Connecting PAF Windings

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Introduction

If you ever wish to change the timbre of an electric guitar then switching pickups is a ‘very first’ consideration, and inevitably all electric guitars have a switch (or two) on them to facilitate the choice of pickup position (Bridge, Mid, Neck), and/or the facility to parallel connect these pickups – and the range of timbres is amazing – but little understood.

When it comes to ‘Hum Bucker’ pickups, these are most commonly provided commercially with a screened output lead with the two coils connected in series.

Now, it has already been clearly proven on earlier Web pages that the generally so-called (lateral / horizontal) PAF humbucker pickup is not really a hum bucker – but really an electromagnetic pickup with a slightly tighter magnetic circuit than that of the typical Stratocaster family of pickups, and consequently, this type of magnetic structure is comparatively less sensitive to distant magnetic fields.

There certainly is not a winding on there that specifically bucks hum, but the two windings on these commercially available pickups are magnetically mutually coupled to a certain degree.

It seems that many musicians want the full range of the Stratocaster pickup with its ‘bright’ timbre response with the capacity to buck the background interference, and still have a highly sensitive pickup. In practice, the usual commercially available series wound lateral PAF humbucker loses the ‘highs’ and therefore sounds comparatively muffled to the Stratocaster.

Some manufacturers provide lateral humbuckers with a pair screened cable, and the second wire connects to the halfway point between the two series wound coils. This provides musicians with the choice of using the virtual Stratocaster (single coil), or the two coils in series, but sadly, this has a limited value because the inductance of the single coil is greater than the standard Stratocaster pickup – because the magnetic circuit is tighter!

To further disappoint the situation, the floating ‘hot’ coil is a direct candidate for background noise induction, so the single coil connection in a series humbucker pickup is poor direct substitute for a Stratocaster type pickup. But all is not lost!

Series Connected Windings

When we connect two coils in series (like that in a lateral humbucker) these coils have the same common current flowing through both coils and these coils also have a magnetically linked circuit, which is mutually coupled. These coils can be connected in series (magnetically) aiding, or in series (magnetically) opposing, and this is the point where most people become unstuck and simply ‘admire the sound’ without really knowing what is going on!

Irrespective if the coils are connected aiding or opposing, the total resistance of these series connected coils is the sum of the two separate coil resistances (plus the connecting leads), so that part is rather simple and can be very easily understood. Understanding the inductance is rather more complicated – but it is very predictable.

Like self-resistance, each coil has its own self-inductance, but because there is magnetic coupling between the two coils (that is; their magnetic fields interact), there is a mutual inductance (M) induced from each coil to the other coil. The tighter the magnetic circuit, the less the magnetic leakage, the greater the mutual inductance! A schematic picture as the one below better explains this concept of mutual induction:

Where: $L_1 = L_{11} + M_{21}$ and $L_2 = L_{22} + M_{12}$

Because the coils are in series so the current flow is common, summing up the total inductance for the two coils L1 and L2 in series we get:

$L_{tot} = L_{11} + L_{22} + M_{12} + M_{21}$

Where L_{11} (*read as 'el one one'*) is the self inductance induced from coil 1 to coil 1, L_{22} (*read as 'el two two'*) is the self inductance induced from coil 2 to coil 2, M_{12} (*read as 'em one two'*) is the mutual inductance induced from coil 1 into coil 2, and M_{21} (*read as 'em two one'*) is the mutual inductance induced from coil 2 into coil 1.

In a perfectly coupled magnetic circuit, the mutual inductance is equal to the self-inductance, and as the coupling is less than unity, the mutual inductance is therefore less than the self-inductance. Now, because this is a passive circuit, and the current is common through both coils, so the magnetic flux is also common through both coils, so the two mutual inductances (M_{12} and M_{21}) are equal, so this equation can be re-written as:

$L_{aid} = L_{11} + L_{22} + 2\ M$

Now comes the cruncher. The above equation assumes that the mutual inductances are aiding (therefore the mutual inductances are added). If the two coils are connected in series opposing, (that is; one coil connected back to front) then the mutual inductance is subtractive and we get the following equation:

$L_{opp} = L_{11} + L_{22} – 2\ M$

This means that the self inductances do not change but the mutual inductances now act to cancel out the self inductances, and the degree to how well they do this is determined by the magnetic circuit's 'tightness' or coefficient of coupling. Now, the coefficient of coupling (K) of a two-winding structure is defined in terms of the mutual inductance as a ratio of the self-inductance, so:

$K = |M| / (SQRT(L_{11} * L_{22}))$

This means that the self-inductance = $(SQRT(L_{11} * L_{22})$, which is the geometric mean of the two self inductances, and the value of M (the mutual inductance component) defines how well these two coils are coupled. A perfectly coupled magnetic circuit would have a coupling coefficient of unity, while a totally uncoupled magnetic circuit would have a coupling coefficient of zero.

