

## Approximating the Electric Guitar Pickup

Malcolm Moore  
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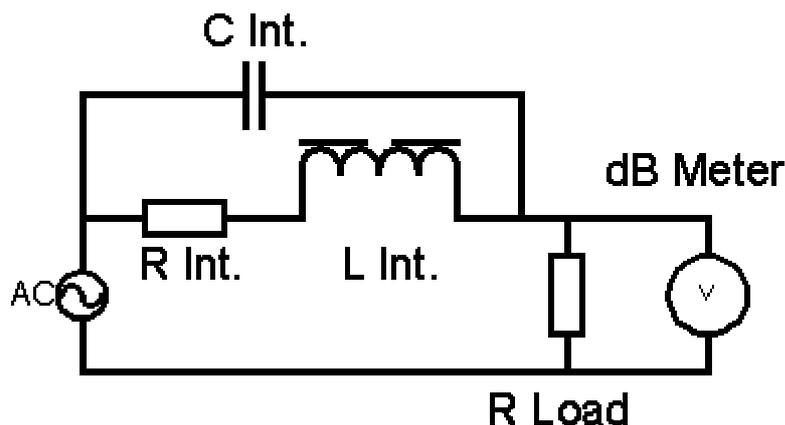
(Jan 2003, Sept 2007)

### **Thevenin's Equivalent**

Having measured the distributed coil resistance and treated it as a lumped resistor, and then measured the distributed inductance and assumed that as a lumped inductor, and calculated the intrinsic self-capacitance, a somewhat clear picture is beginning to evolve about the electronic structure of the pickup in simple lumped parameters.

One way of looking at this is that the single coil pickup is essentially a zero impedance voltage generator with a series resistor and series inductor as seen from the soldering terminals.

In Circuit Theory language this is called a "Thevenin's Equivalent Circuit", and this equivalent makes it relatively easy to approximate the circuit of a single coil pickup in lumped parameters, and use this to estimate time responses and frequency responses through performing some basic circuit theory.



If we need to go a little deeper than we can always include the apparent self-capacitance, which could appear as if it is across the terminals of the lumped parameter approximation of the pickup.

Unfortunately the self-capacitance is not that simple, as it is distributed through the coil and not as a simple lumped parameter. Some of the capacitance is between the windings and some of the remaining capacitance is between the windings and the frame, pole pieces and other components surrounding the coil itself.

It is probably easier to neglect the self-capacitance component for the meanwhile and get to better understand more about the simplified Thevenin's Equivalent circuit.

Just to clarify a little, the circle on the left hand side with the sinusoidal wave in it is representative of a variable frequency sine wave generator or a "zero impedance voltage generator" and this is a theoretical tool as the voltage source. In this case we do not need to "pluck the string" and have it sustain for infinity time. We merely use maths to simulate whatever signal we want to analyse.

The pickup coil consists of two distributed components that are rather easy to measure with a fairly good degree of accuracy (about +/- 1%) and these are the internal resistance (R Int.) and the internal Inductance (L Int.), and these can be shown as lumped components in the Thevenin Equivalent circuit above. Some other tests showed that the coil has a self-resonance, and this happens because of distributed capacitance - shown as a lumped capacitor across the whole pickup.

For musical purists this approach could be seen as severe sacrilege but for all cases of practicality, this little circuit can work wonders, as it is the stepping-stone to realising the next step in unearthing the 'hidden mysteries' of the guitar pickup! As it is, the guitar pickup is connected where the two dots are and the symbol of the circle with the arrow is representative of a meter (with an infinitely high input impedance), and the component marker R Load is the load applied - in the first case a resistor.

In later tests, R Load will be replaced with Z Load, where the load is not simply resistive but also capacitive and there are several possibilities from there too - because this series inductance with a shunt resistor is the start of what is called a passive "Ladder" network - and the R Load could be the start of a repeating "L-C" Ladder.

This all looks fairly simple on paper but in practice some other work has to be done to make it 'work'. Firstly most frequency generators do not have a zero output impedance, so a good amplifier is needed here - not necessarily a power amplifier, but one that can put out a few volts and keep a low impedance, and have a very flat frequency response over the audio band, and many Transistor-based Hi-Fi Amplifiers eloquently fit this bill.

The "Load" side needs a special buffer amplifier in front of the level meter - even though the level meter has an impedance of 1 M ohm // 30 pF, this is far too low and the lead capacitance is another problem to be removed. In this case a Field Effect Transistor (FET) Operational Amplifier with a 'bootstrapped' biasing arrangement has an input impedance of about 50 M ohms and virtually no shunt capacitance as the leads are very short (about 20 mm) and spaced out. It's these little things that get highly repeatable results!

### ***The Pickup Load***

This is probably one of the most important parts in this whole report.

In theory, if we have a load that is infinity in value, then there will be no current flow from the zero impedance voltage source, and the voltage that is produced by the generator will appear at the terminals. This is an extremely important concept, and it directly implies that if in practice we have a near infinity load (for example a 50 M ohm load), then the frequency response shall be flat – irrespective which single coil pickup is tested!

In practice, a zero impedance generator in these circumstances really refers to a low impedance generator (less than say 50 ohms), and the pickup can then be connected in series with the active leg of the generator/amplifier to the load. This concept may appear to be quaint, but this concept works!

If in practice the frequency response is not flat, then the intrinsic shunt capacitance is playing an effect and causing the response to roll off. Again if the frequency response is plotted, then it should be possible to closely approximate this frequency

response with lumped components utilising circuit theory techniques. This subject is touching on theoretical electrical (analogue electronic) engineering.

Another variation is to use a defined load resistor as the load, and measure (and calculate) the frequency response of the pickup. For example if a 100 k ohm load resistor is used, then with a direct current situation, the resistance in the pickup will cause a loss in output level and this can be readily calculated as one comparative measure.

