Guitar Pickups - Some Electronic Characteristics

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Introduction

The basics of an electro-magnetic guitar pickup is that it is a highly inductive coil placed in the near vicinity of a constant magnetic field, that incidentally also has magnetic guitar strings in that field.

Any relative movement of the magnet, and strings that causes a change in the reluctance of the magnetic circuit will induce a voltage into the coil. This part of the study is focussed on the physical characteristics of the coil (or coils) in a few sample pickups.

Because of the inter-winding capacitance, and the self-inductance due to the huge number of turns on these pickups, the coils have a relatively low self-resonant frequency.

Also, the resistance is relatively high in comparison to the inductance. To get a better understanding of these pickups, there are some basic applied mathematical formulas that can characterise the pickups.

As these pickups are basically highly inductive coils, there are two simple electrical measurements that can be performed to measure the resistance and the inductance and these both give a clear picture of the pickup coil and its electrical properties.

Resistance Factor

The resistance factor (Ar) is entirely dependent on the geometry of the bobbin and the filling of the bobbin with copper wire by a specified number of turns. The wire diameter (and insulation) limits the number of turns that can be fit onto the bobbin, and that in turn directly relates to the resistance.

The resistance is related to the resistivity of the wire, which relates to the square of the cross sectional area of the wire strand.

Hence the very simple formula

R (micro ohms) = n^2 * Ar (micro-ohms)

This formula is fairly useful if you are engineering the design of a coil, as you will have previously determined the number the number of turns, and this then gives an expected terminal resistance value – as you should already know the Ar value for that bobbin.

Most coil bobbins are constructed in a regular cylinder or square rectangular cylinder, but in the case of guitar pickups, the shape is usually very flat, and can usually be seen as two semi-circles joined by an extended straight section. It is important to understand this structure, as it is definitive in formulating the resistance factor.

With a circular cylindrical bobbin structure, the wire winds on over itself, and as it does, the radius incrementally increases. This incremental increase in the radius causes the length per turn to also incrementally increase in a compound fashion and this is compound increase in length is directly proportional to the resistance per turn. The formula for compound interest (Amount = Principal * Interest ^ Term in years) follows this same structure.

In reverse, as this is a power (geometrical) relationship, the mean radius is the square root of the inner radius multiplied by the outer radius of the windings (excluding insulation tapes).

Having now realised that the physical structure of the pickup bobbin is not a round cylinder, it can be better understood as two parts brought together:

Resistance = Ar.n^2 + Ax.n

In this case the Ar part related to the circular ends and the Ax part related to the straight part of the winding (bobbin). The number of turns associated with the Ax factor is linear (order 1) because the length is consistent irrespective of the number of turns on the bobbin.

So with two bobbins of different lengths (x), between end centres then with the same number of turns with the same type wire the Ar part will be constant – leaving the Ax part to be simply calculated with simultaneous equations! This leaves the Ar part to then be calculated for that same bobbin type – and this then gives a predictive equation for coil resistance before the coil is manufactured!

We don't need to get into the depths of this to better understand pickups, simply measuring the resistance is a good starting point. What we do now understand is that the internal resistance is very closely related to the square of the turns the bobbin, and that the bobbin by its physical shape (specifying the cross sectional winding area, and the mean length of the winding) totally defines the resistance (Ar) factor of the bobbin that holds the wire.

This branch of applied mathematics involves considerable approximation because there are so many variables that surface; like bobbin filling factor (the proportion of the bobbin that is filled with windings), wire insulation factor (the insulation thickness compared to the wire diameter), winding factor (the total winding cross sectional area compared to the total conductor cross sectional area), etc.

All these and other considerations can be included to obtain a far more accurate approximation of the total resistance, but the range of available wire diameters is limited, and this diameter varies - simply because the diamond drawing die wears with use - so it is reasonable to expect considerable variation in resistance in production runs, and my guess is that about +/- 5% variation would be reasonable for production runs, and +/- 10% between production runs.

While these variations might seem quite wide, it has to be understood that the bobbin is not round, and the winding tension is really like a series of pulses as the ends of the bobbin come around, so the wire gets stretched as it is wound on and this too will vary the resistance, and the thickness of the total winding - as these impact on the winding factor too!

With different production runs the winding speed may be different, tension different, wire source from another batch, enamel insulation thickness different - so there is lots of room for production variation - especially as this wire is so thin and there are so many turns, and the bobbin is not a regular (round) shape for winding!