If the coupling (K) between the two coils was perfect (1), then with the two identical coils connected in series opposing, the total inductance would be zero, and there would be no induction from the string movement to cause an output, and there would be no far-field noise that would commonly induce an output from the coils!

Similarly, if the coils were connected in series aiding and had perfect coupling (K), then the total inductance would be four times that of one identical winding, and there would be no induction from the string movement to cause an output, and there would be no far-field noise that would commonly induce an output from the coils!

These situations do not happen in the PAF, as the coupling (K) is far less than perfect!

To find the Mutual Inductance then all we need to do is to connect the two coils in series, measure the inductance and then switch one coil around and measure the inductance again, so we will get:

$L_{aid} – L_{opp} = L_{11} + L_{22} + 2M – L_{11} – L_{22} + 2M = 4M$

So $M = (L_{aid} – L_{opp}) / 4$

Now, if we measure the inductances of each coil separately, then mutual inductances will not play a direct part, so we can deduce that the geometric mean of the two coil inductances is:

$L_{geom} = SQRT(L_{11} * L_{22})$

So with these two equations put together we get:

K (coupling factor) = $(L_{aid} – L_{opp}) / (4 * SQRT(L_{11} * L_{22}))$

Nothing too hard there if you have a good inductance meter!

In practice it should show that irrespective of which brand lateral humbucker is chosen and measured, they will all have virtually the same coupling coefficient because they are all manufactured as the same or very similar family of pickups!

Parallel Connected Windings

When we connect two coils in a commercial humbucker (PAF) in parallel these coils have the same common voltage across both coils, but they have separate current flows through each coil and these coils also have a magnetically linked circuit, which makes these two coils mutually coupled.

These coils can be connected in parallel (magnetically) aiding, or in parallel (magnetically) opposing, and this is the point where most musicians and manufacturers don't have a clue what is happening except that the timbre is not nearly as dull as the series aiding connection described briefly in theory above!

Irrespective if the coils are connected aiding or opposing, the total resistance of these parallel connected coils is the sum of the two separate coil conductances (the reciprocal of resistance), plus resistances the series connecting leads, so this part is immediately far more complex than the simple series connected structure. In essence for the parallel coils, the resistance can be calculated from:

$G_{par} = 1 / R_{par} = 1 / R_{L1} + 1 / R_{L2}$, which can be translated to

$R_{par} = (R_{L1} * R_{L2}) / (R_{L1} + R_{L2})$

This calculation is rather simple and can be relatively easily understood. Understanding the inductance relationships is rather more complicated – but it is also very predictable.

Like self-resistance, each coil has its own self inductance, but because there is magnetic coupling between the two coils (that is; their magnetic fields interact), there is a mutual inductance (M) induced from each coil to the other coil. A schematic picture as the one below in this case better explains this concept of parallel-connected mutual induction:

Because the coils are in parallel, the current flow is not common, but the voltage across the coils is common; so summing up the total inductances is done in a similar manner as the parallel resistances were managed in a similar manner.

Where: $L_1 = L_{11} + M_{21}$ and $L_2 = L_{22} + M_{12}$

Because the coils are in parallel and the voltage is common, summing up the total reciprocal inductances for the two coils L_1 and L_2 in series we get:

$1/ L_{par} = 1 /L_1 + 1 / L_2$ So when this is translated for two coils we get:

$L_{par} = (L_1 * L_2) / (L_1 + L_2)$

Now substituting in the mutual inductances, this becomes:

L_{par} = ((L_{11} + M_{21}) * (L_{22} + M_{12})) / (L_{11} + M_{21} + L_{22} + M_{12})

At this point it becomes rather difficult as the mutual inductances do not have a common current and common flux, therefore the mutual inductances are not necessarily equal, and this equation needs to be resolved by determinants and matricis, but all is not lost! If we assume that both coils are virtually identical, then we can assume that the mutual inductances are also virtually equal, and the whole equation radically simplifies into:

L_{par} = (L + M) /2

Now comes the second cruncher! The above equation assumes that the parallel mutual inductances are aiding (therefore the mutual inductances are added). If the two coils are connected in parallel opposing, (that is; one coil connected back to front) then the mutual inductance is subtractive and we get the following equations:

L_{aid} = (L + M) /2 and L_{opp} = (L – M) /2, and solving these simultaneous equations for M in the parallel identical coil case we get:

M = L_{aid} – L_{opp}

Now, as the coefficient of coupling (K) of a two-winding structure is defined in terms of the mutual inductance as a ratio of the self-inductance, so:

K = |M| / (SQRT(L_{11} * L_{22}))

This means that the self-inductance = SQRT(L_{11} * L_{22}), which is the geometric mean of the two separate inductances, and the value of M (the mutual inductance component) defines how well these two coils are coupled.

Now, if we measure the inductances of each coil separately, then mutual inductances will not play a direct part, so we can deduce that the geometric mean of the two coil inductances is:

L_{geom} = SQRT(L_{11} * L_{22})

So with these two equations put together for the parallel case we get:

K (coupling factor) = (L_{aid} – L_{opp}) / (SQRT(L_{11} * L_{22}))

In practice it should show that irrespective of which brand lateral humbucker is chosen and measured, they will all have virtually the same coupling coefficient because they are all manufactured as the same or very similar family of pickups!

So what does this all Mean?

We now have truly workable simple equations that can be readily applied to dual coil humbucker pickups (that have virtually identical coil structures for each coil in the parallel case).

Because we can measure the inductance of each coil and also measure the inductance of the coils in series aiding and opposing and parallel aiding and opposing, we should find that the coupling between these two coils is consistent by either measuring method.

From this analysis stage, some less obvious observations will now become apparent:

Connecting a lateral humbucker in series opposing is virtually the same as connecting two much less turns coils in series aiding and including the extra series resistance. Yes this will sound sharper (but fainter), and now we know why, and by how much!

Connecting a humbucker coil pair on parallel aiding will halve the winding resistance and radically reduce the winding inductance, and yes this will sound much sharper (and maybe very slightly fainter), and now we know why, and by how much!

If the Stratocaster constant for inductance was chosen as an arbitrary reference (because the of the apparent spectrum coverage), then a backward engineering approach could be to make the inductance of a lateral humbucker the same (or very similar) to the Stratocaster inductance as this inductance should make a lateral pickup have a very similar electrical and musical characteristics to that of the Stratocaster in the same guitar body – without the background noise.

If we introduce a thick known air gap (or series of known air gaps) in place of the strings, we can also measure the resultant inductances and resistances and determine the relative incremental changes in inductance, mutual coupling, sensitivity and spectral density (timbre), with a range of coil winding structures.

Practical Measurements and Fascinating Results

Firstly thanks to Guitar World in Parramatta (Australia) for the loan of a series of pickups for measuring! The other pickups came courtesy Turramurra Music (Australia) and Ebay!

By making a little test jig that could connect a pair of coils in series / parallel / aiding / opposing; this really sped up the measuring process and reduced what would have been many hours to a few hours, and it introduced a good degree of continuity and repeatability into the results.

The pickups that were on hand I believe were: Epiphone, DiMazero, Seymour-Duncan, a PAF Humbucker with Allen key screws on one side, another PAF Humbucker with chromed screws on one side and an EMG-HZ with black screws on one side. If these pickups did not have the availability of both coils separately, then appropriate changes were made to separate the coil windings and bring out the leads for these tests.

In the table below, each pickup was put through the same set of measurements under the same conditions (within a couple of hours). The term “Base L” means basic inductance with an open-faced pickup.

The term “1 Shim” refers to one layer of printed circuit board (1.65 mm) over the pickup before a sheet of tinplate soft iron was pressed on to make a loose magnetic circuit like the strings could. “2 Shims” and “3 Shims” refers to the number of layers of printed circuit board (Vero-Board).

Resistance is in Ohms and all the inductances are in milli-Henrys.

