Measurement of the Electromagnetic Properties of Electric Guitar Pickups

Introduction:

Examples of two venerable types of electric guitar pickups are shown in the pictures below – on the left, a pair of single-coil Fender Stratocaster (Strat) pickups and on the right, a pair of single-coil Gibson P-90 pickups.

Figure 1: Left – Fender Stratocaster Pickups; Right – Gibson P-90 Pickups

A single-coil electric guitar pickup typically consists of a coil of several thousands of turns of very fine, insulated copper wire (e.g. # 42 and/or # 43 AWG) wound on a fiber or plastic bobbin/form; permanent magnets of some kind, and possibly other materials/components, used *e.g.* for attaching/mounting the pickup to the body of the guitar. There are many interesting physical properties of electric guitar pickups – all of which can have significant/profound impact on the tonal properties and output signal strength of the pickup. The type and size of fine-gauge copper wire used in winding the pickup coil, how the pickup coil is wound, how many turns of wire the pickup coil has, the geometry of the coil, the type and geometrical aspects of the permanent magnets used in the pickup, how they are configured relative to the pickup coil & strings of the guitar, the properties and geometry of the magnetically permeable materials used in the pickup (if any), the bobbin material, the type and length of pickup leads attached to the pickup, etc. – everything matters!

We summarize below some of the physical measurements that we carry out to characterize the electromagnetic properties of electric guitar pickups, in order to make comparisons with other pickups, and more importantly, in order to correlate these physical measurements of the electromagnetic properties of pickups with the tonal properties of the pickups – *i.e.* how the pickup actually sounds/will sound in a guitar.

1.) The DC resistance (*i..e*. the zero-frequency limit of the AC impedance) of an electric guitar's pickup coil, R_{DC} (in Ohms) is measured using a Fluke 87 DMM at room/ambient temperature (T ~ 22° C). Typical values for R_{DC} are several kilo-Ohms, for # 42 or 43 AWG insulated (varnish/ enamel/formvar/*etc*.-coated) copper wire. The DC resistance of an electric guitar's pickup coil is temperature dependent, increasing with temperature, typically the temperature coefficient $dR_{DC}/dT \sim O(100$ Ohms/°C).

2.) The magnetic polarity (North or South) of pickup poles is measured/defined using a simple magnetic compass, at the top of the pickup – *e.g.* if the red (white) compass needle points/is attracted to the pickup pole at the <u>***top***</u> of the pickup, then this pole has ***south*** (***north***) polarity, respectively. {*n.b.* Recall that the Earth's north geo-magnetic pole is actually a south magnetic pole!}. The magnetic polarity of the pickup poles can also be determined using the Gauss meter from sign (polarity) information of the readout of the Gauss meter – see below…

3.) The magnetic polarity and magnetic field strength of an electric guitar pickup's poles, B_{pole} (in Gauss) is measured using a Walker Scientific MG-50 Gauss meter in conjunction with a transverse Hall probe placed in <u>*direct*</u> contact with each pole of the pickup, at the ***top*** of the pickup. If the reading of the Gauss meter is ***positive*** (***negative***), then the pole has ***north*** (***south***) magnetic polarity, respectively {*n.b* agrees/checks with the above compass needle test}. The *maximum* magnetic field reading per pole is recorded, rounded off to the nearest 5 Gauss (the intrinsic reproducibility/accuracy of these measurements). Typical values for B_{pole} range from ~ 300-400 G for ~ 50% charged AlNiCo-III (*i.e* ~ 600-800 G for fully-charged AlNiCo-III), ~ 800-900 G for fully-charged AlNiCo-II, ~ 900-1100 G for fully-charged AlNiCo-V, and ~ 800-1100 G for ceramic magnets, depending on their composition. The B-field from an electric guitar pickup poles decreases rapidly as one moves away from them, the exact dependence is rather complicated due to the finite size of the poles (diameter & height) as well as the presence of magnetically permeable and other permanent magnets in proximity to the magnet pole undergoing measurement, however very crudely, the B-field decreases approximately as ~ $1/r^3$ (*i.e.* that of a pure, point magnetic dipole).

