How Electric Guitar Pickups Work

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The Four Components

There are basically four components in the structure of the magnetic pickup and these four all work together to cause the transduction from movement into voltage for amplification.

The Permanent Magnet

The first and not so obvious component is the permanent magnet. A permanent magnet is an object that holds (retains) its energy charge as a magnetic field and this field is concentrated through the magnet forming two 'poles' of concentration usually termed North (pole seeking) and South (pole seeking).

The permanent magnet has a magnetic circuit that forms a complete loop with itself, and this field extends beyond one pole of the magnet, through the air (in this case), strings, through the plastic and through the body of the guitar and then back to the other pole in the magnet.

The ability for any object to carry a magnetic field through itself is called 'permeability' and permeability is measured in relation to a vacuum.

For iron the relative permeability varies considerably with magnetic field intensity but the relative permeability is in the order of 200 to 1000 times that in air, vacuum, wood, or plastic. Some special magnetic alloys such as Mumetal have much higher relative permeabilities in the order of 20,000 to 40,000.

The Magnetic Circuit

Just like an electrical circuit where there is Resistance to limit the Current flow due to Electrical Potential Difference, in a magnetic circuit there is Reluctance to limit the Flux flow due to Magnetic Potential Difference.

Unlike electrical circuits where the current density can be sharply defined with conductors and non-conductors (insulated wires), ***magnetic circuits are very leaky making analysis far more difficult***.

In electrical circuits, wires have well defined current densities as the cross sectional areas of wires are tightly defined, but in magnetic circuits, Flux Densities (or field strength) are highly dependent on the position of the measurement and the shape of the magnetic field.

This magnetic field is the unseen second component in a pickup and this field can extend for several metres before becoming unnoticeable.

The Pickup Coil Winding

The third component in a pickup is the coil winding and this coil is engineered to sit around the magnet so that it captures changes in the flux density of the magnetic field.

These coils follow both electrical and magnetic laws in that the resistance of the coils is entirely calculable through length measurements and the resistivity of copper. In the other hand, inductance measurements are somewhat from first principles, but including a very leaky magnetic structure makes associating these calculations to reality rather difficult.

Moreover it is equally important to position the coil so that it surrounds the highest magnetic flux density, as the voltage generated from the pickup comes from variations in the flux density caused by the relative changing position of the strings to the magnetic structure.

I have no doubt that there has been an inordinate amount of work done on coils, and to most people that have done this work it seems to be a black art – that is, the reasons for change have not been accurately quantified – so it is largely guess work!

The (Magnetic) Strings

The fourth area is the strings themselves – be they iron or nickel, or other magnetic alloys. The strings actually form part of the magnetic circuit and the magnetic flux actually passes through the strings. I believe that this phenomenon is very poorly understood for several reasons – mostly aesthetic.