Brand	Structure	Connection	Resistance	1 Shim	2 Shims	3 Shims	Base L
Epiphone HB	LHB1	Coil 1	7,320	4,820	4,530	4,380	4,010
Epiphone HB	LHB1	Coil 2	7,070	4,550	4,300	4,180	3,930
Epiphone HB	LHB1	SeriesAid	14,390	11,080	10,280	9,890	9,250
Epiphone HB	LHB1	SeriesOpp	14,390	8,065	7,730	7,560	7,100
Epiphone HB	LHB1	ParrAid	3,590	2,710	2,520	2,430	2,270
Epiphone HB	LHB1	ParrOpp	3,590	2,000	1,920	1,880	1,765
Dimazero	LHB2	Coil 1	7,890	4,850	4,550	4,390	4,100
Dimazero	LHB2	Coil 2	7,900	4,840	4,550	4,390	4,100
Dimazero	LHB2	SeriesAid	15,820	11,555	10,605	10,150	9,470
Dimazero	LHB2	SeriesOpp	15,820	8,580	8,110	7,960	7,460
Dimazero	LHB2	ParrAid	3,940	2,760	2,560	2,460	2,300
Dimazero	LHB2	ParrOpp	3,940	2,120	2,030	1,975	1,850
Seymour-Duncan	LHB3	Coil 1	7,410	4,900	4,680	4,580	4,410
Seymour-Duncan	LHB3	Coil 2	7,580	4,900	4,680	4,580	4,420
Seymour-Duncan	LHB3	SeriesAid	14,980	13,160	12,520	12,280	12,030
Seymour-Duncan	LHB3	SeriesOpp	14,980	7,630	7,300	7,100	6,640
Seymour-Duncan	LHB3	ParrAid	3,760	3,110	2,970	2,910	2,850
Seymour-Duncan	LHB3	ParrOpp	3,760	1,850	1,769	1,720	1,615
HB Allen Key	LHB1	Coil 1	3,940	2,480	2,310	2,220	2,070
HB Allen Key	LHB1	Coil 2	3,730	2,365	2,240	2,180	2,050
HB Allen Key	LHB1	SeriesAid	7,680	5,430	5,070	4,870	4,570
HB Allen Key	LHB1	SeriesOpp	7,680	4,250	4,060	3,960	3,700
HB Allen Key	LHB1	ParrAid	1,910	1,365	1,271	1,219	1,143
HB Allen Key	LHB1	ParrOpp	1,910	1,061	1,013	990	925
HB Lat Screws	LHB1	Coil 1	6,450	4,735	4,370	4,200	3,870
HB Lat Screws	LHB1	Coil 2	6,520	4,360	4,130	3,990	3,710
HB Lat Screws	LHB1	SeriesAid	12,980	11,055	10,135	9,695	8,950
HB Lat Screws	LHB1	SeriesOpp	12,980	7,460	7,110	6,920	6,435
HB Lat Screws	LHB1	ParrAid	3,230	2,710	2,490	2,380	2,200
HB Lat Screws	LHB1	ParrOpp	3,230	1,860	1,770	1,728	1,606
EMG-HZ Coil 1	LHB1	Coil 1	6,740	4,300	4,130	4,040	3,840
EMG-HZ Coil 2	LHB1	Coil 2	6,750	4,170	4,010	3,930	3,740
EMG- HZ	LHB1	SeriesAid	13,480	9,420	9,010	8,770	8,370
EMG- HZ	LHB1	SeriesOpp	13,480	7,460	7,260	7,150	6,790
EMG- HZ	LHB1	ParrAid	3,380	2,350	2,250	2,190	2,090
EMG- HZ	LHB1	ParrOpp	3,380	1,865	1,815	1,790	1,695

Skimming over these figures shows that there is a remarkable similarity with the various pickups – but beware the Seymour-Duncan is a dual rail structure that has a narrower magnetic field and taller coils (to fit the windings in)!

As the shims of printed board are added the inductance incrementally drops, and this is a first step in analysing the possibilities of this pickup family. The problem now is to do the maths to calculate the coupling factors of these pickups in various quantum operational conditions as set out above.

Below is the following table that calculates out the various values for **Lgeo**metric mean (mH), **Lsdiff**erence (Series aiding – Series opposing) (mH), **Kser**ies (units), **Lpdiff**erence (Parallel aiding – Parallel opposing) (mH), **Kpar**allel (units), and the results are extended over the four various cases for different thickness air-gap shims.

