[The G word: Demo project - A balanced volume controller]

[Bruno Putzeys] - June 25, 2014

[Part 1 introduces the topic of grounding and "GND-think." Part 2 considers the ideal differential input. Part 3 looks at impedance balance vs. current balance, instrumentation amps and cable shielding.]

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Demo project: a balanced volume controller
According to a quick scan of professional audio forums, a perennial question is how to build a purist balanced volume controller. Two recurring themes are H-pad attenuators and dual-gang pots.

H-pads attenuate the differential-mode component without affecting the common-mode component. At low volume settings, effective CMRR of the whole system may even become negative. H pads are out. A two-gang potentiometer will convert CM to DM unless matching is phenomenal. Other than that, CM impedance is directly determined by DM impedance.

For noise and distortion reasons you'd like a low-resistance pot; for CMRR reasons you'd like high resistance. This is going nowhere either. It turns out that there is no acceptable method of constructing a balanced passive volume controller. In fact, there is no sensible way to arrange a potentiometer in a differential fashion.

I have a double agenda in presenting this demonstration project. Firstly just to demonstrate how the "new" design methodology works in practice, but secondly to invite doubters to discover for themselves how a bit of rational engineering can produce staggeringly good sonics without resorting to boutique parts or boutique thinking. This is going to be the cheapest and best-sounding preamplifier you've ever built (**figure 25**).

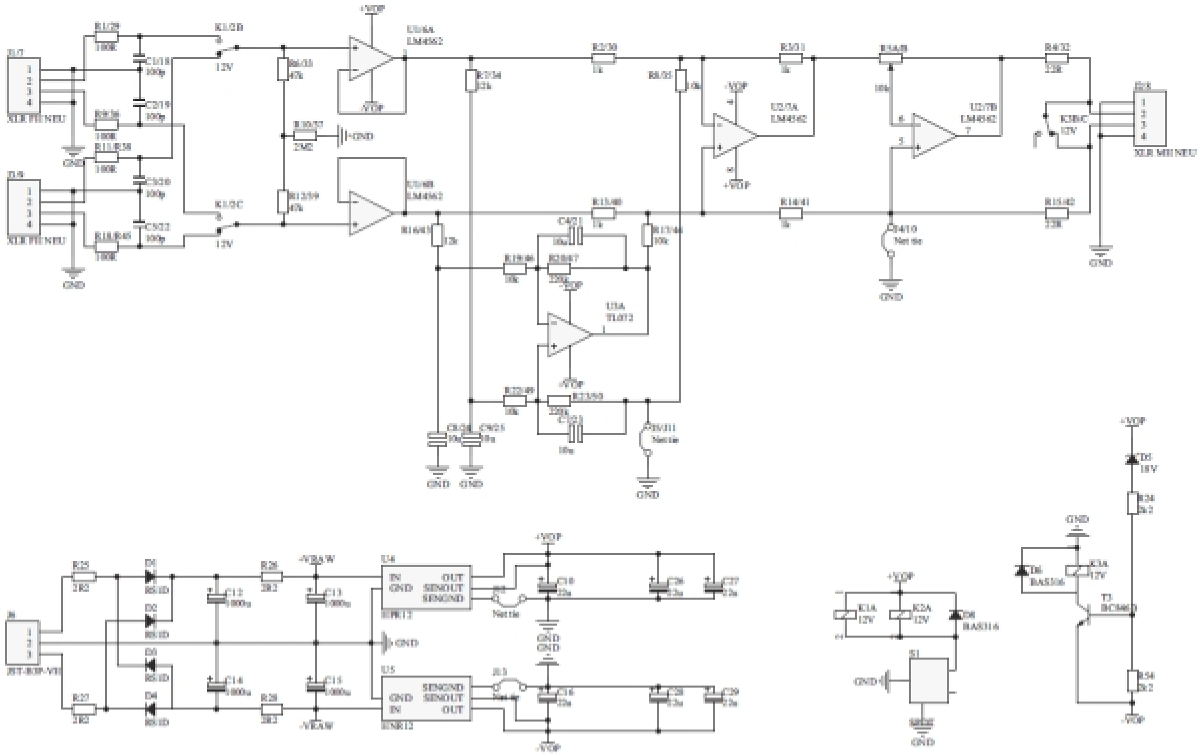

Figure 25: Complete balanced preamp/volume controller

The input stage
The input stage is a straight buffer implementing the improved input biasing network. I would've used Whitlock's input chips and implemented the capacitive bootstrap technique as well, except that the distortion performance is not good enough in my view.