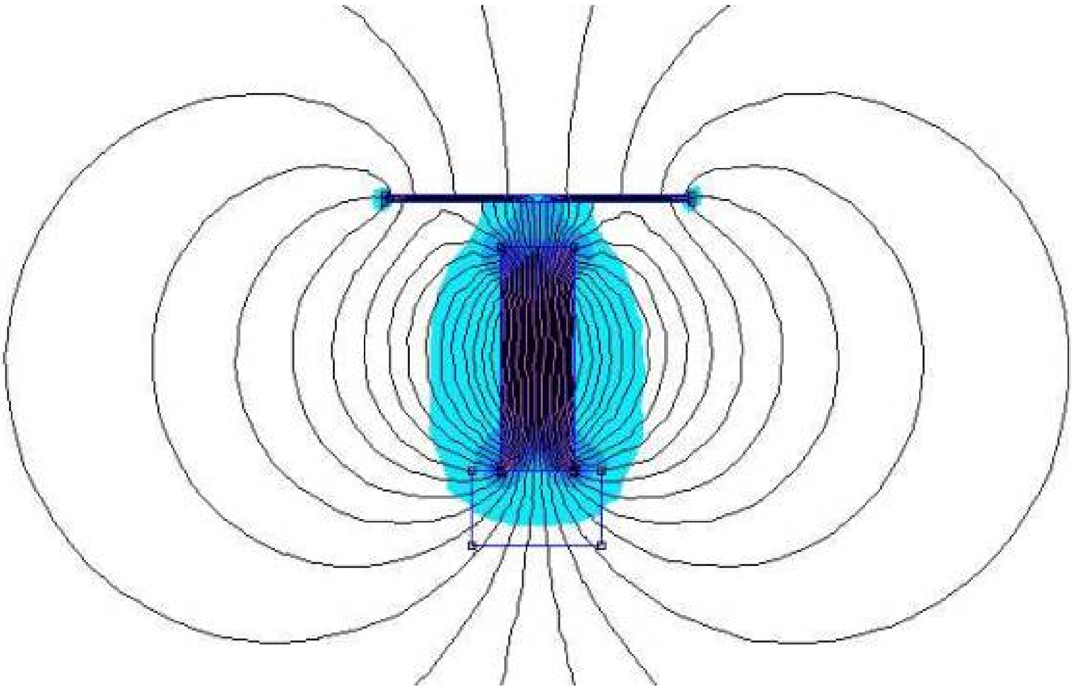
While it is obvious that the pickup must not be on both sides of a string – as it would interfere with playing the guitar – the size of most pickups magnetic coupling to the strings is at best miniscule with tiny rod magnets in many cases as the near point for the magnetic loop, and it is no wonder that many pickups are highly susceptible to external electromagnetic interference!

What Really Happens

The above is a picture of an electric guitar (lefty) looking across the string plane (x) across the screen, and (y) from near to far - the brick wall!

The (z) axis extends from the floor to the sky through the body of the guitar. Keep these Cartesian (x, y, z) coordinates in mind as they are used extensively throughout these documents. In doing this research work I re-discovered Polar coordinates (Radius, angle, angle, angle) and these are of immense value, and I have swapped around as necessary, but remember, this research is more applied (practical) than theoretical, making it fairly easy reading - because pictures tell more than words and pictures tell much faster.

We are now going to move from reality into the world of approximation with the use of several tools, and to get a little taste of it the picture below represents what could be seen if you could visualise the magnetic field looking end-on to one of the pickups! (Just like the picture above where we are looking end-on to the pickups.)



The above picture is a **Finite Element Modelling (FEM)** representation of one of the pickups in the guitar above and the magnetic lines of force and field strength given in a two dimensional picture (‘y’ – along the string axis (left to right), ‘z’ vertically through the pickup (bottom to top) of a magnetic guitar string in the vicinity of a small bar magnet.

A magnet in this case is sitting vertically at the bottom with the string positioned horizontally across the top. It is usual that the pickup coil sits over the middle of the magnet.

Note in this case the string is not shown in its entire length, merely about 60 mm to get a good enough approximation of what is going on.

Because the string has a rather small cross section and is in the vicinity of the magnetic field, this magnetic field is concentrated in the string so internally, the string itself is fairly highly magnetised.

The FEM picture above assumes that the two dimensional slice is right in the middle of the pickup.

The next level of understanding is that the string is in an almost constant magnetic field and moving the strings' position relative to the magnet only minutely alters the high and consistent concentration of magnetising flux in that string, so the magnetic flux in the string does not move all the way along the B-H (magnetic) curve for that magnetic string, but simply hovers in a strongly biased position in sympathy with that part of the string moving in the magnets' field.

The magnetic field around the pickup is concentrated through the winding by the pole pieces, and as the total strength of the magnetic field is changed in time - relative to the previous total field strength, it will cause a voltage to be generated in the coil.

When the steel string vibrates, it causes the magnetic field to fluctuate in strength - relative to the position of the string and the magnetic field, and an oscillatory voltage signal is generated from the changing magnetic field. That’s how it works, but it is not that simple! This is a very loosely coupled magnetic circuit, and there are a lot of stray fields that are highly susceptible to interference - which will come out as hum or buzz!

Assume that the string moves in a sinusoidal fashion – towards and from the magnetic field. When the string reaches its maximum and minimum positions, it is temporarily still – just like being on a child's swing.