Brand	**Structure**	**Connection**	**1 Shim**	**2 Shims**	**3 Shims**	**Base L**	
Epiphone HB	LHB1	Coil 1	4,683	4,414	4,279	3,970	**Lgeom**
Epiphone HB	LHB1	Coil 2					
Epiphone HB	LHB1	SeriesAid	3,015	2,550	2,330	2,150	**Lsdiff**
Epiphone HB	LHB1	SeriesOpp	0.161	0.144	0.136	0.135	**Kser**
Epiphone HB	LHB1	ParrAid	710	600	550	505	**Lpdiff**
Epiphone HB	LHB1	ParrOpp	0.152	0.136	0.129	0.127	**Kpar**
Dimazero	LHB2	Coil 1	4,845	4,550	4,390	4,100	**Lgeom**
Dimazero	LHB2	Coil 2					
Dimazero	LHB2	SeriesAid	2,975	2,495	2,190	2,010	**Lsdiff**
Dimazero	LHB2	SeriesOpp	0.154	0.137	0.125	0.123	**Kser**
Dimazero	LHB2	ParrAid	640	530	485	450	**Lpdiff**
Dimazero	LHB2	ParrOpp	0.132	0.116	0.110	0.110	**Kpar**
Seymour-Duncan	LHB3	Coil 1	4,900	4,680	4,580	4,415	**Lgeom**
Seymour-Duncan	LHB3	Coil 2					
Seymour-Duncan	LHB3	SeriesAid	5,530	5,220	5,180	5,390	**Lsdiff**
Seymour-Duncan	LHB3	SeriesOpp	0.282	0.279	0.283	0.305	**Kser**
Seymour-Duncan	LHB3	ParrAid	1,260	1,201	1,190	1,235	**Lpdiff**
Seymour-Duncan	LHB3	ParrOpp	0.257	0.257	0.260	0.280	**Kpar**
HB Allen Key	LHB1	Coil 1	2,422	2,275	2,200	2,060	**Lgeom**
HB Allen Key	LHB1	Coil 2					
HB Allen Key	LHB1	SeriesAid	1,180	1,010	910	870	**Lsdiff**
HB Allen Key	LHB1	SeriesOpp	0.122	0.111	0.103	0.106	**Kser**
HB Allen Key	LHB1	ParrAid	304	258	229	218	**Lpdiff**
HB Allen Key	LHB1	ParrOpp	0.126	0.113	0.104	0.106	**Kpar**
HB Lat Screws	LHB1	Coil 1	4,544	4,248	4,094	3,789	**Lgeom**
HB Lat Screws	LHB1	Coil 2					
HB Lat Screws	LHB1	SeriesAid	3,595	3,025	2,775	2,515	**Lsdiff**
HB Lat Screws	LHB1	SeriesOpp	0.198	0.178	0.169	0.166	**Kser**
HB Lat Screws	LHB1	ParrAid	850	720	652	594	**Lpdiff**
HB Lat Screws	LHB1	ParrOpp	0.187	0.169	0.159	0.157	**Kpar**
EMG-HZ Coil 1	LHB1	Coil 1	4,235	4,070	3,985	3,790	**Lgeom**
EMG-HZ Coil 2	LHB1	Coil 2					
EMG- HZ	LHB1	SeriesAid	1,960	1,750	1,620	1,580	**Lsdiff**
EMG- HZ	LHB1	SeriesOpp	0.116	0.108	0.102	0.104	**Kser**
EMG- HZ	LHB1	ParrAid	485	435	400	395	**Lpdiff**
EMG- HZ	LHB1	ParrOpp	0.115	0.107	0.100	0.104	**Kpar**

In all cases the K factor (done in series or in parallel – it does not matter here) is very consistent when measured in series mode or in parallel mode, so this implies that for each pickup, the coils inductances are very close in value to each other. Even when the air-gap is added into the arrangement the K factor incrementally increases as the air-gap is incrementally decreased – implying that there are substantial magnetic leakages losses elsewhere in these magnetic circuits.

Note that the K factor for the PAF family is generally in the order of 0.100 to 0.161 which is rather low, and the S-D structure has a K factor in the order of 0.257 to 0.305 which is substantially higher (and the pole pieces cover a considerably larger area than the standard PAF humbuckers. Understanding the realisation that if there are substantial leakages, then this radically increases the susceptance to external noise interference – and so these PAF humbuckers seem to have a large room for constructional improvement to considerably reduce the leakage and/or work very well with much weaker magnets.

