The Electromagnetic Properties of Electric Guitar Pickups

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Introduction

• Pickups consist of several thousand turns of thin copper wire wrapped around 6 magnetic poles.

• Pickups convert the mechanical vibrations of the guitar string into an electrical signal.

• The goal of this project is to understand the underlying physical processes at work in electric guitar pickups.

• Correlating the physical and tonal properties allows us to build better sounding pickups.

Image courtesy of http://www.electric-guitar-info.com/electric-guitar-pickups.html
4-parameter pickup model

- Single coil pickups can be modeled as LR_CR circuits.

- Lumped parameter model (i.e., all capacitive effects are lumped into the parameter C).

- Information about the electromagnetic properties of the pickup is contained in the frequency dependence of the 4 parameters.

\[
\tilde{Z}_L = R_L(\omega) + i\chi_L(\omega)
\]

\[
\tilde{Z}_C = R_C(\omega) - i\chi_C(\omega)
\]
Extracting the Parameter Values

• Complex current and voltage data were measured across the pickup from 5-20005 Hz in 10 Hz steps.

• Matlab least squares fitting program finds the values of the 4 parameters that minimize the square of the difference between the measured and calculated values of 16 constraints (power, impedance, current, and voltage, each with real and imaginary components, magnitude, and phase) at each data point.

• Redundant constraint equations were used to minimize the adverse effect of noise in the impedance data on the least squares fitting.
Converts output of function generator into a near constant current source

Measures complex voltage

Sets frequency/amplitude of pickup excitations

Controls function generator

Stores data

Converts analog signals from the lock-ins to digital signals to be sent to the PC

Measures complex current
Gibson P90 pickup configurations

- Complex impedance measurements and least squares fitting was carried out for several Gibson P90 pickups in the following configurations:
  
  bare coil
  coil + magnetically permeable materials
  coil + magnetically permeable materials + magnets
  complete pickup (w/ cover and base plate)

- Extracting the parameter values ($L$, $C$, $R_L$, and $R_C$) for each of these configurations revealed a lot of interesting physics!
Least Squares Fit Parameter Results

- Resistance in inductive branch obeys power law ($\sim f^2$).
- $R_L$ increases when magnetic materials are added, due to magnetic dissipation.
- Data is not reliable in the $f < 100$ Hz range, uncertainties are too large.

Results of the least squares fit parameters for a 1952 Gibson BR-9 Lap Steel P90 pickup.
Resonances in Capacitance Data

• Peaks appear in the C data in the 200-1000 Hz range only when magnetically permeable materials are added to the pickup.

• The magnetic domains of the magnetic materials can be modeled after a simple harmonic oscillator.

• If the damping is small, the resonant frequency of the $i^{th}$ sized domain is

$$\omega_{oD_i} = \sqrt{\frac{k_{D_i}}{m_{D_i}}}$$

• The size of the resonances therefore should be proportional to the number density $n_i$ of the $i^{th}$ sized domain. That’s what we believe we are seeing in the data!
Effective Relative Magnetic Permeability

- By definition, the effective permeability is the ratio of the inductance when magnetic materials are present to the inductance of the

\[ \mu_{rel}^{eff} (f) \equiv \frac{L_{mag}(f)}{L_{coil}(f)} \]

- A pickup is not a perfect inductor, so we can only calculate the effective *relative* permeability (i.e., only a fraction of the magnetic flux created by the pickup magnets couples to the magnetically permeable materials).

\[ \mu_{rel}^{eff} (f) = \frac{\mu_{rel}^{eff} (f)}{f_\Phi} \]
Our results (above) agree qualitatively with the complex permeability of single crystal magnetite (left).

Our results at very low frequencies (i.e., $f < 100$ Hz) are unreliable due to the large uncertainties in the fit parameters at these frequencies.
Future work

• Investigate the origin if the \( \sim f^2 \) dependence of the \( R_L \) parameter.

• Take data in finer (1 Hz) steps and with less noise in order to better resolve the resonances in the C data.

• Investigate possible ways to on the expand the current model.
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