At those instances, there is no changing in the magnetic field intensity – because the string is temporarily still – so there is no induced voltage from the pickup coil at that instant.

When the string <u>is moving</u> through its rest or zero position, the string is moving at maximum velocity (again just like on a swing) and at these points, the <u>magnetic field is going through maximum change</u> with time and this produces <u>maximum voltages in the pickup coil</u> – either positive or negative – depending on the direction of the string movement relative to the magnetic field, the polarity of the magnet, and which way the coil winding is connected. ***If the string moves in a sinusoidal fashion parallel to the pickup face, then the magnetic field will not be varied - and no voltage will be produced!***

So the instantaneous voltage produced is related to the <u>rate of change of the string position</u> relative to the magnetic field strength, and not the instantaneous position of the string. Most people find this a tough bullet to swallow! And it takes time!

The voltage produced is not proportional to the relative position of the string near the magnet, but the rate of change in position of the string relative to the magnetic field. It is worth reading these two paragraphs several times until this concept is clearly understood.

Spectrum Requirements

The spectrum needs are wide. When we listen we perceive frequency as fundamentals and harmonics (logarithmically related), and the second harmonic is twice the frequency of the fundamental – and it sounds ‘smooth’, as does the fourth harmonic, sixth harmonic and the eighth harmonic etc. Conversely, a fundamental with the third harmonic (three times the fundamental) sounds very harsh, as does the fifth harmonic, seventh harmonic etc. with the fundamental.

The lower open E string has a fundamental of about 128 Hz, and significant harmonics are the second, fourth, sixth and eighth meaning the spectrum here extends to 1024 Hz. On the twelfth fret on the upper E string the fundamental is about 1,024 Hz, and the spectrum extends to about 8.192 kHz.

On the 21st fret the fundamental at C#’’ is about 1,722 Hz, and the spectrum extends to almost 14 kHz! The transduced (string movement to electrical) frequency response needs to be virtually flat from less than 100 Hz to greater than 14 kHz to faithfully reproduce the vibrations from the guitar strings - before anybody starts to play with the audio spectrum, develop distortion, or introduce echo and / or reverberation.

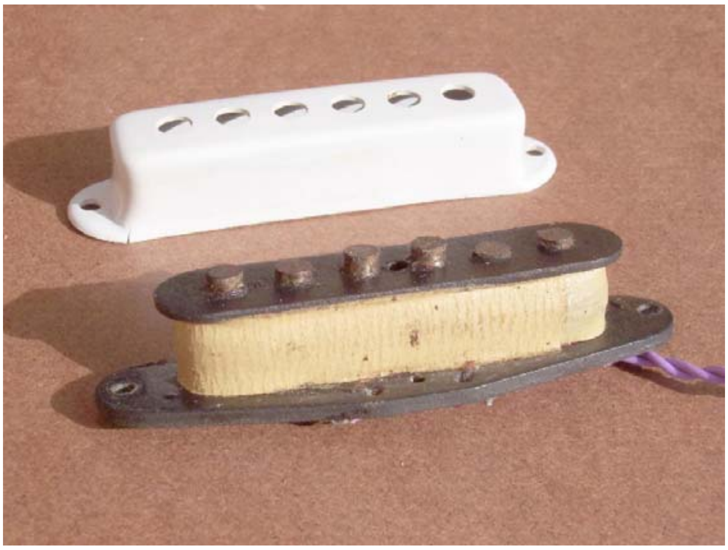
A Few Good Pickups

Getting started on this journey was not that easy as it took some years to better understand coils, magnetics, and decoding sales talk from reality! Having had a few pickups for several years, I decided to get some more pickups and then start measuring against known references and surely something would come out of the figures that would have some correlation.

But first the pickups. To simplify the documentation procedure, each pickup has been given a name and a very brief description so that with later document recording, the chance of assigning incorrect data is minimised. (The names that are chosen may be incorrect – but they are just names to correlate data in later documents.)

Strat 01

This is a single coil design with 6 Alnico 5 bar magnets of differing lengths.

