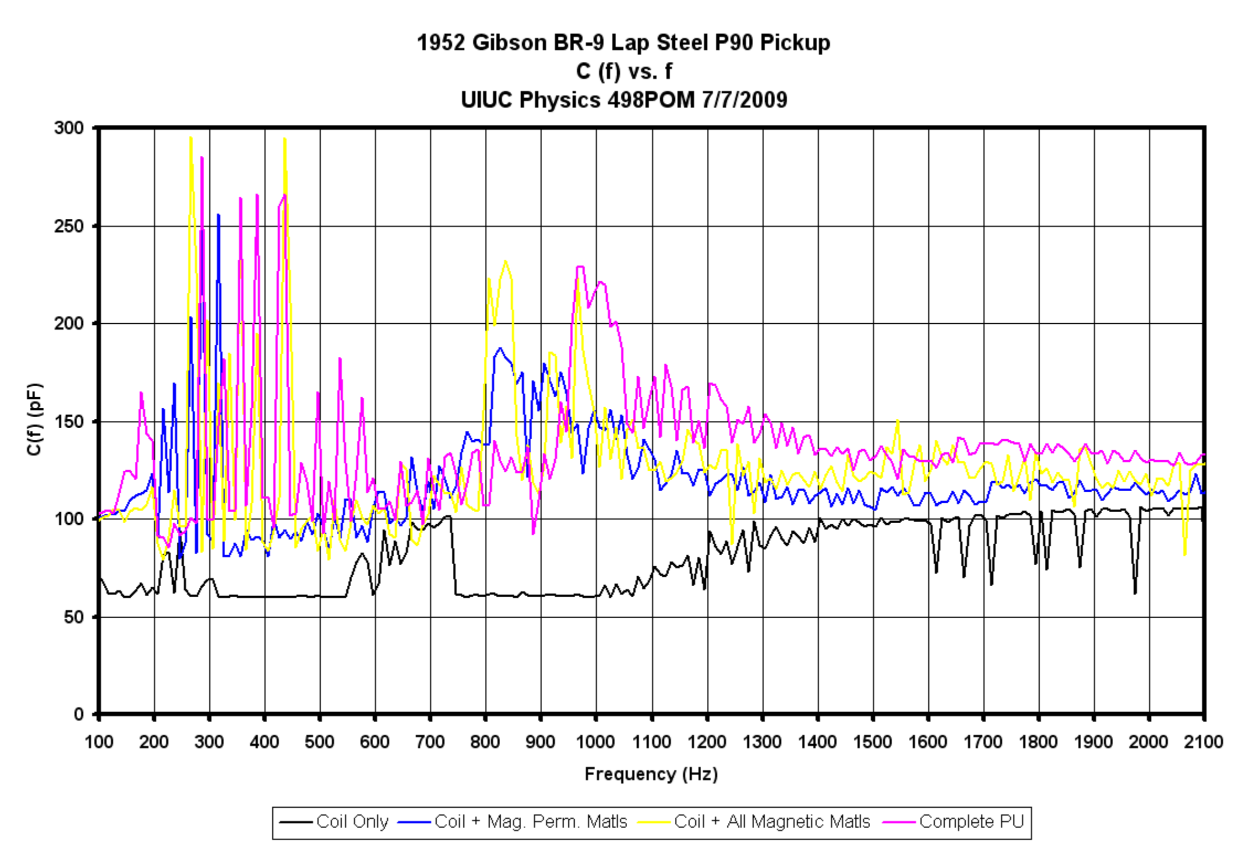


**Figure 6.** Overlay of plots of the least squares fit results for *C*(f) vs. *f* in the low frequency region for a 1952 Gibson BR-9 Lap Steel P90 pickup for the 4 different electric guitar pickup measurement configurations.