As the frequency is increased, the output level will drop a further 3 dB and this is where the total resistance equals the inductive reactance of the pickup. The response will then fall away at a nominal rate of 6.02 db per octave (20 dB per decade), as this is a second order low pass filter. At a higher point, the response will null out and this is where the internal capacitance causes a resonance with the inductive reactance of the pickup.

(Do not take much notice of this resonance effect, as this is seriously compromised in practice.)

That was a fairly heavy couple of paragraphs, and they need some backing up – so here:

This is table of some pickups, with a few theoretical values calculated to show the basic circuit theory side of pickup circuit analysis – using a 100 k ohm load resistor.

<b>Bobbin Description</b>	<b>Resistance (k) HP 100 Hz</b>	<b>Resistance (k) DC</b>	<b>Inductance (H)</b>	<b>Intrinsic loss (dB)</b>	<b>Upper 3 dB freq limit (kHz)</b>
Strat 01	6.09	5.87 k	2.76 H	0.49 dB	6.1 kHz
Strat 02	6.67	6.48 k	2.93 H	0.53 dB	5.8 kHz
White Single	7.49	6.73 k	4.44 H	0.57 dB	3.8 kHz
Black Single	5.44	5.12 k	3.05 H	0.43 dB	5.5 kHz
Kinman Strat		6.08 k	2.96 H	0.51 dB	5.7 kHz
Kinman Tele		6.88 k	3.45 H	0.58 dB	4.9 kHz
HMB-01					
R-Shield	15.48	14.3 k	9.05 H	1.20 dB	2.0 kHz
R-W	7.42	7.18 k	3.92 H		
W-Shield	7.31	7.16 k	3.84 H	0.60 dB	4.4 kHz
HMB-02					
Additive	8.72	8.45 k	4.59 H	0.70 dB	3.8 kHz
Subtractive	8.35	8.45 k	3.72 H		
Gr-Wh	4.30	4.33 k	2.07 H		
Cm-BI	4.13	4.12 k	2.08 H	0.35 dB	8.0 kHz

So with 100 k ohms all these pickups under test lose about 0.5, dB which would be totally unnoticeable, but the cut-off frequencies vary from about 4 kHz to about 8 kHz – which is about an octave.

If there were no other colouration in the frequency spectrum this might be noticeable by those with the lower cut off (the HMB-01 and HMB-02) having a spectral tone that is less 'clear' or sound more muffled than the others.

*(Note that the HMB-01 W-Shield is using only one coil and to all intents and purposes this is acting like a single coil pickup. The HMB-02 using the Cm-BI winding is also*

*acting as if it was a single coil pickup! The intrinsic loss and upper 3 dB frequency figures reflect this relationship.)*

By bringing the load resistance down to 10 k ohms instead of 100 k ohms we get another story:

<b>Bobbin Description</b>	<b>Resistance (k) HP 100 Hz</b>	<b>Resistance (k) DC</b>	<b>Inductance (H)</b>	<b>Intrinsic loss (dB)</b>	<b>Upper 3 dB freq limit (kHz)</b>
Strat 01	6.09	5.87	2.76	4.0 dB	0.911 kHz
Strat 02	6.67	6.48	2.93	4.2 dB	0.885 kHz
White Single	7.49	6.733	4.44	4.5 dB	0.599 kHz
Black Single	5.44	5.123	3.05	3.6 dB	0.789 kHz
Kinman Strat		6.08	2.96	4.1 dB	0.864 kHz
Kinman Tele		6.88	3.45	4.5 dB	0.779 kHz
HMB-01					
R-Shield	15.48	14.3	9.05	7.7 dB	0.427 kHz
R-W	7.42	7.18	3.92		
W-Shield	7.31	7.16	3.84	4.7 dB	0.712 kHz
HMB-02					
Additive	8.72	8.45	4.59	5.3 dB	0.640 kHz
Subtractive	8.35	8.45	3.72		
Gr-Wh	4.30	4.33	2.07		
Cm-BI	4.13	4.12	2.08	3.0 dB	1.080 kHz

So lowering the load resistor to 10 k ohms from 100 k ohms appreciably drops the output level and really cuts the frequency spectrum – in theory. By all accounts here the output level drops by at least 3 dB (as shown by "Intrinsic Loss (dB)" and for double coils as used in the hum buckers as the coils are in series in this case, the loss is typically 6 dB and this would be quite noticeable.

Looking at the upper 3 dB cut off point reveals some very interesting data. In this case the nominal 3 db point is about 800 Hz and the hum buckers (in the two coils connected in series mode) have a 3 dB point of about 400 Hz - which is an octave below. With middle A about 440 Hz, it should be obvious that with this load the frequency response will be quite muffled, and with hum buckers (in series mode) the frequency response will be very muffled.

Looking at the hum bucker coils – these pickups in general have a higher self inductance and a larger internal resistance, so they are a couple of dB quieter, and in general have a lower cut-off frequency. The results derived from theory tells us why this type of hum-bucker pickup coil should be both quieter, and had a lower cut-off frequency. *(Note again, the HMB-01 and HMB-02 when using a single coil; these have all the electronic appearance of single coil pickups!)*

Putting this in 'guitar speak', this means that in general Strat pickups have a higher cut-off frequency and therefore should produce a 'sharper' or 'clearer' sound, and the hum-bucker pickups (using both coils in series) should have a lower cut-off frequency and therefore produce a more 'muffled' or 'muddy' sound than a Strat. (The sibilances say it all!) But using one coil of the hum-bucker appears to produce a near identical spectrum and level to that of a Strat style pickup.

So now we have the basic theory to explain why some guitarists prefer a pair of hum-buckers with a switch to remove the buck coil, and that way they get the Strat sound

and the hum-buck sound. Purists would be very upset to see this because these figures allude to the fact that changing the load resistance changes the frequency response of the pickup.