Now, the voltage (output level) generated is proportional to the relative change in inductance caused by the (magnetic) string movement and the quantum air-gap approach has provided a series of stepped incremental inductances that relate to the number of circuit board shims between the pickup pole pieces and the tin plate iron “string equivalent” magnetic circuit component.

Simply calculating the difference in inductances gives incremental inductance figures that cannot be directly compared, so by dividing this answer by the average inductance (the sum of the two inductances divided by two), this provides a comparable figure as a ratio, but this ratio is small, so by first multiplying the ratios by a common factor (say 100) and then utilising the dB formula we have an equation that looks like:

$\text{Output Level} = 20 * \text{Log}_{10} (100 * (L1 - L2) / (L1 + L2))$ dB

Where L1 and L2 are the actual inductances for various quantum air-gap (shim) thicknesses. In using this equation we now can have a set of equivalent output levels that can be directly compared with each other.

In the table below, the comparative output levels caused by incremental inductance changes (as indicated by 1 SH – 2 SH; meaning the change caused from going from one shim to two shims of printed circuit board etc.) are given for the six possibilities of every two winding coil is given in dB so these are directly comparable. Note that the dB results here are not referenced to a specific level like dBV or dBu or dBm etc., so they are only directly comparable to each other.

Brand	Structure	Connection	1 SH - 2 SH	2 SH - 3 SH	3 SH - Open	1 SH - 3 SH
Epiphone HB	LHB1	Coil 1	15.9	10.5	18.9	19.6
Epiphone HB	LHB1	Coil 2	15.0	9.0	15.8	18.6
Epiphone HB	LHB1	SeriesAid	17.5	11.7	16.5	21.1
Epiphone HB	LHB1	SeriesOpp	12.6	6.9	16.0	16.2
Epiphone HB	LHB1	ParrAid	17.2	11.2	16.7	20.7
Epiphone HB	LHB1	ParrOpp	12.2	6.5	16.0	15.8
Dimazero	LHB2	Coil 1	16.1	11.1	16.7	20.0
Dimazero	LHB2	Coil 2	15.8	11.1	16.7	19.8
Dimazero	LHB2	SeriesAid	18.7	12.8	16.8	22.2
Dimazero	LHB2	SeriesOpp	15.0	5.4	16.2	17.5
Dimazero	LHB2	ParrAid	17.5	12.0	16.6	21.2
Dimazero	LHB2	ParrOpp	12.7	8.8	16.3	17.0
Seymour-Duncan	LHB3	Coil 1	13.2	6.7	11.6	16.6
Seymour-Duncan	LHB3	Coil 2	13.2	6.7	11.0	16.6
Seymour-Duncan	LHB3	SeriesAid	14.0	5.7	6.3	16.8
Seymour-Duncan	LHB3	SeriesOpp	12.9	8.9	16.5	17.1
Seymour-Duncan	LHB3	ParrAid	13.3	6.2	6.4	16.4
Seymour-Duncan	LHB3	ParrOpp	13.0	9.0	16.0	17.2
HB Allen Key	LHB1	Coil 1	17.0	12.0	16.9	20.9
HB Allen Key	LHB1	Coil 2	14.7	8.7	15.8	18.2
HB Allen Key	LHB1	SeriesAid	16.7	12.1	16.1	20.7
HB Allen Key	LHB1	SeriesOpp	13.2	7.9	16.6	17.0
HB Allen Key	LHB1	ParrAid	17.1	12.4	16.2	21.1
HB Allen Key	LHB1	ParrOpp	13.3	7.2	16.6	16.8
HB Lat Screws	LHB1	Coil 1	18.1	12.0	18.3	21.6

HB Lat Screws	LHB1	Coil 2	14.7	10.8	17.2	19.0
HB Lat Screws	LHB1	SeriesAid	18.8	12.9	18.1	22.4
HB Lat Screws	LHB1	SeriesOpp	13.6	8.7	17.2	17.5
HB Lat Screws	LHB1	ParrAid	18.5	13.1	17.9	22.3
HB Lat Screws	LHB1	ParrOpp	13.9	7.6	17.3	17.3
EMG-HZ Coil 1	LHB1	Coil 1	12.1	6.9	14.1	15.9
EMG-HZ Coil 2	LHB1	Coil 2	11.8	6.1	13.9	15.5
EMG- HZ	LHB1	SeriesAid	13.0	8.6	13.4	17.1
EMG- HZ	LHB1	SeriesOpp	8.7	3.7	14.3	12.6
EMG- HZ	LHB1	ParrAid	12.8	8.6	13.4	17.0
EMG- HZ	LHB1	ParrOpp	8.7	2.8	14.7	12.3
		Average	14.5	9.0	15.4	18.2
		STDev	2.5	2.7	2.8	2.5