The resonances in *C(f)* vs. *f* in the ~ 100-2000 Hz region arise from motion of magnetic domains in the magnetic permeable materials and AlNiCo magnets of the pickup due to the driving force associated with the sinusoidal magnetic field. The basic features of the complex motion of the ferromagnetic domains as a function of frequency can be understood via a simple 1-D damped harmonic oscillator model, whose equation of motion is of the following form: $m_{D_i}\ddot{\tilde{x}}(\omega,t)+m_{D_i}\gamma_{D_i}\dot{\tilde{x}}(\omega,t)+k_{D_i}\tilde{x}=\tilde{F}_m(\omega,t)=2\vec{M}_{sat}\bullet\tilde{B}(\omega,t)$ where $m_{D_i}$ is the mass of the $i^{\text{th}}$ size-type of magnetic domain, $\gamma_{D_i}$ and $k_{D_i}$ are its associated damping and spring constants, respectively. If the damping is small, the natural resonant frequencies of the $i^{\text{th}}$ size-type domains are $\omega_{oD_i} = \sqrt{k_{D_i} / m_{D_i}}$ . The resonant peaks in *C*(f) vs. $f$ (~ 20-30 *Hz* wide, *FWB*) are thus proportional to the number densities $n_{D_i}$ of the $i^{th}$ size type of domain; the width of each resonance yields information on the magnetic dissipation present in the motion of domains, via the *Q*-factor of the resonance for each of the $i^{th}$ size-type domains: $Q_{D_i} \equiv f_{oD_i} / \Delta f_i = \omega_{oD_i} / \gamma_{D_i}$ , or $\gamma_{D_i} = \omega_{oD_i} / Q_{D_i}$ . In order to investigate the nature of these resonances further, we need to take data in finer steps in frequency (e.g. 1 Hz) and we must also reduce the noise in the electric pickup data.

Understanding the frequency dependence of the *uncertainty* associated with the each parameter of the least squares fit is important when interpreting these results. Estimates of the 1-sigma uncertainties were obtained from four diagonal elements of the Jacobian matrix of the least-squares fitting algorithm. From zero to a few hundred Hz, the 1-sigma uncertainties associated with the fitted parameters are much larger than their corresponding fit parameter values (as shown below in Figure 7) except for $R_L$, i.e. the least-squares fit program has little analyzing power for *L*, *C* and $R_C$ in the very low frequency region. The uncertainty on $R_L$ and $R_C$ is at a minimum at resonance, whereas the uncertainties for *L* and *C* peak at resonance (~7500 Hz). This is because the reactances associated with *L* and *C* cancel (i.e., $\chi_L - \chi_C = 0$), i.e. the pickup impedance is purely real at resonance. However, the size of the uncertainties for *C* and *L* are reasonable (i.e., they are smaller than the fit parameter values) at frequencies near resonance. $R_C$ has very large uncertainties compared to the fit values (except close to resonance), and thus is not very sensitive to the least squares fitting.