***In other words it would be entirely possible to have a load switch or potentiometer in a guitar that in by changing the resistance of the load changes the upper 3 dB cut off point in the spectral response of the pickup - as though you were changing pickups!***

These two sets of figures with 100 k ohm and 10 k ohm loads show that merely changing the load causes a tremendous difference in spectral response, and if this was taken a little further with the load resistor incrementally altered, then the tonal response can be significantly changed with rather small change to the available output signal. The Table below shows just that with a hypothetical pickup that has a 6 k ohm internal resistance, and a series 3 H self inductance. (In this case there is not inter-winding capacitance!)

Load Resistance (k ohms)	Output Level (dB)	Cut-Off Frequency (kHz)
Infinity	-0.00 dB	Infinity
10 M ohms	-0.01 dB	530 kHz
5 M ohms	-0.01 dB	266 kHz
2 M ohms	-0.02 dB	133 kHz
1 M ohms	-0.05 dB	53.3 kHz
500 k ohms	-0.10 dB	26.8 kHz
250 k ohms	-0.21 dB	13.6 kHz
100 k ohms	-0.51 dB	5.62 kHz
50 k ohms	-0.98 dB	2.97 kHz
25 k ohms	-1.87 dB	1.64 kHz
10 k ohms	-4.08 dB	849 Hz
5 k ohms	-6.85 dB	584 Hz
2.5 k ohms	-10.6 dB	451 Hz
1 k ohms	-16.9 dB	371 Hz
0.5 k ohms	-22.3 dB	344 Hz
250 ohms	-28.0 dB	331 Hz

These formulas are essentially very simple:

$$\text{Loss dB} = 20 * \text{Log}(\text{Load Resistor}/(\text{Load Resistor} + \text{Pickup Resistance}))$$

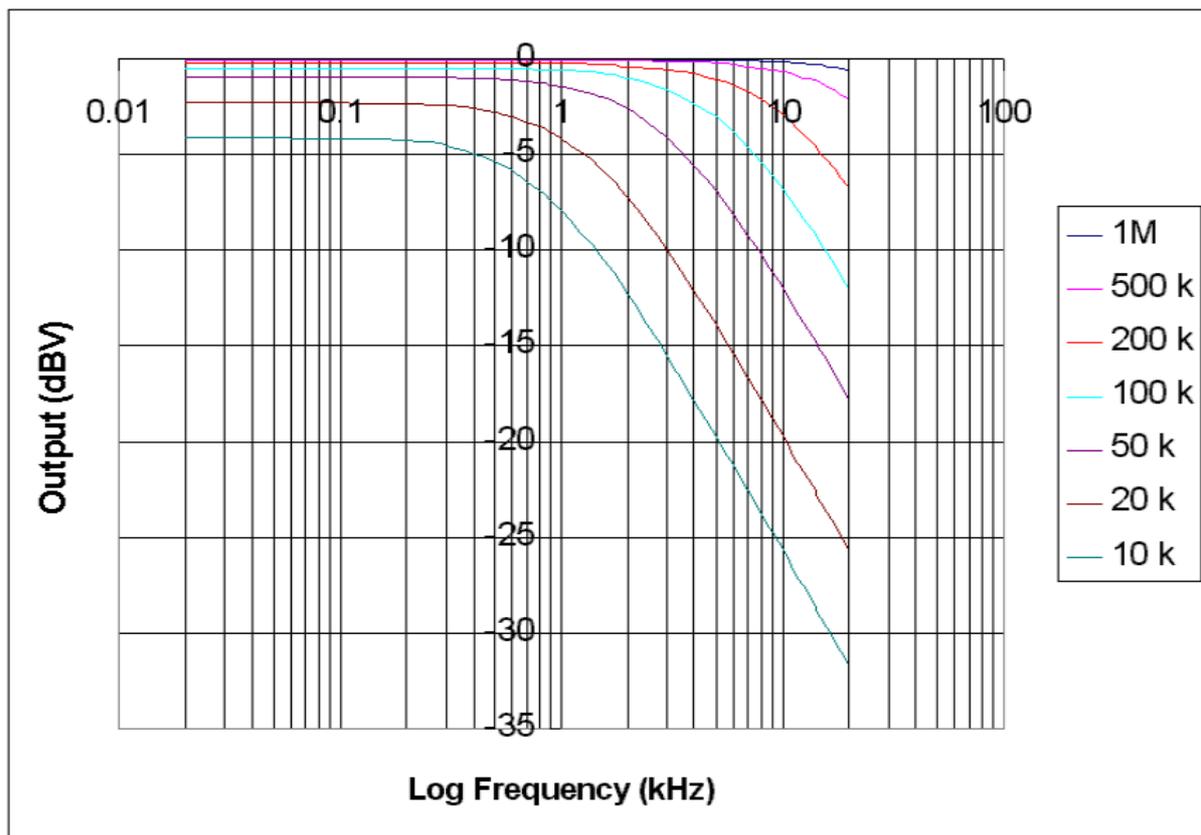
$$\text{Frequency Limit} = (\text{Load Resistor} + \text{Pickup Resistance})/(2 * \text{PI} * \text{Pickup Inductance})$$

This table shows some amazing figures and they have to be read more than once to get the message.

- In the first case, the load resistance needs to fall to lower than 25 k ohms before the sound level appreciably decreases. (After all, humans are struggling to detect a 3 dB difference in sound level.

- In the second case, the cut-off frequency drops with load resistance, and under 50,000 ohms the audio spectrum is beginning to be affected.

Looking at figures is somewhat boring and it has also to be realised that this is 1<sup>st</sup> order system so the drop-off rate will be asymptotic to a 6 dB per octave or 20 dB per decade slope, which in electronic filter terms is not that significant – but it is in musical terms! The graph below shows the figures in another form:



This graph shows the theoretical roll off of a pickup with a fixed resistive load. In this case the load is 100 k ohms and the pickup is the Hum Bucker with one then both coils.