4.) The winding direction of the coil(s) of an electric guitar pickup is defined from visual inspection, using the convention of CW/CCW winding, from start to finish of the coil wind, viewed from the top of pickup.

5.) The "pull-off" polarity (= output voltage sense) of the pickup is measured using *e.g.* a small screwdriver, with the pickup under test connected either to a DMM on 300 mVdc scale or to an oscilloscope, with the "hot" (ground) lead of the pickup connected to the + (−) terminal of the DMM/oscilloscope respectively. The blade of the screwdriver is slowly (and gently!) brought into direct contact with a pickup pole of the pickup at the top of the pickup, and then abruptly pulled vertically upward, away from the pickup, while simultaneously observing the polarity of the time-dependent voltage deflection V(t) either on the DMM or oscilloscope. For a is positive (negative) voltage deflection V(t) as the screwdriver blade is pulled of the pickup pole, the "pull-off" polarity of the pickup is positive (negative), respectively.

6.) The (lumped) inductance, L(f) and its associated dissipation, $D_L(f)$ of an electric guitar pickup are measured using a Hewlett-Packard 4262A LCR meter at three different frequencies: f = 120 Hz, 1 KHz and 10 KHz. The HP LCR meter analyzes inductance L(f) and dissipation $D_L(f)$ as a "2-component black-box" – i.e. either as a simple lumped <u>series</u> L-R network or simple lumped <u>parallel</u> L-R network. The former (latter) is appropriate/physically meaningful for low (high) frequencies for electric guitar pickups when the reactance of the pickup χ(f), at the frequency, f = 120 Hz, 1KHz or 10KHz, is χ(f) << R_{DC} (χ(f) >> R_{DC}) for series L-R (parallel L-R), respectively. Note that the dissipation, $D_L(f)$ is related to the quality factor, $Q_L(f)$ by $Q_L(f)$ = $1/D_L(f)$ or $D_L(f)$ = $1/Q_L(f)$. Physically, for <u>ideal</u> inductors (or capacitors), their impedances Z are purely imaginary – i.e. purely reactive. However for <u>real</u> inductors (or capacitors), any real

(*i.e.* in-phase) component of impedance can only be due to dissipation of some kind – e.*g.* a resistance. The mathematical formula for dissipation, $D_L(f)$ is defined as the ratio of the real (in-phase) component of the complex impedance to the reactive (90° out-of-phase) component of the complex impedance, i.e. $D_L(f) = Re(Z(f))/Im(Z(f))$ of the pickup at each frequency, so analyzed by this device. Thus, dissipation is a dimensionless quantity. We call the real part of the complex impedance for an inductor (or capacitor), the AC resistance $R_D(f)$.

For a series L-R network: $R_{Ds}(f) = \chi_{Ls}(f) \, D_{Ls}(f) = 2\pi f \, Ls(f) \, D_{Ls}(f)$.

For a parallel L-R network: $R_{Dp}(f) = \chi_{Lp}(f)/D_{Lp}(f) = 2\pi f \, Lp(f)/D_{Lp}(f)$.

If the electric guitar's pickup resonant frequency is 1 *KHz* < f_{res} < 10 *KHz*, where the pickup impedance, $Z(f = f_{res})$ is a maximum in this frequency range, then no measurement of the inductance, $L(f)$ at f = 10 KHz is possible with the HP 4262A, due to the measurement technique used by the HP 4262A (one form of AC bridge). However, one can instead measure the capacitance, $C(f)$ of the pickup at f = 10 KHz with the HP 4262A, analyzing the electric guitar pickup as a lumped, parallel C-R circuit, because the reactance, $\chi(f)$ on the high side of the resonance of the pickup, *i.e.* f > f_{res} has negative slope (i.e. $d\chi(f)/df$ < 0), due to the dominance of the pickup's capacitance, C over the pickup's inductance, L in this frequency region, *i.e.* $\chi_C(f)$ > $\chi_L(f)$ when f > f_{res} (conversely, $\chi_C(f)$ < $\chi_L(f)$ when f < f_{res}). Again, we can also simultaneously obtain a measurement of the dissipation, $D_C(f)$, which is again related to the quality factor, $Q_C(f)$ = $1/D_C(f)$, or $D_C(f) = 1/Q_C(f)$. The mathematical formula for the dissipation, $D_C(f)$ can again be used to calculate the resistive/dissipative (real/in-phase) component, $R_D(f)$ of the complex impedance of the pickup, $Z(f)$ at the frequency, f, so analyzed by this device.