Inductance Factor

The Inductance of a coil (L) is entirely dependent on the geometry of the magnetic circuit and the magnetic components together with the number of turns in the coil. In the same fashion as the Resistance Factor (Ar) is related to the physical structure of the bobbin, the Inductance Factor (Al) is totally related to the magnetic resistance (Reluctance) of the magnetic circuit, which is totally dependent on the physical shape of the magnetic circuit.

These two entities Ar and Al fit like two pieces of a metal chain, where each is an entity all by themselves but together they form an electro-magnetically coupled circuit!

Reluctance is far more difficult to calculate than resistance, as the magnetic field is very leaky, while with resistance the current that flows through a wire has very clear boundaries making resistance relatively easy to approximate, the magnetic flux that flows in a magnetic circuit passes through air, wood, plastic, brass, iron, nickel etc. and all of these materials have differing permeabilities and solving these problems usually reverts to rather complex mathematics called Field Theory, and another associated branch of mathematics called Finite Element Analysis.

For a known magnetic circuit the formula follows a similar shape as the resistance factor.

Inductance (nH) = n^2 * Al (nH)

Again this formula is fairly useful if you are engineering the design of a coil, as it will give you the expected inductance value from the number of turns – as you would already know the Al value from that magnetic construction (coil and magnet assembly) from earlier measurements of a similarly constructed coil and magnetic components. So in practice it would be the case of first wind a reference coil - with known number of turns, assemble the magnetic structure and measure the inductance, then deduce the inductance (Al) factor from the above formula.

As with the resistance factor and its association in a circular cylinder, the inductance factor follows the same geometrical (power) relationship – but inductance is also proportional to the square of the mean area defined by the straight length (x) and the mean radius (y), so the more complete formula for inductance is:

Inductance = Al * n^2 + Am(x) * n * Am(y) * n

Inductance = Al * n^2 + Am(xy)* n^2

Inductance = Al * n^2 by including Am(xy) into Al

The Al factor is not that hard to deduce, once a bobbin is filled and the inductance measured and the maths done against the number of turns. We now have a direct way to predict the inductance with reasonable accuracy before we even start winding any pick up coils. Just as before with the resistance factor being determined by many approximated sub-factors, so too some of these similar sub-factors play a part in determining the inductance (Al) factor.

Wheeler's Formula (and its extensions) go a long way to relate the physical shape of a coil to the expected inductance and all of this is approximation theory at its best! Wire diameters and bobbin filling factors are other issues that will play big parts here as the (enamel) wire insulation is comparatively thick but that is not in this scope.

What has to be realised here is that the bobbin cross sectional magnetic path area is a vital component of the Reluctance of the magnetic circuit and if this area is changed then it will have a major effect on the overall reluctance, and this will have a direct effect on the inductance.

As the sides of the magnetic pickup are usually flat, then they can be squeezed, and this could change the inductance - but we are not going there!

The magnetic reluctance path is through the magnet(s) then through the air and partially through the strings, then through the air again all the way round to the distant end of the magnet. Now a few home truths!

If the magnets were made a little bit bigger/longer (like in the Telecaster) then there is more surface area for the magnet field to launch itself compared to the air, and consequently the reluctance is less, and the comparative inductance is greater for a similar number of turns.

For Hum Buckers, there are two coils in series, and these have their magnets, and magnetic joining plate, and pole pieces to draw the magnetic field around towards the strings. You would think that with all this, that the inductance would be far greater and that the output level would be far louder - or "hotter" in guitar speak!

Initial Measurements

For consistency, all initial inductance tests were carried out at 1 kHz and the resistance was initially measured at 100 Hz with a HP 4262A LCR bridge.

The physical structure of these pickup coils are reasonably similar, with a series of (pseudo) bar magnets through the centre of the pickup coil, and the bobbins have a fairly consistent shape between each other, and the resistances are fairly close at about 6.0 k ohms. It would be reasonable to expect that the number of turns would be fairly consistent between these four pickups, so the inductance is the variable!