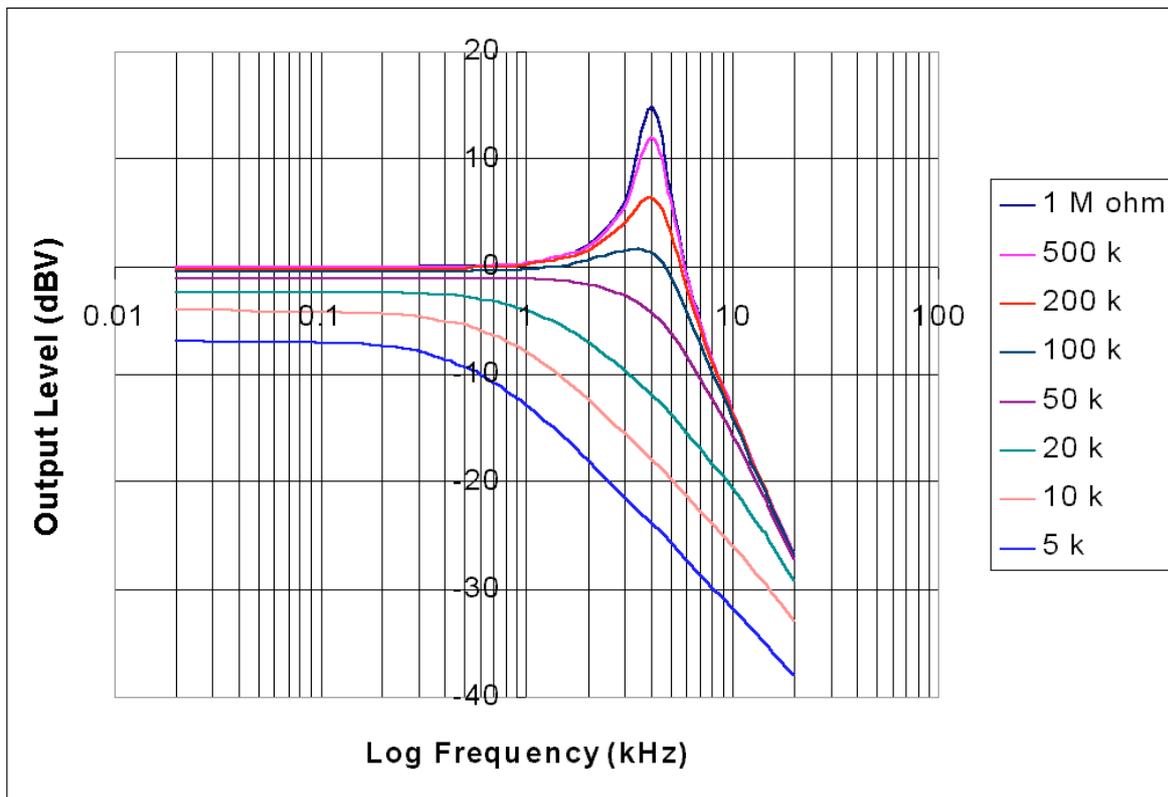
What has to be realised is that the centre of the human audio range is about 720 Hz and the spectrum is in these cases rolled off at about 6 kHz and 2 kHz respectively. The lower roll off situation could sound considerably “dull” or “muffled”.

In this case to prove the point, the load resistor is changed and as the value is pulled down the output level drops due to the internal winding resistance, and the frequency response cuts in lower - some people may actually want this sound - and it should be possible with one pickup - just change the load resistor.

This concept should not be that far-fetched; simply use a 250 k ohm volume pot with a switched bank of resistors to shunt the pot and pickup, else utilise a 500 k log pot for the volume and a 500k log pot connected with a 1 k ohm in series sitting across the volume pot will virtually act as a 'timbre' control! Now that has possibilities in simple theory land that have a direct practical use!

Now with this resolved, it is time to consider capacitance (both self capacitance, and added external capacitance). As stated before, self capacitance is distributed throughout the windings of the coil to other windings in the coil and to the surrounding structures - largely depending on the surface areas and the relative distances.

In practice the coil has a self resonance that is gives an idea of the total distributed capacitance, but surprisingly enough in practice this self capacitance almost all appears as if to the surrounds. Also the capacitance is quite small but big enough to compromise the total audio frequency response in most cases.



By adding a shunt capacitor across the load resistor, this very closely emulates the real life situation of a tone control and/or cable to the amplifier.

The graph below shows a typical pickup with 6000 ohms and 3.05 H in series, connected to various load resistors (1 m ohm through to 5 k ohms), all in parallel with a 0.00047 uF - or 470 pF capacitor. Note that as the resistance is lowered the peak in the frequency response flattens out, then becomes like the earlier graphs where the 470 pF did not exist.

So in theory we have a simple method of firstly measuring the resistance and capacitance, and by knowing the shape of the frequency response, it is a simple matter to 'back calculate' the resistance and capacitance required to get the desired frequency response. All that is needed is some practical proof that it works!

## The Practical Side

### *Insertion Loss*

To test this basic theory, it is a matter of connecting an oscillator to an amplifier that has a very low output impedance then connect this to a level meter that has a 10 k ohms total load.

***By cutting the active leg and inserting the pickup coil in series, the level to the level meter will drop - and this is called 'Insertion Loss' for the very obvious reason.***

In fact, the level is actually read on the Oscillator side and then on the Load side of the inserted component (or set of components) and the difference is called Insertion Loss. This practice removes the errors introduced by levels slightly changing with frequency, time etc..