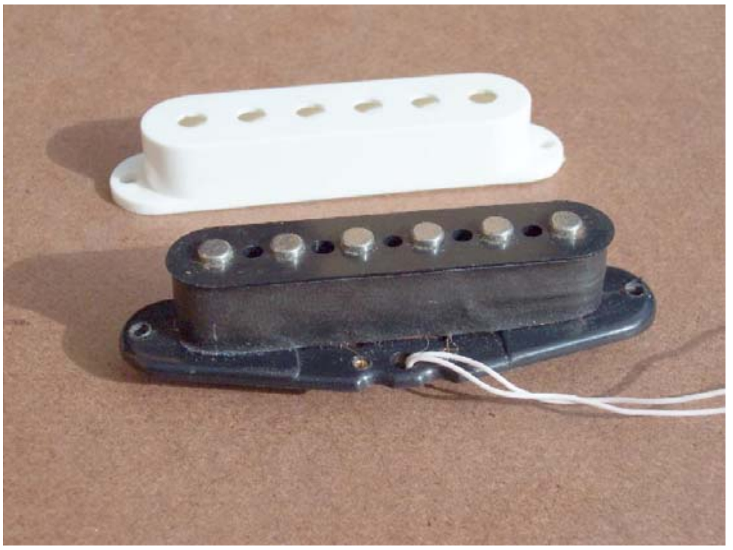


Strat 02

This is also a single coil design with 6 Alnico 5 bar magnets of differing lengths.

White Strat

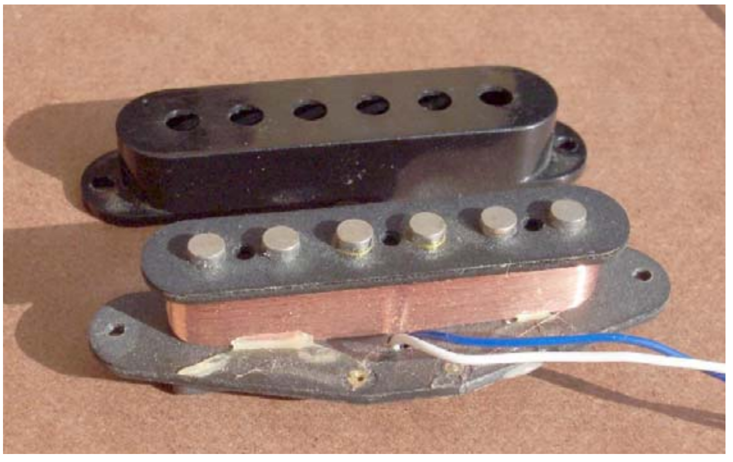
This is a single coil design with 6 common length soft iron rods as pole pieces and a common Ferrite magnet underneath.



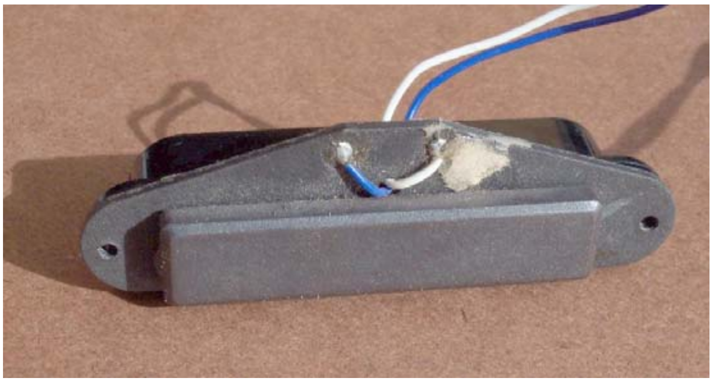
This is the underside showing the flat ferrite / ceramic bar magnet. The poles of this flat bar magnet are on the large faces (opposite each other).

Black Strat

Single coil design with 6 common length soft iron rods as pole pieces and a common Ferrite magnet underneath.