For a series C-R network: $R_{Ds}(f) = \chi_{Cs}(f) \, D_{Cs}(f) = [1/(2\pi f \, Cs(f))] \, D_{Ls}(f)$.

For a parallel C-R network: $R_{Dp}(f) = \chi_{Cp}(f)/D_{Cp}(f) = [1/(2\pi f \, Cp(f))]/D_{Lp}(f)$.

In reality, an electric guitar pickup is considerably more complicated than the simple, very crude model of a pickup consisting of a lumped series L-R in parallel with a lumped C, because the actual L, R and C are distributed over the many thousands of turns of the pickup coil. Furthermore, the pickup inductance, L is not a constant, independent of frequency due to frequency-dependence of the magnetization, M (magnetic dipole moment per unit volume) of the permanent magnet(s) used in the pickup, how fully the magnets are charged (i.e. where the permanent magnets reside on the B-H hysteresis curve) as well as the frequency-dependent properties of the magnetically permeable material(s) used in the construction of the electric guitar pickup – soft iron pole pieces, booster plates, even frequency-dependent eddy current effects in nonmagnetic metal components associated with the pickup – booster plates, mounting brackets, screws, etc. Thus, L = L(f). In addition to these effects, even the pickup resistance at finite frequency, R(f) differs significantly from that at zero frequency, *i.e.* R(f) ≠ R_{DC} = R(f = 0) due to frequency-dependence of turns of wire in the coil coupling to each other and also the magnetic dissipation processes extant in the electric guitar pickup associated with the permanent magnets and the magnetically permeable materials of the pickup, the effects of eddy currents induced in conducting materials used in the construction of the pickup (and/or in proximity to the pickup) and also frequency-dependent resistivity effects associated with the fine-gauge pickup wire (immersed in the magnetic field of the pickup) of the pickup coil. Nevertheless, the measured pickup capacitance C(f = 10 KHz), and corresponding D_C(f = 10 KHz) info obtained is useful. We also compute $R_C(f)$ from this data.

7.) The complex impedance of the pickup Z(*f*) and output voltage V(*f*) as a function of frequency *f* are measured using a PC-based DAQ system that we have specifically designed to carry out these measurements. As shown schematically in Figure 3 below, the PC controls the internal sine-wave of one of two lock-in amplifiers via GPIB. We set the sine-wave amplitude to 1.0 volt and step through the frequency from 5 Hz to 20.005 KHz in 2000 frequency steps of 10 Hz. The 50 Ohm, low-impedance output of the sine wave oscillator (an ~ constant voltage source) is converted to a high-impedance, ~ constant current source (in order to ~ emulate the ~ constant-current excitation of the pickup via a vibrating electric guitar string, when plucked) using a 1.5 meg-ohm metal-film (low Johnson noise) resistor in series with the sine wave oscillator's output. The "hot" lead of the electric guitar pickup is connected to the output side of the 1.5 Megohm resistor. The other lead of the pickup is connected to a 100 Ohm shunt resistor, and the other lead of this resistor is connected to the signal ground of the sine wave oscillator. We measure the complex voltage (real/in-phase and imaginary/90-degrees out-of-phase voltage components) across the pickup and using a Stanford Research model SRS 830 DSP-based lock-in amplifier. We do not connect pickup directly to the input of the lock-in amplifier, but first unity-gain buffer the voltage signal from the pickup using an Analog Devices AD624AD low-noise JFET instrumentation op-amp, which has very low output impedance and thus can very easily drive the input of the lock-in amplifier over the entire audio frequency range (*n.b.* the dynamic input impedance of the lock-in amplifier varies significantly with frequency and filtering options/settling time, etc and loads down the high-impedance of the pickup, if connected directly, giving very significantly biased results over the entire audio spectrum). We also explicitly measure the complex current (real/in-phase and imaginary/90-degrees out-of-phase current components) flowing through the pickup via the voltage developed across the 100 Ohm shunt resistor, and again use a unity-gain AD624AD low-noise JFET instrumentation op-amp to buffer the current signal before inputting it to a second SRS-830 lock-in amplifier. The two AD624's are housed in a shielded/grounded metal box to suppress RFI/60Hz/etc. noise pickup. Short alligator leads are used to connect the leads of the pickup to this front-end electronics. The sine-wave signal from internal oscillator of one of the lock-in amplifiers is used as a reference signal for the complex voltage and current measuring lock-in amplifiers.

