Practical Guitar Pickup Measurements

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Loose Coupling with Stings

In this area, this is getting into measuring and resolving what really happens.

Earlier studies in this series have shown that there is a quasi-stable magnetic field in the vicinity of an electromagnetic guitar pickup caused by the internal permanent magnet(s), and that a voltage is produced in the pickup coil that is proportional to the relative change in flux density of the magnetic field due to the string moving relative to the permanent magnet – and that sounds very Einsteinian!

In more simple English any time related change in magnetic flux density would produce a voltage in the pickup coil. How the flux density is changed is now up for brief discussion, as until now it has been only considered that string movement will change the flux density.

Louis Clerk Maxwell's[1] discovery of the transformer[2] (circa 1853) brought this to a new level where one winding on a coil assembly can induce into the other winding – and this is entirely by moving the flux density.

We already know that the electromagnetic guitar pickup is a very loosely coupled transducer, because the strings continue to vibrate in the magnetic field, and intensifying the magnetic field has virtually no effect on damping the strings vibratory motion.

The two biggest damping effects on the string are the air that gets pushed around the string while it vibrates, and other mechanical damping like fingers over frets, neck and body weaknesses - all that also suck energy from the strings vibratory motion.

If you put a relatively powerful magnet near the strings, they may be very marginally pulled towards the magnet.

The pitch is effectively not changed and the string still sustains as before. In other words, the string moves virtually freely through the magnetic field, and there is virtually no magnetic interaction to prevent the string from oscillating.

Even with a pickup very close to the strings and the leads of the pickup shorted to form a shunt, so there is appreciable current in the pickup that will in itself create am opposing magnetic field that will oppose the string movement (see Lenz' Law), then this also has virtually no effect – so it should now be obvious that the electromagnetic guitar pickup is very loosely coupled to the strings!

An oscillating string has a very high "Q Factor". Another way to measure Q is to set a body in vibrating motion and count the oscillations before it dies down.

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1 http://www.sonnetsoftware.com/bio/maxbio.pdf
2 http://en.wikipedia.org/wiki/Faraday's_law_of_induction

In the case of a steel guitar string, this time will be several seconds, and considering that the fundamental resonance is about say 500 Hz then the Q is in the order of 2500, (with or without the vicinity of the magnet and coil of the pickup)!

Measurement Tools

What is not so obvious here is that we have a pseudo linear system that produces a voltage when the magnetic field in the vicinity of the pickup is disturbed. The obvious disturbance factor is a vibrating string, and another far less obvious disturbance factor is another electromagnetic field.

This is now touching on "Field Theory" which is getting into heavy maths involving three-dimensional calculus with time varying situations. In practice using a reference field in the vicinity of a pickup will produce results that are highly repeatable – far more repeatable than using a plucked string.

Single Coil Pickups

The first consideration is to use a single coil pickup as a receiving reference. The reasoning behind this is that they are simple in design and should have repeatable results. (Well that is the thought – anyway!)

Reference Field

Making a practical reference field is much harder to conceive than to construct, or is that the other way around! What was needed was a 'one sided' magnetic field so that when it is energised by an oscillator/amplifier, it produces an oscillating magnetic field that emulates a similar effect to that of having a steel string vibrating near an electromagnetic pickup.

In this case, the answer came in part of a power transformer, where the secondary winding was used and the "E" laminations formed a one-sided doublet magnetic field. (All magnetic fields are loops – so you can't have an isolated magnetic pole – which would be ideal.) This is the next best thing - for these measurements.

Practical Bench Setup

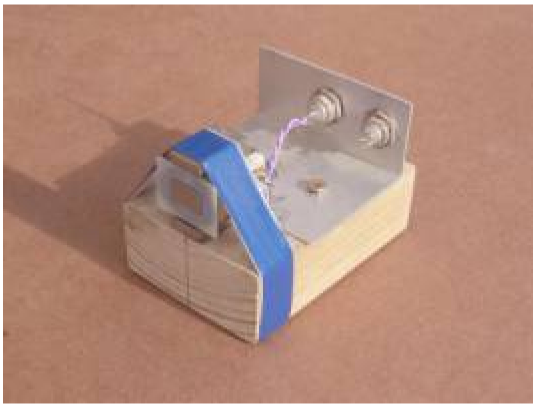
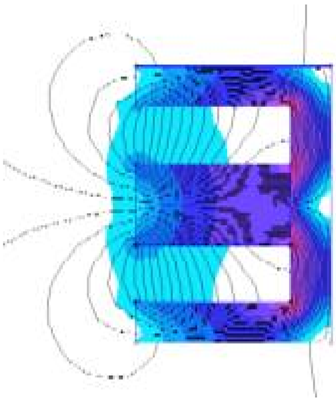
For consistency sake it was necessary to avoid all metallic objects where possible and rely on wood mounts. By mounting the pickups on wood blocks based on 75 x 35 mm building studs, it was relatively easy to position both the pickup and the exciter reference field and perform highly repeatable measurements – and these measurements told a wide range of stories that you will find fascinating!