The Table below shows in practice what happens with pickup coils with a 10 k ohm load:

Bobbin Description	Intrinsic loss (dB)	Upper 3 dB freq limit (Hz)	Practical Loss at 100 Hz	3 dB Loss frequency	Max Trough Frequency kHz
Strat 01	4.0 dB	911 Hz	4.0 dB	1050 Hz	12.9 kHz
Strat 02	4.2 dB	885 Hz	4.2 dB	1050 Hz	10.9 kHz
White Single	4.5 dB	599 Hz	4.5 dB	610 Hz	9.2 kHz
Black Single	3.6 dB	789 Hz	3.6 dB	950 Hz	10.9 kHz
Kinman Strat	4.1 dB	864 Hz	4.1 dB	970 Hz	10.2 kHz
Kinman Tele	4.4 dB	781 Hz	4.4 dB	840 Hz	7.0 kHz
HMB-01					
R-Shield	7.7 dB	427 Hz	7.9 dB	510 Hz	6.9 kHz
R-W					
W-Shield	4.7 dB	712 Hz	4.7 dB	700 Hz	6.6 kHz
HMB-02					
Additive	5.3 dB	640 Hz	5.6 dB	600 Hz	13.8 kHz
Subtractive					
Gr-Wh					
Cm-BI	3.0 dB	1080 Hz	3.1 dB	1100 Hz	13.8 kHz

It should come as no real surprise that the simple theoretical loss is rather close to practice and that the 3 dB frequency loss in practice is also very close to that derived in simple theory.

This little experiment has opened the door to show that the pickup coil actually can be approximated using a Thevenin's Equivalent Circuit - that is - the pickup coil looks like a zero impedance voltage generator with a series resistance and series inductor equivalent - both of which can be measured relatively easily. On top of that, the intrinsic winding capacitance provides a trough in the response at or near the self (parallel) resonance of the coil.

So now we know that simply by measuring the internal coil resistance, and the coil inductance, and maybe finding the self-resonant frequency; we can expect the frequency response to be predictable depending on the applied resistive load.

What we have not accounted for is load capacitance and that is a whole new structure, and until now, the measuring technique has been careful to minimise capacitance by using short thin leads that are loosely twisted, and barely any shielding.

### ***A New Order***

Until now (2004) these tests merely covered resistance and inductance, and the results were close to theory - because we avoided capacitance where possible.

In practice there is capacitance and this completely changes the analysis process. The cable has capacitance of about 47 pF per metre, so a 10 metre cable has about 470 pF in it. This capacitance sits across the resistive load.

If this resistive load was say 1 M ohm, then as the test frequency is raised, the capacitive reactance of the 10 metre cable reduces in value.

One way to comprehend what happens is to consider the frequency where the capacitive reactance equals the resistive load and at that point, if being fed by an infinite impedance source (a Norton's Equivalent) the voltage level will have dropped

by 3 dB and in this case that 3 db point would be about 339 Hz, for 500 k ohms load it would be about 677 Hz and for 250 k ohms it would be about 1.35 kHz - in other words the cable can really muffle the spectral response - simply because the load might be a high impedance (but the source is not yet considered).

We do know that the resistive part of the source impedance is about say 6 k ohms, so neglecting the inductance, the nominal high frequency limit would be about 54 kHz using a 10 metre cable into a 1 M ohm load (eg an amplifier - no volume or tone controls on the guitar)! This is well above the audio range and it should not be a problem - but it is - because we have to take into account the inductive reactance of the coil, and not just the resistance of the pickup coil.

Reactance is an interesting phenomenon in that unlike resistance, reactance is frequency dependent. In a pure resistor - the current and voltage are strictly in phase with each other and the power loss is very real.

With an inductor or capacitor the current and voltage are 90 degrees out of phase with each other, and because of that, energy is stored in the magnetic and electric fields respectively and returned momentarily later, so the power is totally apparent - not real.

In an inductor the voltage 'leads' the current by 90 degrees and in a capacitor, the current leads the voltage by 90 degrees - so together they have a 180 degree relationship and this sets up all that is needed for resonance. This is a major topic in its own right (Circuit Theory and AC Analysis) and it will not be a tutorial here.

When Nikola Tesla developed the three phase power generation and distribution system (virtually all by himself), he also developed the maths that covered this, and later went on to invent several hundred machines and devices that all used this maths of AC Circuit Analysis and its practical applications. This same maths (pure and applied) has a direct application in understanding how guitar pickups work!