The quasi-static voltages present on the X (in-phase) and Y (90° out-of-phase) outputs of the two lock-in amplifiers used for measuring the complex voltages & currents in the pickup at each frequency are measured using four ADC's (Analog-to-Digital-Converters).

We use a National Instruments LabPC+ DAQ card, which has eight 12-bit gain-programmable ADC's and two 12-bit DAC's (both with +_5 V max. dynamic range), and 24 TTL I/O lines, to digitize the analog outputs of the SRS-830 lock-in amps at each frequency setting of the sine wave oscillator using four ADC channels of the NI LabPC+ DAQ card. After stepping the frequency of the sine wave oscillator, we wait ~ 5-6 lock-in settling times (~ several seconds). We then digitize/measure Re(V(f)), Im(V(f)), Re(I(f)) and Im(I(f)) at each frequency, *f*. The Pickup DAQ program uses signal averaging techniques – we waveform record 10000 digitizations of each of the 4 ADC channels, and then compute the means/averages: <Re(V(f))>, <Im(V(f)>, <Re(I(f))> and <Im(I(f))> in software - online. The Pickup DAQ program then computes <|V(f)|>, <|I(f)|>, and using these results also computes complex impedance components <Re(Z(f))>, <Im(Z(f))>, <|Z(f)|>, complex power components <Re(P(f))>, <Im(P(f))>, <|P(f)|> and also <phase(V(f))>, <phase(I(f))>, <phase(Z(*f*))> and <phase(P(*f*))>

in software - online, for each frequency, f. These quantities are all stored in arrays. The Pickup DAQ program can also display all of these quantities - there are many online plots, and also write out all of the data to a text file. It takes ~ 3 hours per pickup to make this measurement. Prior to carrying out these pickup impedance measurements, we also run the Pickup DAQ setup with no signal from the function generator, to obtain zero-signal, ADC <voltage> offsets (aka ADC "pedestals") which are subtracted from the raw ADC data, online for each measurement. The ADC pedestals/voltage offsets are quite small, but it is important to remove them in order to obtain accurate impedance measurements - which we have explicitly checked the Pickup DAQ setup over the entire frequency range using various resistors of known/measured resistances - e.g. 1, 56, 100 & 1000 Kohms. The impedance measured for these resistors is as expected (i.e. purely real), and flat, independent of frequency.

When pickup impedance measurements are carried out, we place the pickup at the center of a large-bore mu-metal cylinder in order to suppress extraneous magnetic noise pickup. The primary reason for doing this is due to the fact that electric guitar pickups, due to their large inductances (typically several Henries) are incredibly sensitive devices – they can very easily detect the passage of cars, trucks and buses from the 6th floor of the Engineering Sciences Building on the UIUC Campus! Passing cars/trucks/buses on the street below primarily manifests itself in the form of transient/low-frequency current noise – due to the remnant magnetic field(s) of these vehicles coupling to the guitar pickup being tested. Placing the pickup at the center of the large-bore mu-metal cylinder helps significantly in reducing/suppressing such noise, but it does not eliminate all noise sources. Note that the average/typical pickup excitation current is ~ 665 nA, comparable to that induced by a vibrating guitar string.