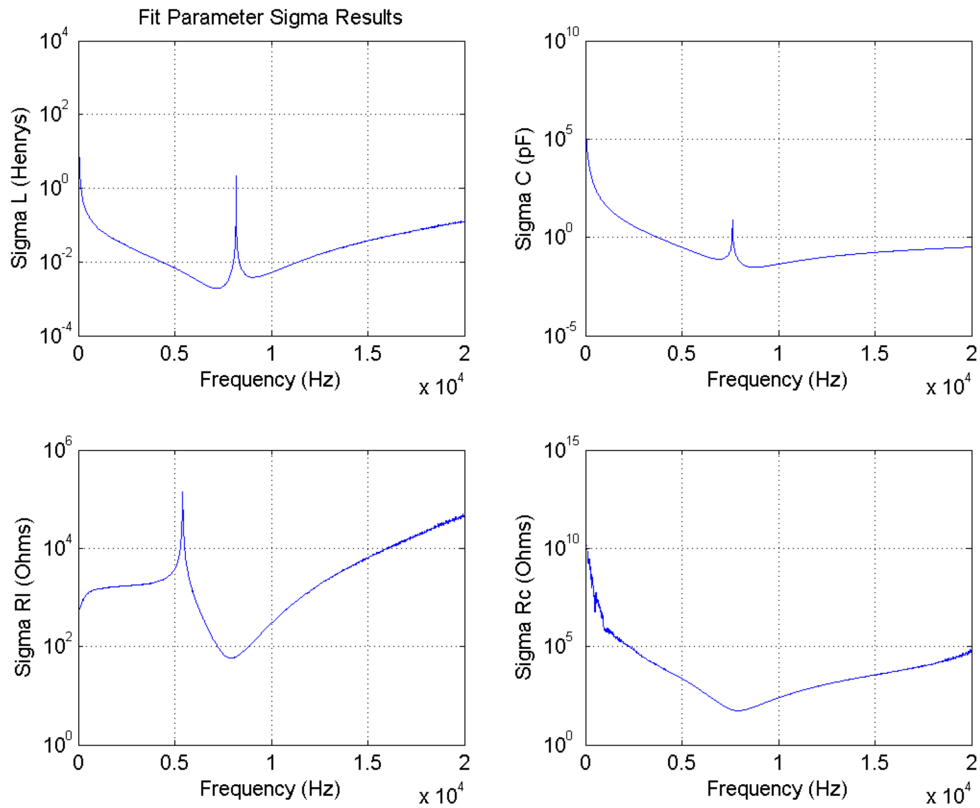


**Figure 7.** Semi-log plots of 1-sigma uncertainties for the 4 fitted parameters vs. frequency. At resonance, the 1-sigma uncertainty peaks for *L* and *C* parameters, whereas it is at a minimum for the $R_L$ and $R_C$ parameters. Note that at very low frequencies, the *fractional* 1-sigma uncertainties on the fitted *L*, *C* and $R_C$ parameters are >> 1.

A Matlab-based program was developed to extract the *effective* relative magnetic permeability $\mu_{rel}^{eff}(f) \equiv L_{mag}(f)/L_{coil}(f)$ of the pickup from the inductance (*L*) data. Since an electric guitar pickup coil is far from a perfect solenoid, only a fraction $f_\Phi$ of the magnetic flux produced by the pickup's coil will couple to the magnetic materials in the pickup. The *fractional* magnetic flux ($f_\Phi$) is assumed to be frequency independent, hence the *true* relative magnetic permeability is related to the *effective* relative magnetic permeability via the relation $\mu_{rel}(f) = \mu_{rel}^{eff}(f)/f_\Phi$ ). Thus, the plots produced should be qualitatively correct (i.e., in terms of shape). The imaginary part of the effective complex relative magnetic permeability is computed via $\mathrm{Im}\{\mu_{rel}^{eff}(f)\} \equiv \omega^2 R_L^{mag}(f)/\omega^2 R_L^{coil}(f) = R_L^{mag}(f)/R_L^{coil}(f)$.