### ***The Second Order Low Pass Filter***

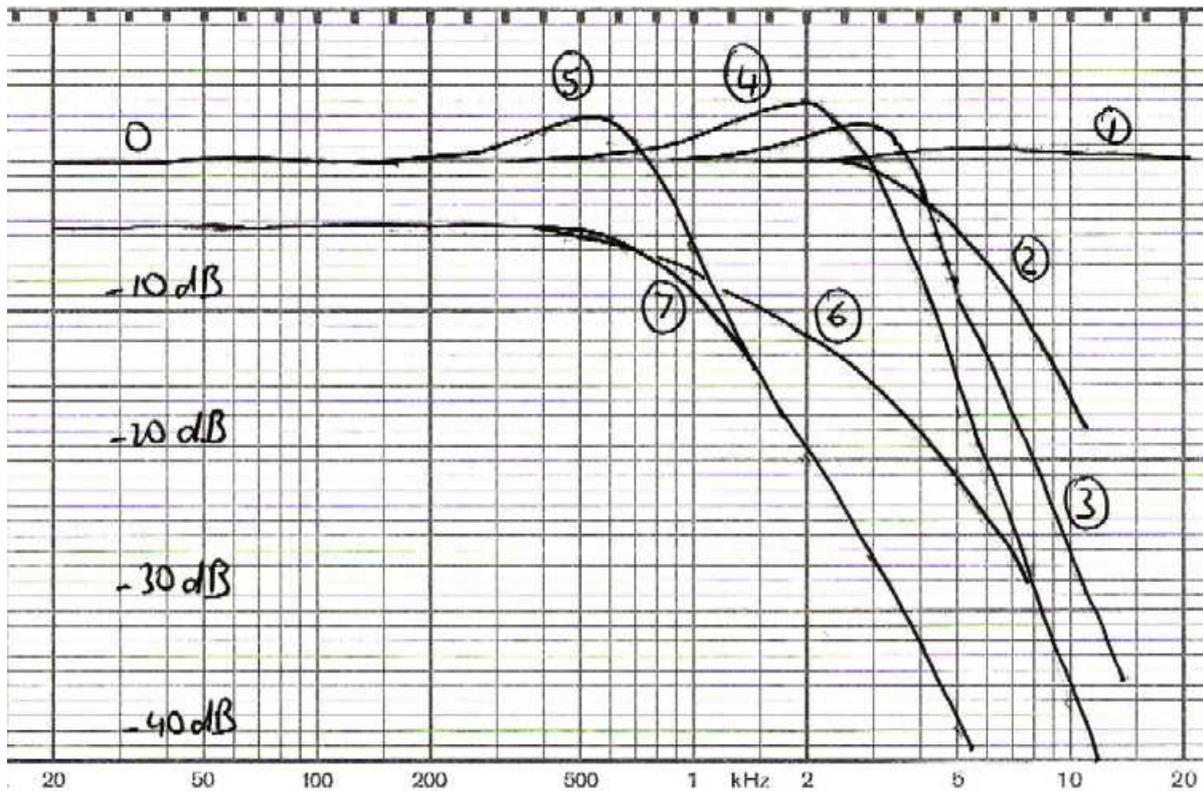
By deliberately putting capacitance across the load of an inductive source this changes the structure of the generator from a first order low pass filter (Inductance - Resistance) low pass filter, into a second order low pass (Inductance - Capacitance - Resistance) filter. This filter has a sharper "skirt" on it at 40 db per decade as opposed to a 20 dB per decade for the first order filter.

Very quickly, we have moved from a pickup coil with a cable attached to a theoretically predictable low pass filter (and this is covered in detail in what is called Control Theory, Circuit Theory, and in Communications Theory - in very different aspects)!

Not only has the shape of the frequency response become highly predictable, through the application of filter design but the shape itself also can have a peak in the response before falling down the 'skirt' and this peak has the ability to also 'colour' the sound.

The graph below shows the 'Strat 01' pickup with various loads on it, and it should be very clear that if other pickups were put in place, then the shapes of the frequency response curves would follow the same. In other words, it does not really matter which pickup is used, with a bit of load tailoring, (adjusting the load resistor value and

the load capacitor value) virtually any magnetic pickup manufactured along these lines can all be made to have virtually identical frequency responses.



Curve 1: Straight into the ultra high impedance preamplifier

Curve 2: 100 k ohms

Curve 3: 100 k ohms parallel to 0.001 uF

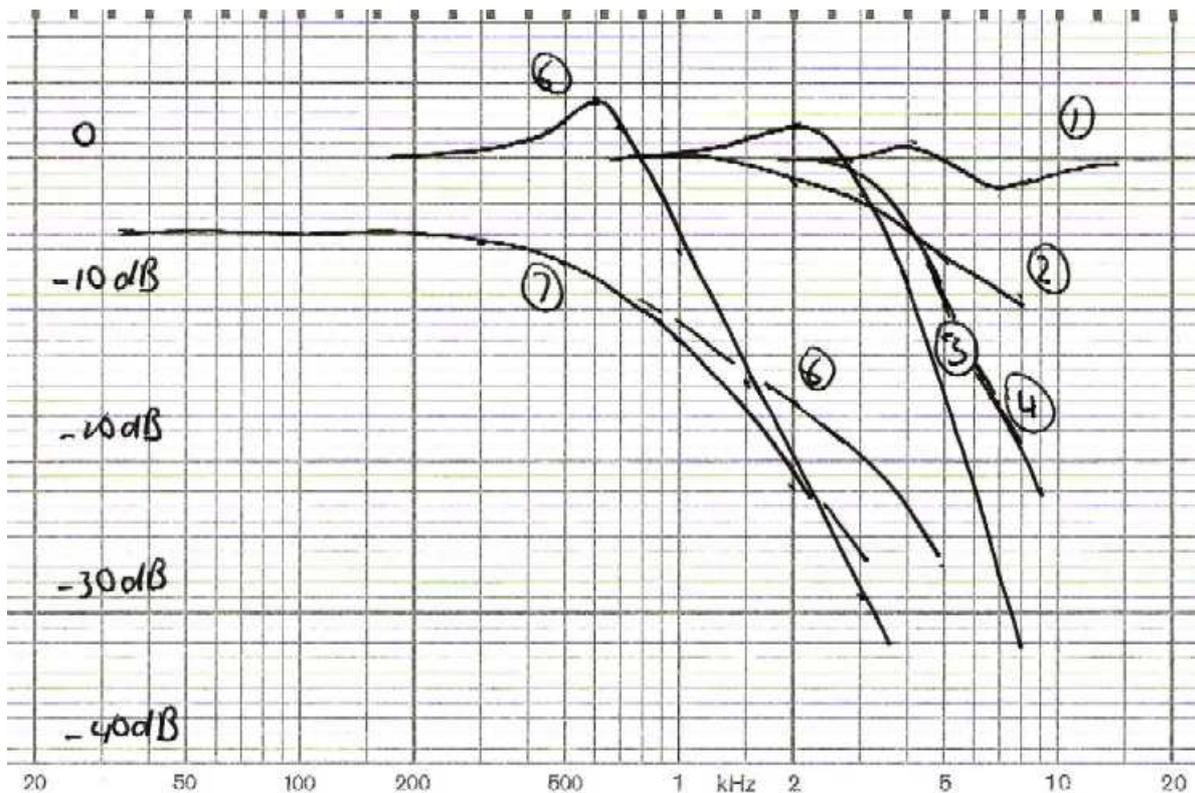
Curve 4: 100 k ohms parallel to 0.0027 uF

Curve 5: 100 k ohms parallel to 0.027 uF

Curve 6: 10 k ohms

Curve 7: 10 k ohms parallel to 0.027 uF

Just to prove the point, this second set of frequency response curves was created while using the Hum Bucker 02 which has a much larger inductance and internal resistance than the Strat 01 structure.