Bobbin Description	**Resistance (k) 100 Hz**	**Resistance (k) DC**	**Inductance (H)**
Strat 01	6.09 k	5.87 k	2.76 H
Strat 02	6.67 k	6.48 k	2.93 H
Kinman Strat		6.08 k	2.96 H
Kinman Tele		6.89 k	3.45 H
White Single	7.49 k	6.73 k	4.44 H
Black Single	5.44 k	5.12 k	3.05 H
HMB-01			
Additive	8.72 k	8.45 k	4.59 H
Subtractive	8.35 k	8.45 k	3.72 H
Gr-Wh	4.30 k	4.33 k	2.07 H
Cm-Bl	4.13 k	4.12 k	2.08 H
HMB-02			
R-Shield	15.48 k	14.3 k	9.05 H
R-W	7.42 k	7.18 k	3.92 H
W-Shield	7.31 k	7.16 k	3.84 H

It became obvious from the results below that measuring the resistance must be done with a direct current, as even at 100 Hz a considerable error can exist. A 100 uA DC current source with a DVM gave reliable results. This is a low current, and the resultant field (about 1 AT) is barely enough to affect the permanent magnets.

The inductance was measured at 1 kHz with the same HP 4262A LCR measuring bridge, and the results were tabulated above:

These results showed that even as low as 100 Hz the reactive inductance had an appreciable effect on the impedance of the pickups, but the resistance figures were consistent, indicating that these resistance values were reliable and repeatable.

Now that the resistances and inductances have been measured for these coils, and we have relationships that tie resistance to the bobbin construction, and inductance that ties to the magnetic construction, we are in a position to characterise various pickups in relation to these measurements.

Quality Factor

For a coil, if an exciting current is introduced, then current will flow through the coil, and the current will lag the impressed voltage by an angle determined by the resistance and the reactance of the coil. As the inductance is measured at 1000 Hz, it makes sense to use this frequency as the measurement base.

The “Quality Factor” or "Q Factor" is an easy method to determine the magnetic efficiency of a coil (at a specified frequency), and it is simply the ratio of the inductive reactance (at 1000 Hz in this case), divided by the resistance. Coils with tight magnetic circuits can have the Quality Factor well exceeding 100 in the audio range. The formula for Quality Factor is:

Quality Factor (1000 Hz) = 2 * PI * f * L / R   Where R is the winding resistance (at that frequency).

In the table below the Q Factor was derived by putting the measured inductance and resistance figures into the equation and this gave the nominal Q Factor value for each pickup coil.

Bobbin Description	Resistance (k) DC	Inductance (H)	Q Factor at 1 kHz	Cut in Freq (Hz)
Strat 01	5.87 k	2.76 H	2.99	338 Hz
Strat 02	6.48 k	2.93 H	2.92	352 Hz
Kinman Strat	6.08 k	2.96 H	3.05	327 Hz
Kinman Tele	6.89 k	3.45 H	3.15	318 Hz
White Single	6.73 k	4.44 H	4.14	241 Hz
Black Single	5.12 k	3.05 H	3.74	267 Hz
HMB-01				
Additive	8.45 k	4.59 H	3.41	293 Hz
Subtractive	8.45 k	3.72 H	2.77	361 Hz
Gr-Wh	4.33 k	2.07 H	3.00	333 Hz
Cm-Bl	4.12 k	2.08 H	3.17	315 Hz
HMB-02				
R-Shield	14.3 k	9.05 H	3.98	251 Hz
R-W	7.18 k	3.92 H	3.43	292 Hz
W-Shield	7.16 k	3.84 H	3.37	297 Hz

These figures showed up a few interesting points. In general the Q factor was in the range 3 to 4, with the White Strat having the highest Q factor – it also has the longest pole pieces, a fuller wound bobbin than the Black Strat and biggest pole spans. Strat 02 had the lowest Q factor, and it also had a two-third full bobbin compared to the Strat 01 bobbin.

Individual measurements of coils for the lateral Hum Buckers proved very interesting as the coils as entities all showed similar figures to that of single coil strat coils - as expected.

When the bucker coil was added in series the resistance added as expected, but the inductance did not dramatically change when one of the coils was reverse connected and this indicated that the mutual coupling (of the magnetic fields) between these two coils was rather low. This needs a little further investigation.

Mutual Inductance

When there is more than one coil, there is coupling between the two coils and this is mutual inductance. In the case of the side by side (or laterally constructed) HMB-02 there are 3 inductance measurements, one for each coil separately L1 and L2 and the combined one in series L(tot). These three figures align with the three inductance values in the following equation and from that, it is very easy to deduce the mutual inductance.

$L(tot) = L1 + L2 \pm 2*M$ Henries

Or $M = 0.5*(L(tot) \pm (L1 + L2))$ Henries

Substituting for the first one
$M = 0.5* (9.05 – (3.92 + 3.84))$ Henries

So $M = 0.645$ Henries

Now, the coupling factor (k) is the ratio of the mutual inductance divided by the mean inductance, and in a coil that has a high coupling factor, then k approaches 1 (unity).