Av	Coil 1	15.4	9.9	16.1	19.1
Av	Coil 2	14.2	8.7	15.1	17.9
Av	SeriesAid	16.4	10.7	14.5	20.1
Av	SeriesOpp	12.7	6.9	16.1	16.3
Av	ParrAid	16.1	10.6	14.5	19.8
Av	ParrOpp	12.3	7.0	16.2	16.1

STDev	Coil 1	2.3	2.4	2.8	2.3
STDev	Coil 2	1.4	2.0	2.3	1.6
STDev	SeriesAid	2.4	2.9	4.3	2.5
STDev	SeriesOpp	2.1	2.0	1.0	1.9
STDev	ParrAid	2.4	2.7	4.3	2.4
STDev	ParrOpp	1.9	2.2	0.9	1.9

At the bottom of the table is a rather interesting addendum where the Average dB level and Standard Deviation for each configuration is calculated. Strictly more than 30 readings needs to be correlated before the Standard Deviation can be considered with much degree of confidence, but in this case a cursory glance over the figures shows where the deviations are.

How Should the PAF Windings be Connected?

These figures clearly show that opposing windings have a significantly lower output level than single coils or aiding connected coils – be they series or parallel connected! If the coupling were in the order of 0.5 then the output level of opposing windings would be far lower than it is shown here. It therefore makes very little sense in connecting opposing wound coils.

Also, the relative output levels from either coil by themselves are very consistent with the other coil. This means that the two coil magnetics on the one magnetic structure is rather consistent – and again this is because the magnetic circuit is both fairly well 'balanced' and the magnetic circuit is rather leaky (away from the strings) – where it should be leaky only near the strings!

Also, the series aiding coil configuration does not put out much more level than one coil by itself – even though the windings are doubled – this is because of the very poor coupling factor. The controlled calculations here show that the comparative levels are almost indiscernible.

Also, parallel-aiding coils put out a comparable level to that of a single coil – but it has half the series resistance of a single coil, and far less inductance, so the spectrum will not be nearly as affected by equivalent loading by the resistance load of Volume pots etc.

Manufacturers would do much better to connect the two coils in parallel aiding and reap the benefit of having a much lower winding resistance, with a far lower source inductance, with more certainty in manufacturing specifications. The parallel aiding configuration provides a considerably wider audio spectrum, and is less prone to noise interference issues caused by 'floating coils' as seen with the series aiding configuration.

Proving the Point!

The table below shows the 3 dB points for all these pickups in all their configurations, based on a 50 k Ohms load, for varying air-gaps as decided above, based on a First Order filter where the inductive reactance equals the winding combinational resistance and the 50 k Ohms load.

You don't have to look far to see that the Series Aiding arrangement has (by far) the lowest bandwidth, and that the smaller the air-gap the lower the cut off frequency. The Parallel Aiding arrangements typically have about another 1.8 octaves up their sleeve virtually the for the same output level.