Practical Reference Field

The purpose here is to establish a reference field that can be used in several experiments and the results can be tied to each other – and practice. The E Core chosen is from a 240 V 50 Hz 7 VA transformer made entirely of two sets of identical E laminations, touch welded on the outer edge extremities to make a closed magnetic circuit. The dimensions are:

Magnetic		Bobbin	
Height	35.2 mm	Outer Centre	22.3 mm
Depth	24.5 mm	Width	16.7 mm
Centre Leg	9.65 mm	Over Centre	11.35 mm
Outer Leg	5.00 mm		
Back	5.00 mm	Outer Stack	30.40 mm
Stack	15.0 mm	Over Stack	16.45 mm

Nominally 30 laminations, each 0.5 mm thick make up the permeable magnetic path.

Here is the unit mounted on a 70 mm by 35 mm by 100 mm long block of wood. The centre of the E laminations is about 50 mm from the base, and with pickups mounted on similar wooden blocks, their centres are also nominally 50 mm up from the base – so the reference field virtually aligns with the centre of all pickups.

This structure was chosen very carefully, as the standard length if the mounting blocks is 100 mm so mounting a pickup in the edge plane of one of these neatly positions the centre of the pickup at 50 mm from the base (the same as the centre of the exciter coil).

Horizontally, if a pickup is positioned on a second mounting block (nominally 35 mm) then the ‘x’ plane axis sits at 52.5 mm which aligns to about 2.5 mm of the centre of the exciter coil.

The ‘E’ core fixed with a couple of turns of electrical tape is a very firm arrangement and it makes measurements quite easy – and replicable.

The picture on the right hand side is an approximation of the field seen around and through the ‘centre lamination’. From in front, this field looks like two little hemispheres with their flat sides stuck to the front faces of the laminations over the ‘E’ laminations face.

This winding on this coil is a secondary coil that is bifilar (pair) wound and series connected as a 9 V + 9 V winding. As this winding is highly inductive, and we know that it was used in a closed core to deliver 18 V ac at 50 Hz, then this core is not going to saturate. This coil has an inductance of about 4.8 mH at 1000 Hz.

This coil produces a doublet magnetic field that has two vertically associated ‘bumps’ in it. It is important to understand this field, as it is not equal on all axes – no magnetic field is!

This little exciter coil is very useful for producing a fluctuating magnetic field and this field can be used for a very wide range of well controlled laboratory/garage related tests.

The only problem with this unit is that when tested against fields that are 90 deg to it, this doublet can cancel out with each half and give misleading results, and a classical case is when testing a lateral (side-by-side) Hum Bucker coil.

To get around this problem a second unit was made like a tuning fork out of a strip of 20 mm * 5 mm iron bar, formed into a 100 mm * 120 mm angle bracket with the longer arm sunk into a wood mount, a ferrite magnet glued to the shorter arm and another exciter coil positioned to make the shorter arm vibrate. This has a natural resonance at about 210 Hz, and the amplitude can be finely adjusted by the using amplifier volume control. The 100 mm arm vibrates like an iron string, and the pickup reacts with it – just as though it was a string!

With both of these coils the 'x' axis is parallel to the surface of the laminations and passes along the centre of the laminations, and cuts evenly through the coil. The 'y' axis is normal to the laminations and passes through the centre of the centre leg, and cuts through the coil.

The 'z' is parallel to the surface of the laminations, passes through the centre of the centre leg and is the rotational centre of the coil. These axis were chosen on purpose as the 'x' and 'y' axis coordinates are 90 deg shifted from the guitar pickup structure.

Mini-Tutorial on dB and all that Stuff!

In days of old when all telephone lines were constructed with telephone poles and aerial wires, the nominal impedance was 600 ohms + 2 uF in series.

To all intents and purposes, over the voice frequency band (300 Hz to 3400 Hz) this impedance is roughly resistive, and the reference power level was 1 mW (milliwatt), which is 1/1000 watt, and this is a real power as the load that it is measured into is virtually resistive!