The coupling factor is $k = |M|/sqrt(L1*L2) = 0.166$ this is a quite low coupling.

In this case, the coupling factor is quite low. In other words, the two coils are rather poorly coupled, and this is not surprising, as there is a big gap between the adjacent pole pieces, and the pole pieces are spread (isolated) from each other - so that the vibrating strings can be a prominent part of the magnetic circuit.
For the second coil set HMB –01

$M = 0.5*(4.59 – (2.06 + 2.08))$ Henries

$M = 0.225$ Henries

And $k = |M|/sqrt(L1*L2) = 0.109$ again very low coupling.

With one of the coils reversed we get:

$M = 0.5 * (3.72 + (2.07 + 2.08))$ Henries

M = 0.215 Henries

So k = |M|/sqrt(L1*L2) = 0.104 which is consistent with above.

Again, ideally perfect coupling is where k = 1, but this arrangement has to be loose as the strings need to be in the magnetic circuit, and it is the string's position that sets the instantaneous reluctance and that in turn sets the flux density and it is the change in flux density that causes a voltage to be induced into the windings. So mutual coupling is important if the lateral hum bucker is to have a relatively closed magnetic field.

Cut-In Frequency

Another way to look at the ratio of resistance to inductive reactance, is to locate the frequency where the inductive reactance equals the winding resistance. In the low end of the audio spectrum there will be a frequency where the pickup's inductive reactance will equal the pickup's resistance and this can be directly related from X_l = 2 Pi f L, where the value of X_l is taken as the dc resistance R.

So f = R / (2 pi L) kHz (R is in k ohms)

Actually the Cut-in Frequency is really a one figure physical description of the structure of the pickup assembly, given as a 'Frequency Value' which really has very little bearing on the actual sound or timbre qualities that the pickup will give – that is much later!

From earlier measurements we knew that:

R = A_r*n^2 ohms

L = A_l*n^2 nano henries

Substituting these physical Inductive and Resistive Factors in place of R and L without the common turns value (n) into this equation for R (Ar) and L (Al), the formula takes on a new light as:

Ar = 2 Pi f Al

or f = Ar/(2 Pi Al) kHz

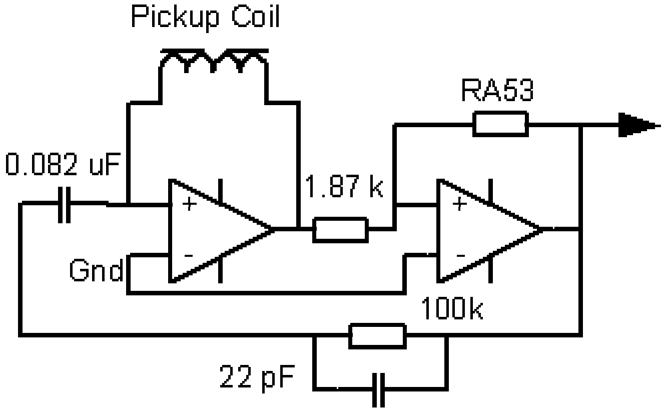
This means that virtually any pickup can be quantified by a couple of simple measurements, a little bit of maths and a look up table, and we don't need the number of turns to work things out! This does not lead anywhere particularly other than it shows that there are general physical relationships that associate with the pickup structures – and the structures are associated by their nature as a transducer for moving magnetic strings.

Resonance Tester

By using a pair of Operational Amplifiers in a positive feedback arrangement, stabilised by a thermistor, it is quite easy to place a pickup coil in as a feedback component, and the circuit will resonate at very near the resonant frequency of the pickup coil.

The 22 pF is a phase corrector that brings the error into less than 3deg at 20 kHz.

This little oscillator circuit puts out about 4 volts peak to peak, and is a nice clean sine wave! The RA53 is a thermistor that lowers its resistance as it warms up, and because the time constant is several seconds, this keeps the output voltage quite constant over a range of pickups.