Brand	Structure	Connection	3 dB 1 Sh	3 dB 2 Sh	3 dB 3 Sh	3 dB Open
Epiphone HB	LHB1	Coil 1	1.89	2.01	2.08	2.27
Epiphone HB	LHB1	Coil 2	2.00	2.11	2.17	2.31
Epiphone HB	LHB1	SeriesAid	0.92	1.00	1.04	1.11
Epiphone HB	LHB1	SeriesOpp	1.27	1.33	1.36	1.44
Epiphone HB	LHB1	ParrAid	3.15	3.38	3.51	3.76
Epiphone HB	LHB1	ParrOpp	4.26	4.44	4.54	4.83
Dimazero	LHB2	Coil 1	1.90	2.02	2.10	2.25
Dimazero	LHB2	Coil 2	1.90	2.03	2.10	2.25
Dimazero	LHB2	SeriesAid	0.91	0.99	1.03	1.11
Dimazero	LHB2	SeriesOpp	1.22	1.29	1.32	1.40
Dimazero	LHB2	ParrAid	3.11	3.35	3.49	3.73
Dimazero	LHB2	ParrOpp	4.05	4.23	4.35	4.64
Seymour-Duncan	LHB3	Coil 1	1.86	1.95	1.99	2.07
Seymour-Duncan	LHB3	Coil 2	1.87	1.96	2.00	2.07
Seymour-Duncan	LHB3	SeriesAid	0.79	0.83	0.84	0.86
Seymour-Duncan	LHB3	SeriesOpp	1.36	1.42	1.46	1.56
Seymour-Duncan	LHB3	ParrAid	2.75	2.88	2.94	3.00
Seymour-Duncan	LHB3	ParrOpp	4.62	4.84	4.97	5.30
HB Allen Key	LHB1	Coil 1	3.46	3.72	3.87	4.15
HB Allen Key	LHB1	Coil 2	3.62	3.82	3.92	4.17
HB Allen Key	LHB1	SeriesAid	1.69	1.81	1.89	2.01
HB Allen Key	LHB1	SeriesOpp	2.16	2.26	2.32	2.48
HB Allen Key	LHB1	ParrAid	6.05	6.50	6.78	7.23
HB Allen Key	LHB1	ParrOpp	7.79	8.16	8.35	8.93
HB Lat Screws	LHB1	Coil 1	1.90	2.06	2.14	2.32
HB Lat Screws	LHB1	Coil 2	2.06	2.18	2.25	2.42
HB Lat Screws	LHB1	SeriesAid	0.91	0.99	1.03	1.12
HB Lat Screws	LHB1	SeriesOpp	1.34	1.41	1.45	1.56
HB Lat Screws	LHB1	ParrAid	3.13	3.40	3.56	3.85
HB Lat Screws	LHB1	ParrOpp	4.55	4.79	4.90	5.28
EMG-HZ Coil 1	LHB1	Coil 1	2.10	2.19	2.24	2.35
EMG-HZ Coil 2	LHB1	Coil 2	2.17	2.25	2.30	2.41
EMG- HZ	LHB1	SeriesAid	1.07	1.12	1.15	1.21
EMG- HZ	LHB1	SeriesOpp	1.35	1.39	1.41	1.49
EMG- HZ	LHB1	ParrAid	3.62	3.78	3.88	4.06
EMG- HZ	LHB1	ParrOpp	4.56	4.68	4.75	5.01

Av	Coil 1	2.19	2.32	2.40	2.57
Av	Coil 2	2.27	2.39	2.46	2.61
Av	SeriesAid	1.05	1.12	1.16	1.23
Av	SeriesOpp	1.45	1.52	1.55	1.66
Av	ParrAid	3.63	3.88	4.03	4.27
Av	ParrOpp	4.97	5.19	5.31	5.66
STDev	Coil 1	0.6	0.7	0.7	0.8
STDev	Coil 2	0.7	0.7	0.7	0.8
STDev	SeriesAid	0.3	0.4	0.4	0.4
STDev	SeriesOpp	0.4	0.4	0.4	0.4
STDev	ParrAid	1.2	1.3	1.4	1.5
STDev	ParrOpp	1.4	1.5	1.5	1.6

At the bottom of this table the averages for each construction has been tallied along with the Standard Deviation. These figures could be slightly misleading as the inductance in these pickups varies considerably.

Conclusion and Where from Here

Looking at this frequency response limitation another way, given that the test load was 50 k ohms and the upper –3 dB frequency were say 4 kHz. If the load resistor were increased to say 100 k ohms, then the upper –3 dB point would be also doubled to 8 kHz and if the load resistor were say 200 k ohms, then the –3 dB point would be now 16 kHz.

So the parallel aiding connected PAF configuration has a lot going for it, specially when it comes to equivalent output level to series aiding, together with a significantly lower total source resistance and lower source inductance.

At this stage the Second Order structure Low Pass (LC) filter has not been really fleshed out, but it would be fair to say that with a parallel aiding configuration for the PAF guitar pickup, a small value shunt capacitor will shape the frequency response with a peak that can be reliably calculated before trying.

Because the parallel configuration is highly repeatable, to me this is the Quality way to wire all PAF guitar pickups, as then the manufacturing and production spread variation for these pickups is minimised, and you can accurately predict the frequency response that you want before you start fiddling with guitar controls!

Malcolm Moore 19 Oct 2008