Apart from our ears working logarithmically for both level (loudness) and pitch (frequency), it is very difficult and somewhat meaningless to work in absolute power levels in this technology, especially when in most cases the power levels are compared with each other as a ratio.

To greatly simplify matters the decibel (1/10 of a bel), after Alexander Graham Bell, was created as the standard unit of logarithmic ratio. This has the formula:

Ratio in dB = 10 log (Power 1 / Power 2)

In terms of a constant voltage and load resistance, power is directly related to the voltage squared as follows:

Power (watts) = (E^2) / R

By referring to two voltages E1 and E2 as voltages read across resistance values that are common in both conditions (for example they are both 600 ohms), and substituting this back into the dB equation, the equation becomes:

Ratio in dB = 10 log ((E1^2)/R / (E2^2)/R)

Now because the resistances are common (the same), this then simplifies back to:
Ratio in dB = 20 log (E1 / E2)
So now all we have to do is read two voltages with a high impedance voltmeter and drop these values directly into this rather simple equation and we have the ratio of the two powers in terms of dB.

So we have a linear perception of the differences in relative power levels in logarithmic terms! Remember - our ears work logarithmically.

As the reference power level used in telephony is 1 mW, and the standard (characteristic) impedance of most aerial wire on telephone poles is nominally 600 ohms, then the reference voltage is 774.6 mV rms (0.7746 volts rms).

If this voltage value was deliberately put into the dB equation as E2, then only one voltage measurement would be enough to give a dB value, but this value is then referred (or referenced) to 1 mW, and the reading would be a relative power level with the notation dBm, where the ‘m’ signifies being referenced to a milliwatt!

This is a major leap and it needs to be thoroughly understood. If the above paragraph is not clearly understood then it is worth reading and considering again till it becomes crystal clear. Communications Level meters are calibrated in dBm, making dB measurements all too easy!

With the technology change to twisted pairs in cables, the voice-band impedance is usually a highly capacitive value that is highly dependent on frequency and this is called ‘complex impedance’.

Real power relates to power measured in a resistive load, but in this case the power is a mix of real and imaginary (out of phase returned) power due to the non-resistive nature of the cable impedance.

As the voltage is still be measured by a high impedance meter, the reference voltage is still the equivalent voltage that produced 1 mW in 600 ohms, and that is 774.6 mV rms. This apparent power level is referred to in terms of dBu and other signal levels can be readily measured in dBu with reference to the 774.6 mV rms and this is 0 dBu.

In another branch of electronics, scientists used 1 volt as the reference level and then used the dBV where the reference is 1 V rms = 0 dBV. Again in some communications (Cable TV) the reference level is 1 mV, so the reference level is 1 mV = 0 dBmV. There should be a pattern forming here!

Acoustic levels are measured in dB with reference to sound pressure level (SPL) and in this case the reference is $2 * 10^{-5}$ newton/metre^2, which is the threshold of audibility (very faint).

The standard nomenclature for acoustic sound is dBA, where the ‘A’ means acoustic, referred to the reference SPL. Acoustic levels are bandwidth related and (unfortunately) the human perception of acoustic level is also somewhat bandwidth related for faint and/or background noise.

This maths gets very complex very quickly, and very few people get it right!

To compound the acoustic issue much further, there are three very different acoustic 'Equalisation Curves' that correspond to human hearing and Fletcher and Munson worked these out[3] in the 1930s. The easy curve to comprehend is the Threshold of Pain curve (which is virtually flat) and this is called the 'C' curve.

The other main curve is the Threshold of Hearing (which has the low audio frequency response attenuated by about 60 dB compared to the centre frequencies, and the upper frequencies attenuated by about 20 compared to the centre of the audio spectrum) and is called the 'A' curve, and the 'B' curve sits halfway between.

Most people who are doing loud acoustic measurements, get an acoustic meter and set it to the A curve, thinking they have the dBA for Acoustic, not the 'A' weighting; then they incorrectly use this weighted scale to measure sound levels at the Threshold of Pain, and get readings lower what they really should be, as the meter should be on the dBC weighting curve for these Threshold of Pain measurements.

Once you have used measurements using dB for a few days, you will never go back!

By the way, the University of New South Wales put out a very easy to read Web Page on dB and Sound Pressure Level[4] and it is worth reading.