We measure/record the resonant frequency, f_{res} of the electric guitar pickup, which we define as that frequency, $f = f_{res}$ for which $|Z(f = f_{res})|$ is a maximum. We also obtain FWHM information from the frequency difference, $FWHM = \Delta f = f_{HI} - f_{LO}$ associated with the two $Z(f) = |Z(f = f_{res})|/\sqrt{2}$ points or, ~ equivalently, the frequency difference, $FWHM = \Delta f = f_{HI} - f_{LO}$ associated with the max/min inflection points of $Im(Z)$. Thus we can also compute the quality factor, Q of the pickup: $Q \equiv f_{res}/FWHM = f_{res}/\Delta f$. Once we have the quality factor, Q, we can then compute the dissipation factor for the pickup, from $D \equiv 1/Q = FWHM/f_{res} = \Delta f/f_{res}$. We also measure/record the magnitude of the voltage output from the pickup on the resonant peak of the pickup, $|V(f = f_{res})|$, which is useful e.g. for the purpose of comparison to other pickups.

For further, detailed information on the Pickup DAQ pickup impedance measuring setup, refer to the UIUC Physics 498POM lab handout for this specific setup.

The UIUC Physics 498POM Electric Guitar Pickup Measuring Facility in shown below in Figure 2. The Main Panel of the Pickup DAQ program is shown below in Figure 3. A comparison of the magnitudes of the impedance, $|Z(f)|$ vs. frequency, f for various Stratocaster and P-90 style pickups are shown below in Figures 4 and 5, respectively. Note that from the complex form of Ohm's law, $V(f) = I(f)Z(f)$, that the voltage output of an electric guitar pickup, $V(f)$, using the idealized (and simplifying) approximation of constant current excitation of a pickup by the strings of the guitar, *i.e.* $I(f) = I = constant$, then $V(f)$ is directly, and linearly related to the impedance of the pickup, *i.e.* $V(f) = IZ(f) = constant*Z(f)$, and thus $|V(f)| = constant*|Z(f)|$. Hence, the importance of the pickup $|Z(f)|$ vs. f curves.

Figure 2: UIUC Physics 193/406 POM Electric Guitar Pickup Measurement Facility

The UIUC Physics 498POM PC-Based Pickup Impedance Measuring System:
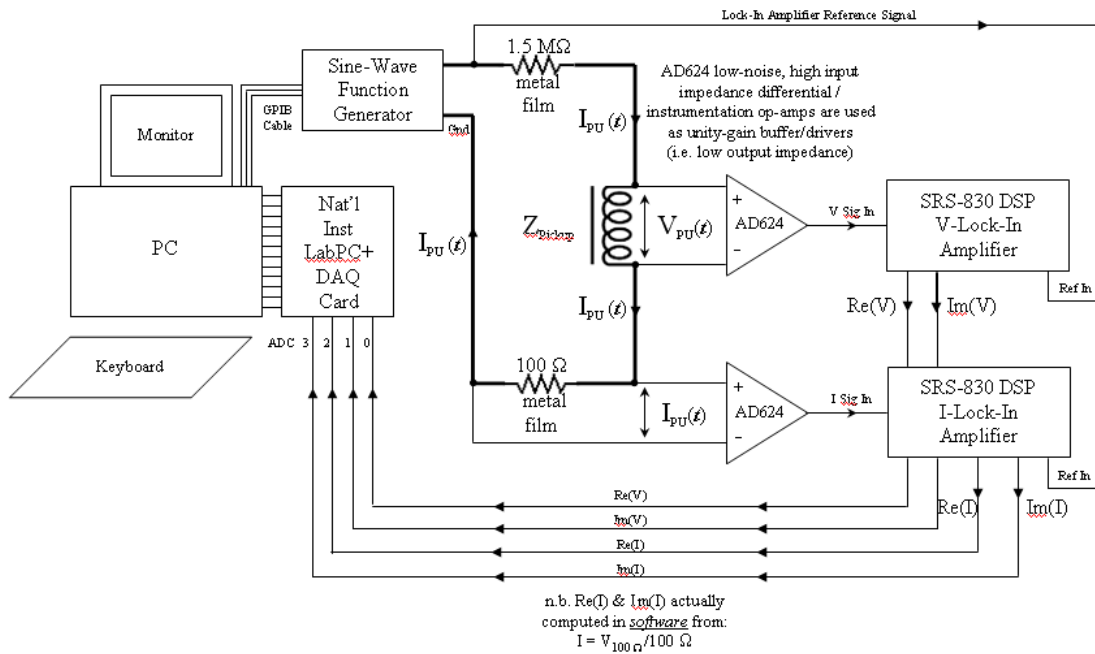