Here are some figures that describe some pickups in terms of Resistance and Inductance and their resonant frequencies:

Bobbin Description	Resistance (k)	Inductance (H)	Frequency (kHz)	Cap (pF)
Strat 01	5.87 k	2.76 H	11.10 kHz	74.5 pF
Strat 02	6.48 k	2.93 H	9.90 kHz	88.2 pF
White Single	6.15 k	4.44 H	9.32 kHz	65.7 pF
Black Single	4.63 k	3.05 H	10.67 kHz	72.9 pF
Kinman Strat	6.08 k	2.96 H	9.91 kHz	87.3 pF
Kinman Tele	6.93 k	3.45 H	6.71 kHz	163.0 pF
HMB-01				
Aiding	7.69 k	4.59 H	11.63 kHz	40.7 pF
Opposing	7.69 k	3.72 H	13.80 kHz	35.7 pF
Coil 1	3.99 k	2.07 H	14.93 kHz	54.9 pF
Coil 2	3.78 k	2.08 H	14.97 kHz	54.4 pF
HMB-02				
R-Shield	12.72 k	9.05 H	6.18 kHz	73.2 pF
R-W	6.60 k	3.92 H	12.74 kHz	39.8 pF
W-Shield	6.55 k	3.84 H	6.38 kHz	162. pF

The Capacitance (C) is calculated from the resonant frequency and the self-inductance from the formula.

C = 1 /((2*PI*f)^2 *L)

C = 1000000 / (39.478 * F * F * L) C in pF L in Henries F in kHz

Do not be mislead by these results! In theory because of the extra resistance in the coils, the resonant frequency will be down by about 5% but in practice this does not matter, as there are several other issues.

What has to be realised is that the resonant frequency is the point where the distributed internal capacitance in the winding forms a parallel resonance with the distributed internal self-inductance in the winding and that from slightly below this frequency and forever above this frequency the output of the pickup is severely limited.

A parallel resonance is very high impedance and therefore the output will be weak at and above this resonant frequency. This is a very powerful concept to comprehend and it is a prime factor in determining the response of a guitar pickup.

A cursory glance over these figures shows that main coil for the HMB-01 (W-Shield) has a self-resonance of about 6 kHz while its associate coil has a resonance of about 13 kHz, which is a bit more than an octave above.

This seems wrong and the calculated self-capacitance is about 162 pF, and not in the range of about 40 pF. All the other self-capacitances are about 40 pF to 70 pF. It may have an electrostatic shield over it to shield it from electrostatic noise and that could significantly increase the apparent self-capacitance.

In and case, the load placed by a cable is highly capacitive (about 47 pF per metre) so a 10 m cable can add about 470 pF to the apparent self-capacitance and really limit the frequency response!

To further compound problems the volume control and tone controls all interact to compromise the spectral output of a pickup and this needs to be better understood.

Conclusions

All these pickup coils are of a rather similar construction and all consist of an inductive winding that has appreciable resistance – because of the thinness of the wire. ***Most of the coils have a resistance of about 4000 to 7000 ohms per coil and the inductance is about 2.7 to about 4.4 Henries per coil.***

With the Humbuck designed coils, these were added in series to the initial coil and although the resistance doubled – as expected, the inductance did not increase by the square of the total turns – even thought the magnetic circuits were coupled.

Humbuck coils are more loosely coupled than the Single Coil designs (which are also loosely coupled). This brought in the thought of loose coupling and with that a poor Quality factor (inductive reactance compared to resistance), and in most cases the Q Factor was in the order of 3 to 4, which was a far cry from coils with a much smaller and less lossy magnetic circuit having Q Factors well beyond 100 at 1 kHz.

Looking at inductive reactance another way, there will be a frequency where the inductive reactance (at 1 kHz) will equal the resistance, and this in general was about 250 to 350 Hz.

In other words, these pickup coils can really be seen as inductive energy sources and not resistive energy sources over much of the audio spectrum. This is a very significant point as it means that the load (volume control, tone control amplifier, cable etc) will have a spectral effect on the response – even if they are resistive!

As the mutual inductance was calculated to be quite low, it then followed on that the coupling factor between the two hum bucking coils was also rather low (somewhere between 0.16 and 0.20), and this may seriously impinge on the ability of this physical arrangement to be effective!

In testing the self-resonance it was then possible to calculate the effective self capacitance of the coils, and this was in general about 40 to 70 pF, with self resonances about 9 kHz to15 kHz. Although this would appear to put the problem of self-resonance outside the audio band, it has to be realised that the cable is highly capacitive, as is the tone control, and these may have serious spectral limiting effects on the overall output.

The spectral response from these types of pickups is very highly controlled by the electronic load placed on the terminals of the pickup.

Now that we have a basic understanding of the external electrical characteristics, these can be used to develop a model to approximate the spectral response of the pickups in a unified manner when being used as a signal generator!

Comments and Corrections are welcome