Curve 1: Straight into the ultra high impedance preamplifier

Curve 2: 316 k ohms

Curve 3: 316 k ohms parallel to 220 pF

Curve 4: 316 k ohms parallel to 470 pF

Curve 5: 316 k ohms parallel to 0.0082 uF

Curve 6: 18 k ohms

Curve 7: 18 k ohms parallel to 0.0082 uF

There is no doubt that the curves do emulate each other but there are disturbing shapes on the curves that are the result of internal resonances caused by parasitic capacitances.

Also note just how small the capacitors are. This is 'ringing alarm bells' as the filter shaping capacitors are barely an order of magnitude greater than the intrinsic capacitances - and that spells trouble that is caused by the very high values of inductance wound with incredibly thin wire - having internal capacitances that are openly interfering with the spectral response.

It appears that the lateral Hum Bucker in its current form and having series connected coils is a very nasty piece of engineering design, and some alternate thinking needs to be applied to reduce these parasitic effects.

## ***Hotting a Lateral Hum Bucker***

This brings up a very interesting point about the way that Hum Bucker coils are connected - apparently always in series! The Hum Bucker lateral arrangement has two coils that to all intents and purposes are identical.

Connecting these coils in series is like connecting two voltage generators in series, then putting the source impedances in series with each other, then adding the induced voltage generators (from coil 1 to coil 2 and vice versa) in series with this again. This also means that in practice there is a high impedance coil floating on top of a high impedance, and if anything will pick up noise, then this will be it!

If the second Hum Bucker coil were to be connected in parallel then five situations occur. Firstly the inductance should not be halved, as these two coils are parallel aiding, it may be slightly reduced - and that is good! Secondly the resistances will be seen as parallel and therefore halved - not doubled - and that is good too.

Thirdly the two voltage generators will be seen as virtually identical and in phase and that will not drop the level, and the induced voltages from one coil to the other will be seen as parallel. So the Hum Bucker in this new parallel configuration should 'sound like a strat' with one coil in circuit, and with the second coil in circuit, it should 'sound like a hot strat'! And fifthly, because the second coil has a leg tied to earth (common) then it should not be a candidate for induced noise like its series connected brother!

Terminating in 10 k ohms:

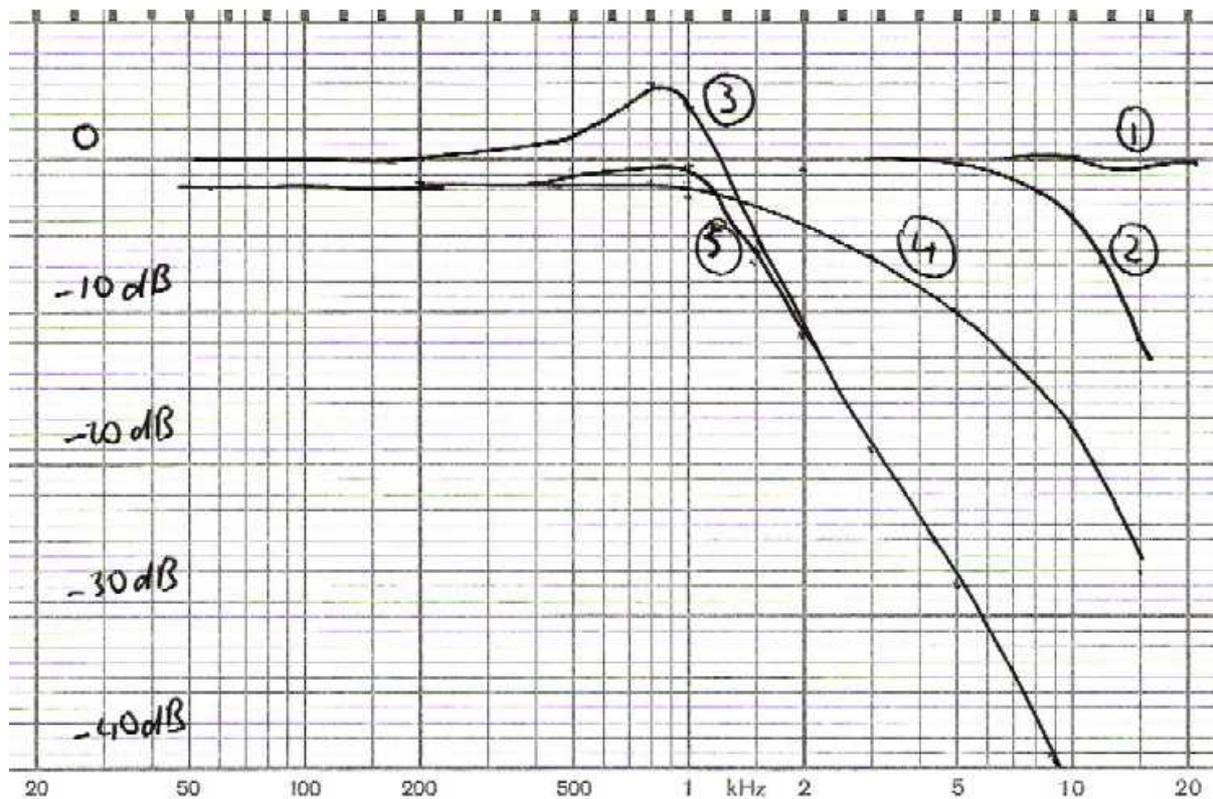
<b>Bobbin Description</b>	<b>Resistance (k) HP 100 Hz</b>	<b>Resistance (k) DC</b>	<b>Inductance (H)</b>	<b>Intrinsic loss (dB)</b>	<b>Upper 3 dB freq limit (kHz)</b>
HMB-01					
Additive	8.72	8.45 k	4.59 H	5.3 dB	0.640 kHz
Subtractive	8.35	8.45 k	3.72 H		
Gr-Wh	4.30	4.33 k	2.07 H		
Cm-BI	4.13	4.12 k	2.08 H	3.0 dB	1.080 kHz
Parallel		2.21 k	1.13 H	1.7 dB	1.719 kHz