Figure 3: Block Diagram of the UIUC Physics 193/406 POM PC-Based Electric Guitar Pickup Impedance Measurement DAQ System
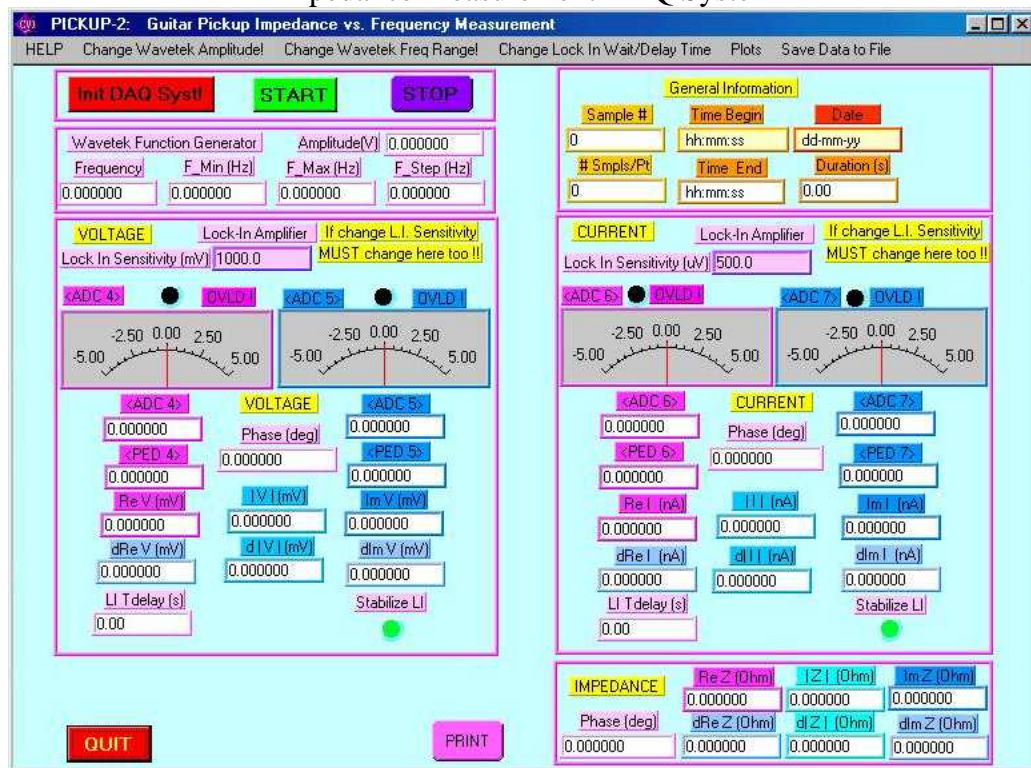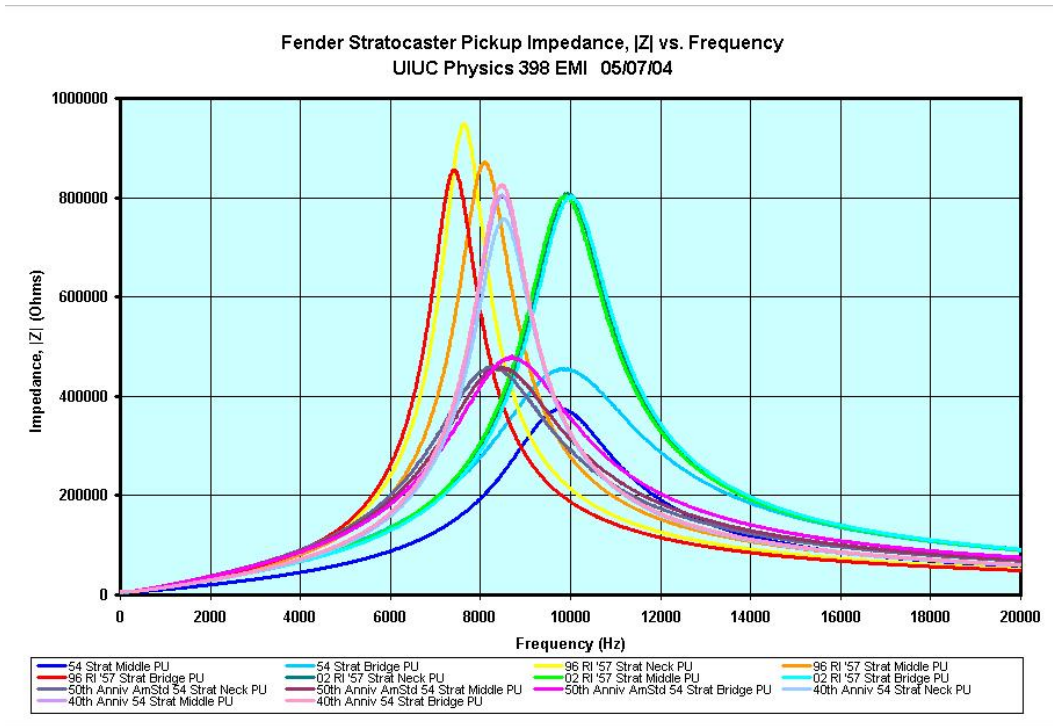