Reference Send Level

To energise the magnetic field, the energiser coil is fed from a very low impedance amplifier set to produce 0 dBV (that is with reference to 1 V rms, where the difference in volts is 0 dB). In terms of a telecomms level this would be +2.22 dBu.

The reference frequency is about 400 Hz, but we already know that at this frequency the system will have a virtually level frequency response with a high impedance load from the pickup.

Reference Pickup

To prove the response of the transmitting exciter coil, another identical 18 V core was used as the receiver. Butted up to the exciter the output level was 0.0 dBV, and the response was virtually flat (+/- 0.2 dB) up to 20 kHz.

With the coil assemblies separated by about 10 mm the level was about –20 dBV and the frequency response remained virtually flat to 20 kHz – so we know that the exciter coil is virtually flat up to 20 kHz too!

In this case the primary winding of the power transformer with its ‘E’ core around it makes an ideal reference pickup. We know that the voltage ratio is 240V: 9V + 9V = 13.3333, and this relates as 22.5 dB if the coupling is virtually perfect – as in a transformer. With the core faces spaced by say 100 mm, the coupling will be much less, and the frequency response of the 240 V winding was tested as a measure with the following interesting results:

Frequency (kHz)	Level (dBV)
0.2 kHz	+0.0 dBV
0.4 kHz	+0.0 dBV
0.8 kHz	+0.6 dBV
1.0 kHz	+0.6 dBV
2.0 kHz	+0.9 dBV
4.0 kHz	+1.9 dBV

Spacing (mm)	Level (dBV)
10 mm	+6.5 dBV
15 mm	+2.3 dBV
20 mm	-2.3 dBV
25 mm	-6.5 dBV
30 mm	-9.0 dBV
35 mm	-12.3 dBV

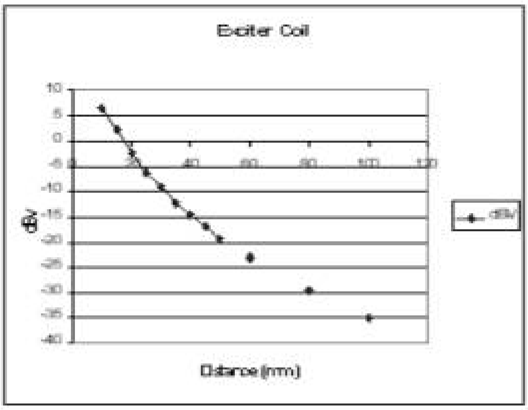
3 http://www.webervst.com/fm.htm
4 http://www.phys.unsw.edu.au/jw/dB.html

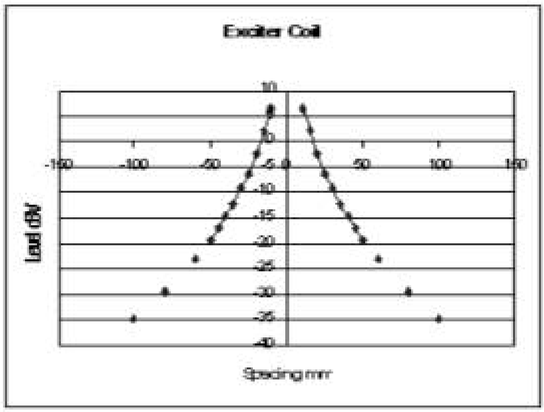
8.0 kHz	+6.9 dBV
9.0 kHz	+9.3 dBV
10.0 kHz	+12.7 dBV
11.5 kHz	+14.5 dBV
15.0 kHz	+2.9 dBV

40 mm	-14.5 dBV
45 mm	-16.9 dBV
50 mm	-19.2 dBV
60 mm	-23.1 dBV
80 mm	-29.6 dBV
100 mm	-34.9 dBV

Although the windings with low turns had a very high self resonance and resulted in a virtually flat response from the exciter coil, the 240 V coil with high turns has a self resonance of about 11.5 kHz (much like many guitar pickups), but because the winding resistance was much lower than for standard guitar pickups, there was a very noticeable 14.5 dB peak in the response. (This is not going to be used as a pickup – but it shows what can happen with self-resonances!)

Using 400 Hz as a test frequency and changing the spacing between the two “E” core sections, the above right-hand table showed that the transferred power drops away with distance. In a table this does not look all that obvious, but when put into a graph an interesting picture forms as follows:





By applying ‘x’ axis symmetry on the left hand side graph, it turns out as the right hand side graph and looks similar to a ‘normal’ or Gaussian curve. This structure will be extensively used from this point.

Comments and Corrections are welcome