The figures on the bottom two lines say it all. Even with a 10 k load, when the second coil is switched in, the output level appears to INCREASE by about 1.3 dB, instead of DECREASE by about 2.3 dB.

If the load was say 100 k ohms then the difference in output would be hard to even read!

But look at the upper frequency limit - it has moved up by almost an octave - instead of losing almost an octave.

A quick look at the frequency response curves in the graph below show that the responses are far more predictable, and the filter capacitances are now at least two orders of magnitude away from the intrinsic self-capacitances in the windings.



Curve 1: Straight into the ultra high impedance preamplifier

Curve 2: 100 k ohms

Curve 3: 100 k ohms parallel to 0.033uF

Curve 4: 10 k ohms

Curve 5: 10 k ohms parallel to 0.033 uF

Now, compare these frequency response curves with those of the series connected Hum Bucker coils, and it can be seen that these curves are far more consistent, and the capacitor values are much greater than an order of magnitude greater than the self capacitance, making the engineering highly repeatable. Compare these curves to those on the 'Strat 01', then there are definite repeatable associations that can be 'engineered in'.

In this case the ultra high terminating impedance gave a virtually flat response from 20 Hz through to 10 kHz (Curve 1). By terminating it with 100 k (a typical volume control pot), the frequency response is still flat as per Curve 2, but it starts to roll off at 10 kHz (about 3 dB there).

By shunting the 100 k with a 0.033 uF, the second order low pass takes effect, Curve 3, and its 3 dB point is about 1.4 kHz, and the slope is about 40 dB/decade above there. Note the peak in the response is about 5 dB at about 850 Hz which is about 0.6 times the 3 dB point.

By reducing the load resistor from 100 k ohms to 10 k ohms, Curve 5, the peak is substantially reduced, and there is a very slight output penalty. If the 0.33 uF capacitor is removed, then the response, Curve 4, has a nominal 3 dB point at about 2.7 kHz and then rolls off at 20 dB/decade - but there is a self resonant trough about 16 kHz.

## ***Pickup Load Rules***

The frequency response is (virtually) flat until the inductive reactance becomes greater than the shunt (terminating) resistance (plus the internal resistance) and then the response falls off at 20 dB/decade - until it approaches its self-resonance point, and the output will dive here as the pickup goes very high impedance with its internal self-resonance. (It is therefore desirable to have the self-resonant frequency well above the audio range. (That means less turns, thicker insulation, and possibly a much better magnetic circuit is required!)

By adding shunt capacitance across the resistive load, the frequency response will peak about 4 dB above the lower frequency range and then fall at 40 dB/decade as the frequency is increased. If the frequency of the peak is in the order of 2 kHz to 6 kHz, this can give a 'crisp' sound to an otherwise smooth frequency response. The size of this peak is limited by the internal resistance of the pickup and the load resistance.

The second order filter cut-off frequency is determined by the values of the pickup inductance and the shunt capacitor (across the load resistor). Once these values are known, the cut off frequency can be calculated. Ideally, the load resistor should be a high value - say 200 k ohms total so the frequency response should be virtually flat over most of the audio range and rolling off at 20 dB/decade above say 10 kHz.

In this situation, the value shunt/load capacitor can then determine the second order cut off frequency, and its associated nominal 4 dB peak (about 0.6 times the 3 dB cut off point).

By lowering the load resistor value, this will reduce the peak in the second order frequency response, at some expense to the overall output.

## ***Conclusions***

The characteristics of any pickup can be reasonably accurately predicted first by measuring the external pickup resistance, inductance and self resonance to then calculate the self capacitance. When these characteristics are put into a Thevenin equivalent circuit, combined with the known load being a resistor in parallel with a capacitor, the expected relative output level and frequency response can then be reasonably accurately approximated.

In the cases shown here the single coil pickups all had reasonably similar responses, and the lateral Hum Bucker pickups as single coils also looked like single coil pickups.

The wiring arrangement of series connected lateral Hum Buckers appears to be suspect as the capacitors required for filtering in the audio range were less than an order of magnitude from the self capacitances of the coils and these coils appeared to have a rather low magnetic coupling factor.

This radically alters the emulation process as the lateral Hum Bucker could also be considered as a two coil filter and with two capacitors - making a fourth order filter, and the mutual coupling will introduce a delay line type filtering characteristic and this will affect the 'group delay' the phase relationship of various frequencies.

Delving into analysis at this level is very interesting, but basically unnecessary and unrewarding! There are alternatives.

By connecting these laterally positioned coils in parallel (aiding of course), this pickup then approximates the values seen in a single coil pickup with an overall lower internal resistance and because the coupling was so low, the inductance value suffered slightly - but this will increase the overall frequency response!

With a little understanding of analogue second order filters using passive components, it has been very clearly shown that the frequency response can be predicted with a very high degree of accuracy, and ***this removes the guess-work that to date has been the 'black art' in pickup sounds.*** No doubt body and neck resonances will colour the sound from particular guitars.

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[Comments and Corrections are welcome](#)