Figure 4: Main Panel of the Pickup DAQ Program

Figure 5: Comparison of the magnitude of the impedance, $|Z(f)|$ vs. frequency, f for various Stratocaster-style single-coil pickups
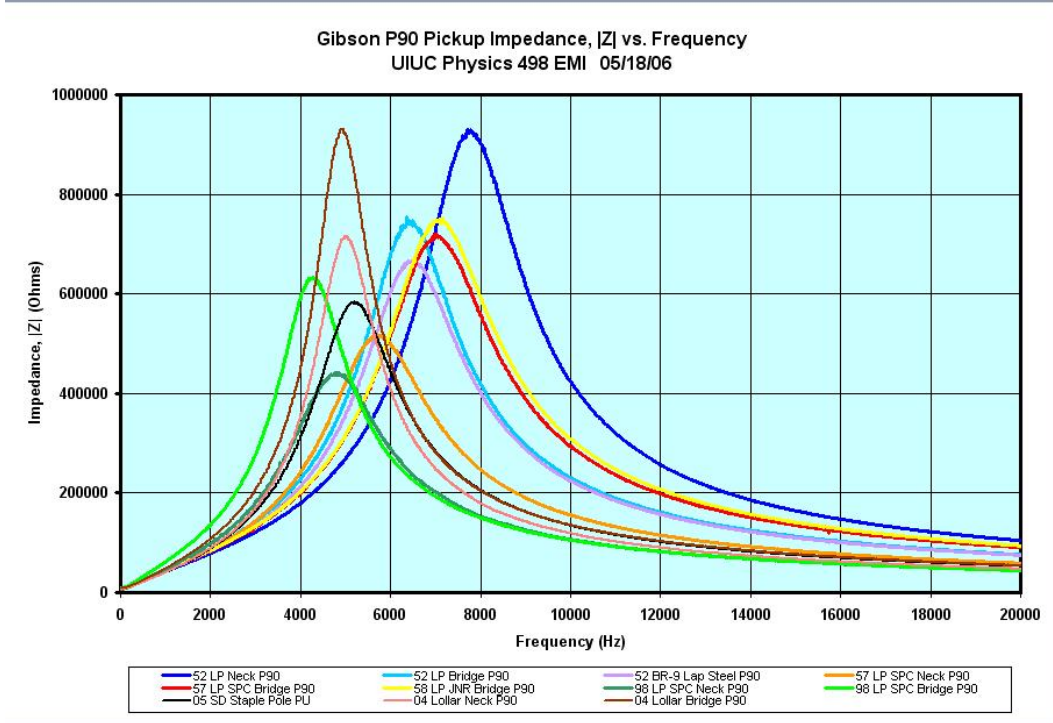