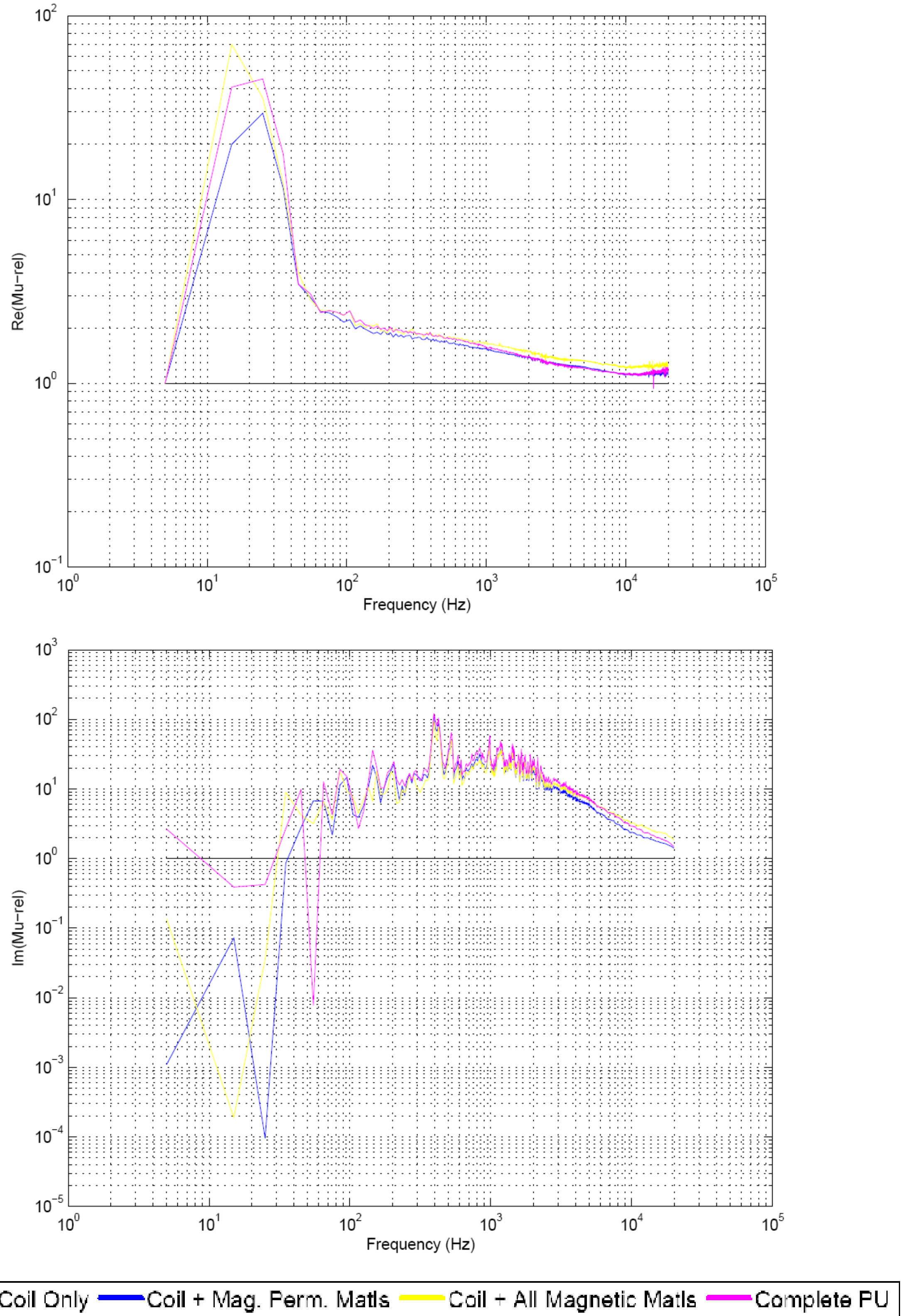


**Figure 8.** Plots of the real and imaginary components of the effective complex relative magnetic permeability vs. frequency. The roll-off in $\mathrm{Re}\left\{\mu_{rel}^{eff}\left(f\right)\right\}$ at very low frequency is an artifact of the data-taking, has very large uncertainties and should be ignored.

The effective complex relative magnetic permeability data is quite noisy at low frequencies, due to the noise in the inductance (*L*) data. These results cannot be analyzed quantitatively until the fraction $f_{\Phi} \sim few\%$ of the magnetic flux in the pickup coil that couples to the magnetic materials is accurately determined (i.e., only the ***effective*** relative magnetic permeability $\mu_{rel}^{eff}(f)$ was obtained). However, the results do appear to be qualitatively correct. The features of the real and imaginary components of the effective complex relative magnetic permeability plots agree qualitatively with those for soft annealed iron, as well as e.g. for a single crystal of magnetite [Craik], as shown below in figure 9:

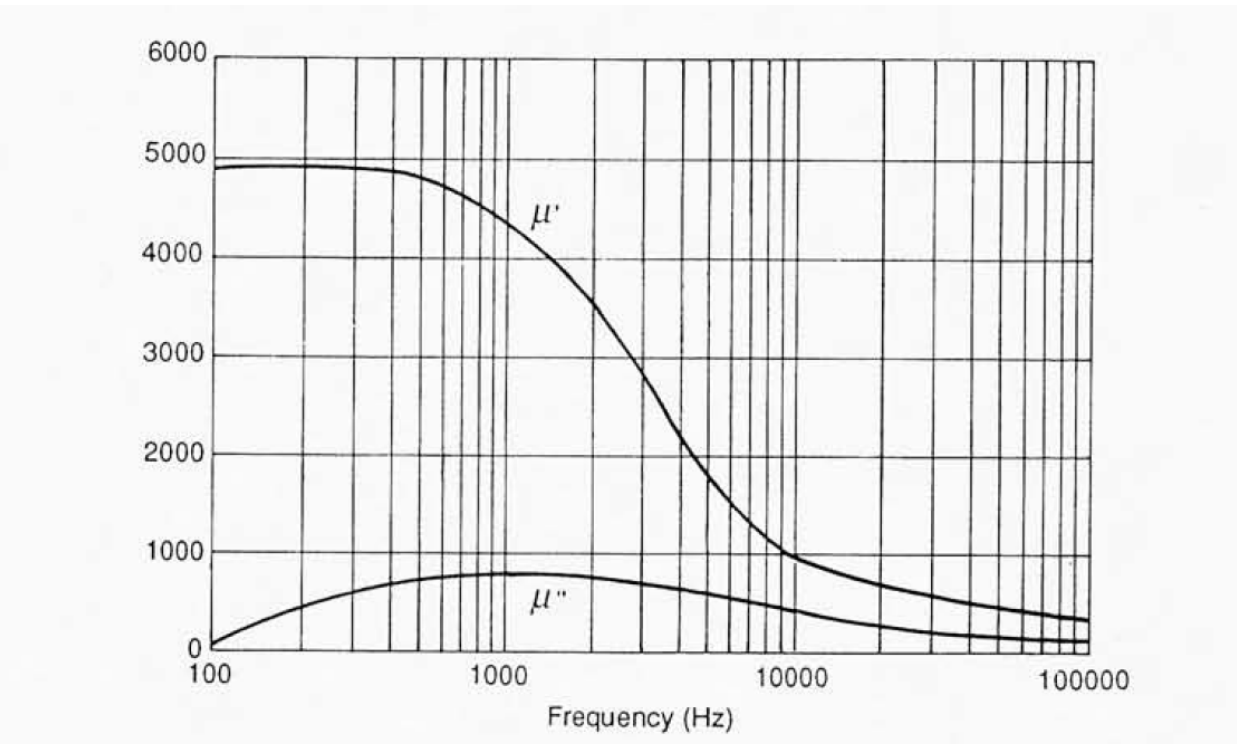


**Figure 9.** The frequency dependence of the real and imaginary components of the complex relative magnetic permeability $\tilde{\mu}_{rel}(f) = \mu'_{rel}(f) - i\mu''_{rel}(f)$ associated with a single crystal of magnetite [Craik].

## Future Work

Future work will involve reducing the noise in the complex impedance measurements (see appendix) in order to obtain more precise least squares fit results. Specifically, reduced noise in the directly-measured complex voltage and current data taken with fine, 1 Hz steps in frequency over the full audio range will result in improvements to fitted parameters, especially the capacitance (*C*) data, which in turn will enable a more detailed investigation into the origin of the resonances seen in the *C* data for pickup coils with the magnetic permeable and/or permanent magnetic materials added. The lumped 4-parameter model of an electric guitar pickup will be further extended by using a modified equivalent electrical circuit electrical/acoustical engineers use for modeling loudspeakers as electro-mechanical motors, which will enable us to relate complex mechanical motion of ferromagnetic domains to our data in a more direct manner.