The difference stage
As said, we're out of luck when it comes to wiring a pot differentially so we won't even try. Instead we'll be using the surrounding stages to reference the cold point of the variable gain stage. So between the input buffer and the variable gain stage we insert a difference amplifier. This is the circuit that'll confer CMRR to our little preamp, so resistor matching is of prime importance here. The output of the difference amplifier is referenced to the cold point of the volume controller.

The DC servo
I've always considered it the task of the preamplifier to remove DC. I've thrown in an unusual DC removal circuit that isn't actually a servo in that it doesn't measure DC at the output. Instead it's a 2nd-order low-pass filter whose output is subsequently subtracted from the signal.

The volume controller

The volume controller
As most experimenters will have noticed, potentiometers leave wildly varying and occasionally unpredictable footprints on the sound. Postmodern etiquette then requires that one congratulates oneself on having heard something that the objectivist clique doubtlessly will never have noticed and will most certainly deny, so the new observation is set aside for wonderment and mysticism and, crucially, exploitation by manufacturers of very expensive parts.

I must disappoint the postmodern set here. The problem is perfectly well known and well-understood if not by too many people. There are two elements at play. The resistive track is rarely linear. On top of that the non-linearity is dependent on the current density in the track. In logarithmic pots the divider ratio becomes non-linear. Also the wiper contact is a source of distortion.

Secondly, very few amplifier circuits have a perfectly linear input impedance. It doesn't even matter whether it's valves, JFETs or bipolar, op amp or otherwise. All have, to a lesser or greater extent, a variable input capacitance. Drive an amplifier circuit with a few kilo-ohms at your peril.

Two exceptions. Virtual-ground circuits have no input capacitance modulation problems because the input signal is zero. Differential circuits have no problem either because the nonlinear charge currents cancel.

Whoa. Not only does differential circuit design do away with current loop problems, it actually eliminates a significant source of distortion. If panaceas exist, this must be one of them.

Long story short. Instead of operating as an attenuator, the potentiometer is used as the sole feedback element in an inverting amplifier. Linearity of the volume control now only hinges on the linearity of the divider ratio. This is almost guaranteed in linear pots. The track resistance can be very very nonlinear before this becomes an issue.

Just to make a point I decided to use a cheap 9mm "car stereo" pot. Distortion performance is top notch. The only drawback is that the thing gets a bit fiddly at low volume settings. We'll have to live with that because adding external resistors to modify the control law will immediately put the linearity of the track resistance back into the equation. As it is, channel matching is surprisingly good even down to moderately low settings.

The output stage?
There's no output stage! Well, there is, in a way. They're the two 22-ohm build-out resistors whose only function is to isolate the cable capacitance from the op amp. Referring back to Figure 6 there's no point in doing anything with the signal other than to provide connections to both ends of the signal i.e., the output pin of the op amp and the potential that the variable gain stage calls "my zero volt reference." The full parts list is shown in **Table 1**.

Designator	Part description	Designator	Part description
C1, C2, C3, C5, C18, C19, C20, C22	100p 50V NPO 0805	R1, R9, R11, R18, R29, R36, R38, R45	100R 0805 thin film
C4, C7, C8, C9, C21, C23, C24, C25	10u 50V Non-Polar	R2, R3, R13, R14, R30, R31, R40, R41	1k 0805 precision thin film
C10, C16, C26, C27, C28, C29	22u 63V	R4, R15, R32, R42	22R 0805
C12, C13, C14, C15	1000u 25V	R5	PTD902-2015F-A103
D1, D2, D3, D4	RS1D	R6, R12, R33, R39	47k 0805
D5	BZX384C18	R7, R16, R34, R43	12k 0805
D6, D8	BAS316	R8, R17, R35, R44	10k 0805 precision thin film
J1, J3, J7, J9	NC3FAH2	R10, R37	2M2 0805
J2, J8	NC3MAH1	R19, R22, R46, R49	10k 0805
J5	JST-B3P-VH	R20, R23, R47, R50	220k 0805
K1, K2, K3	Relay 12V 2x1A DPDT	R24, R54	2k2 0805
U1, U2, U6, U7	LM4562 SO8	R25, R26, R27, R28	2R2 1206 high current
U3	TL072 SO8	S1	Toggle switch SPDT
U4	7812 or HPR12	T3	BC846B
U5	7912 or HNR12		

Table 1: Full parts list.

PCB layout

PCB layout
Differential circuit design treats every signal as a pair of wires. Usually though, only one of them is actively driven. The other is tied to the ground plane at some point by means of which the two processing stages at either end agree to call this particular potential "reference potential."

Circuit board layout programs tend not to like this kind of thing. When a connection is nominally the same net as the ground plane, they'll nail every pin to the ground plane at the slightest excuse. And if you do make it a separate net, anything you do to make a galvanic connection to the ground plane is treated as a design rule error.