Figure 6: Comparison of the magnitude of the impedance, $|Z(f)|$ vs. frequency, f for various P-90 style single-coil pickups
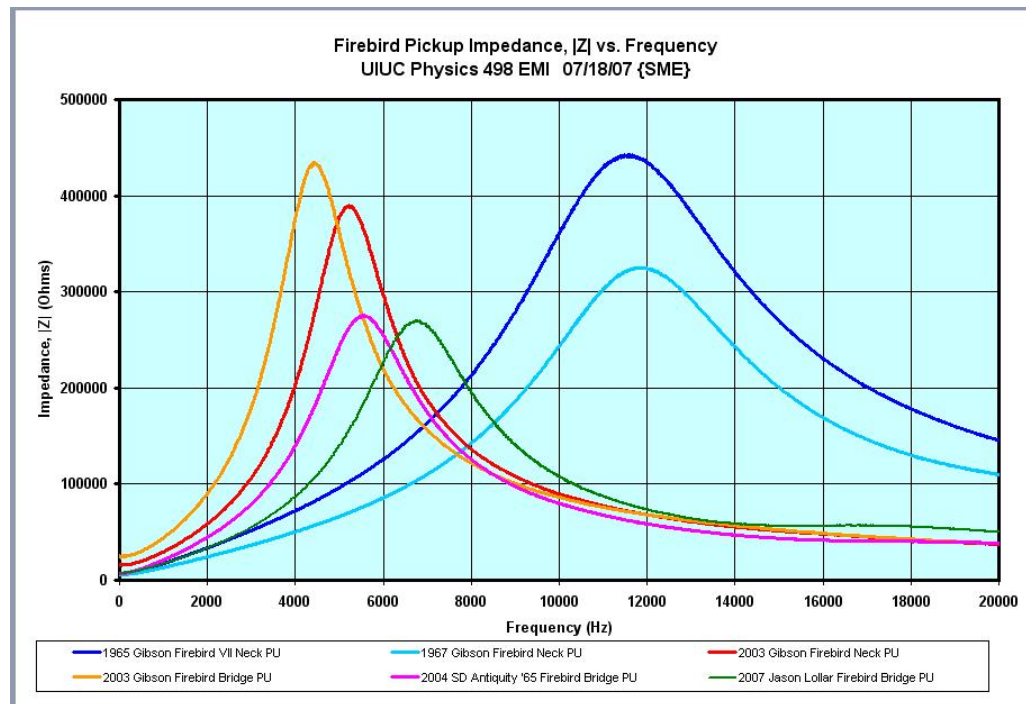
Figure 7: Comparison of the magnitude of the impedance, $|Z(f)|$ vs. frequency, f for various Firebird style humbucking pickups

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