We will also investigate the origin of the $\sim f^2$ dependence of the $R_L$ parameter from a theoretical standpoint – it arises from the fact that an electric guitar pickup is in reality a distributed circuit consisting of infinitesimal inductances, resistances and stray capacitances coupled together. The simple, lumped 4-parameter model of an electric guitar pickup indeed works very well, but it does have its limitations in terms of accurately describing all of the physics operative in electric guitar pickups…

## Conclusions

Significant progress has been made in developing methods to extract the frequency dependence of the lumped parameters in the electric guitar pickup model. Refining our methods has significantly improved the accuracy and precision of complex impedance measurements and has provided valuable insight into the electromagnetic properties of electric guitar pickups. Developing the Matlab least squares fitting code provided an efficient way to extract the values of the frequency dependant parameters $L$, $C$, $R_L$ and $R_C$. Observing the frequency dependence of these parameters has revealed much interesting condensed matter physics and provided insight into new directions for this research. These are all crucial steps towards obtaining an even deeper understanding of the physics of electric guitar pickups.

## References

[] “Guitar Pickups Made Simple”. http://www.guitar-4u.com/guitar-pickups.html.

[] Craik, Derek J. *Magnetism: Principles and Applications*. San Francisco: Wiley, 1997.

[] Withee, Thomas. “Study of the Electric Guitar Pickup”. http://online.physics.uiuc.edu/courses/phys498pom/Student_Projects/Spring02/TWithee/twithee_spr02_indept_study.pdf

[] Schumann Resonances: Prof. S. Errede’s Spring 2008 UIUC P436 Lecture Notes 10.5, p 6-15 http://online.physics.uiuc.edu/courses/phys436/spring08/Lecture_Notes/P436_Lect_10p5.pdf

[] Errede, Steve. Talk on Electronic Transducers for Musical Instruments. UIUC Acoustical Society of Engineers. Nov. 29, 2005. http://online.physics.uiuc.edu/courses/phys498pom/Lecture_Notes/Guitar_Pickup_Talk/Electronic_Transducers_for_Musical_Instruments.pdf

## Appendix

The precision of complex impedance data can be improved by correcting for low frequency lock-in amplifier phase offset and drifting ADC pedestals, which are small voltage offsets in the analog-to-digital converters. The data acquisition program accounts for these pedestals via $V_{ADC}^{true}\left(f\right)=V_{ADC}^{raw}\left(f\right)-V_{ADC}^{pedestal}$ but it has been observed that the value of the ADC pedestals drift (on the order of a fraction of a mV) as the lock-in amplifiers warm up, causing small errors in the data. Allowing the lock-in amplifiers to thermally stabilize for roughly one day prior to taking data, and then updating the Pickup DAQ code with stable values of the ADC pedestals taken immediately before each pickup measurement run ensured that ADC pedestal drift had a minimal effect.

The lock in-amplifiers that were used to measure the complex impedance have a small internal phase shift at low frequencies ($f$ < 200 Hz) which creates a phase shift artifact in the data. This problem is corrected by simply measuring the lock-in phase shift vs. frequency and correcting the complex current and voltage data for the effect of the phase shift. The easiest way to correct for lock-in phase shift in complex impedance measurements is with the lock-in's external positive (ext. pos) edge referenced to the sync output of the function generator, because it gives a ~1.5 deg phase offset which is nearly independent of frequency. Using the internal oscillator of the lock-in amplifier results in negligible phase shift with frequency, however this can only be done for one of the two lock-in amplifiers used in the electric guitar pickup impedance DAQ setup – e.g. the voltage lock-in amplifier, the other (i.e. the current) lock-in amplifier must be externally-referenced (slaved) to the (master/voltage) lock-in amplifier.