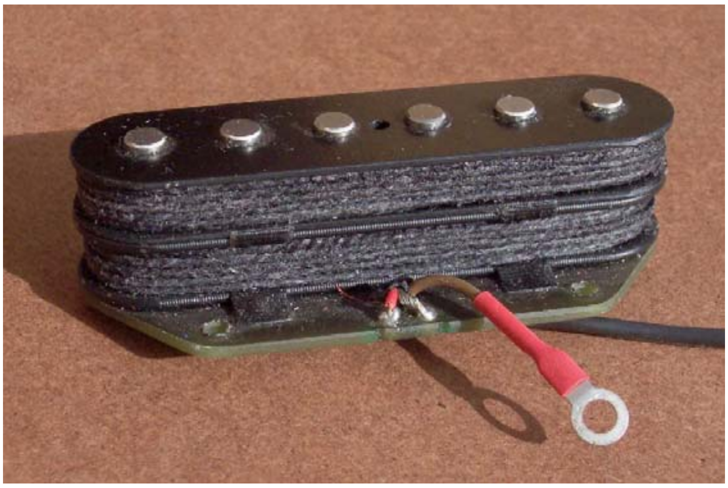


This is the underside showing the flat ferrite / ceramic bar magnet. The poles of this flat bar magnet are on the large faces (opposite each other).



Kinman Tele

Vertical Hum Bucker coils – with what 'appears' like 6 Alnico 5 pole pieces.



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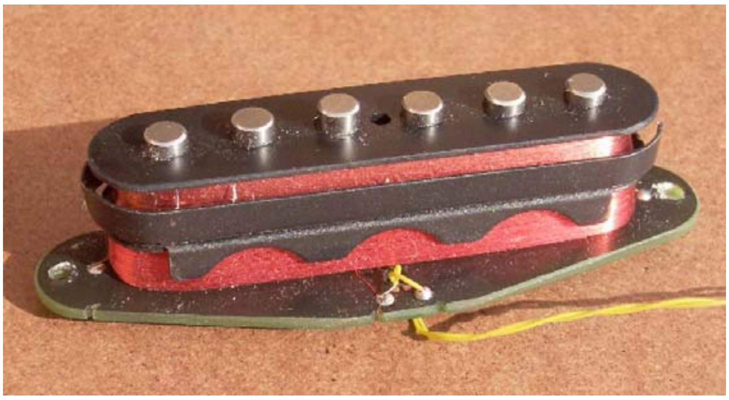
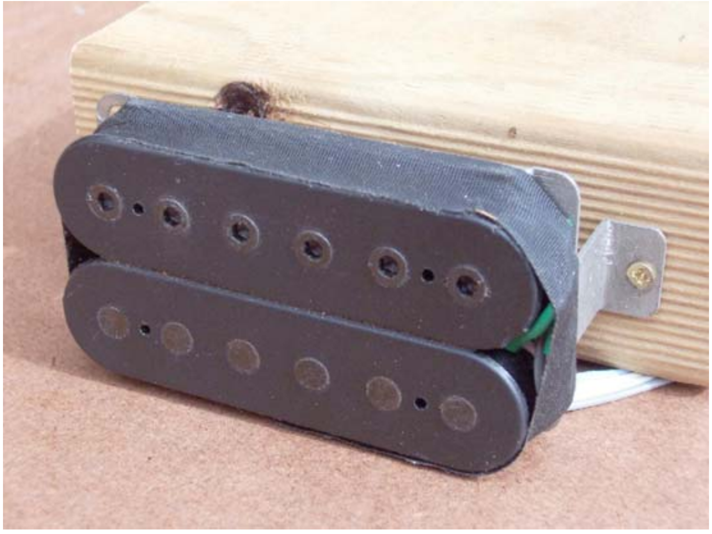


Hum Bucker 01

Horizontal Hum Bucker coils with 6 Alnico 5 rod magnets in the main coil and 6 soft iron (Allen Key) rod pole pieces in the "bucker" coil.

A soft iron plate about 2.5 mm thick magnetically joins the coil assemblies.



Hum Bucker 02

Horizontal Hum Bucker coils with 6 Alnico 5 rod magnets in the main coil and 6 soft iron (Chrome Plated Raised Head) metal thread screws as rod pole pieces in the "bucker" coil.

A soft iron plate about 2.5 mm thick magnetically joins the coil assemblies.

Now that we have a few good pickups – let the testing and analysis begin!

Comments and Corrections are welcome