With some layout tools there is nothing for it but to use a physical zero-ohm resistor to connect the nets together when the board is assembled. Others, like Altium allow a kind of "part" called a "net tie." When a part is declared to be a net tie, short circuit checking is locally turned off for that part allowing you to make overlapping pads. That's what I've done here. My net ties are clearly recognizable in the board layout as two overlapping circular pads to serve as a visual aid to see what's going on.

A salient feature of the board layout is that all components are placed in pairs. This runs counter to the usual practice of making the hot and cold sides of a differential circuit each other's mirror image. But remember what we're trying to do: we're trying to make sure that any interference affects both legs equally. Another way of putting this is that the area enclosed by a differential pair must be as small as possible. Mirror-image layouts are exactly the wrong way to do it. If you want to have a visually appealing symmetry, do so with the left and right channels.

Power supply
As a wink and a nod, the power supply is based on my [HPR12/HNR12 regulators](), available from [Hypex](). The foot-print is compatible with ordinary 7812/7912 parts though.

The PCB layout and Stuffing Guide is shown in **figure 26**.

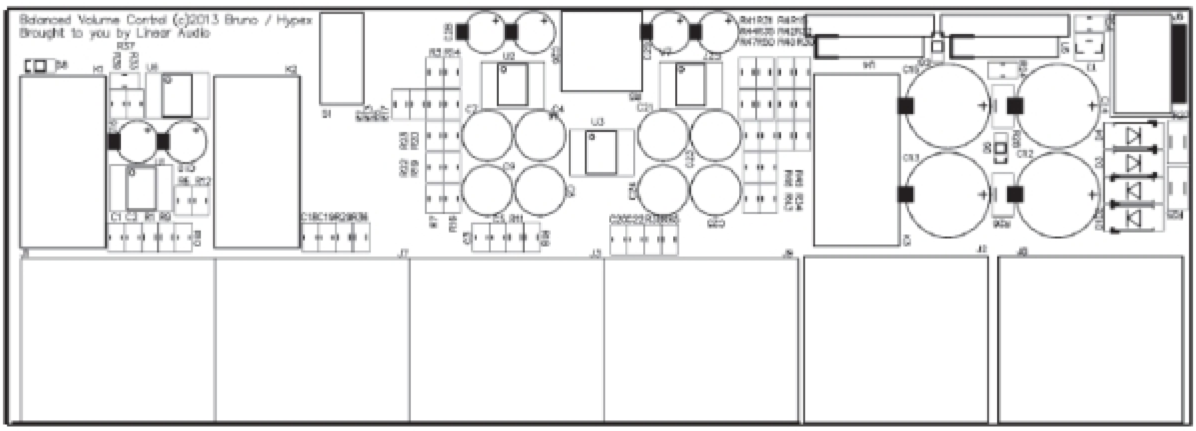

Figure 26a: PCB component placement

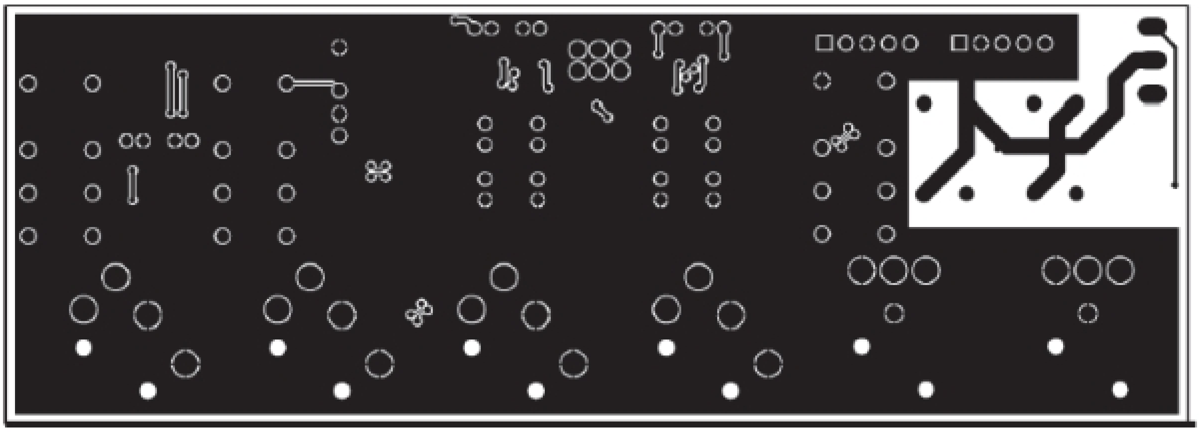

Figure 26b: PCB bottom copper

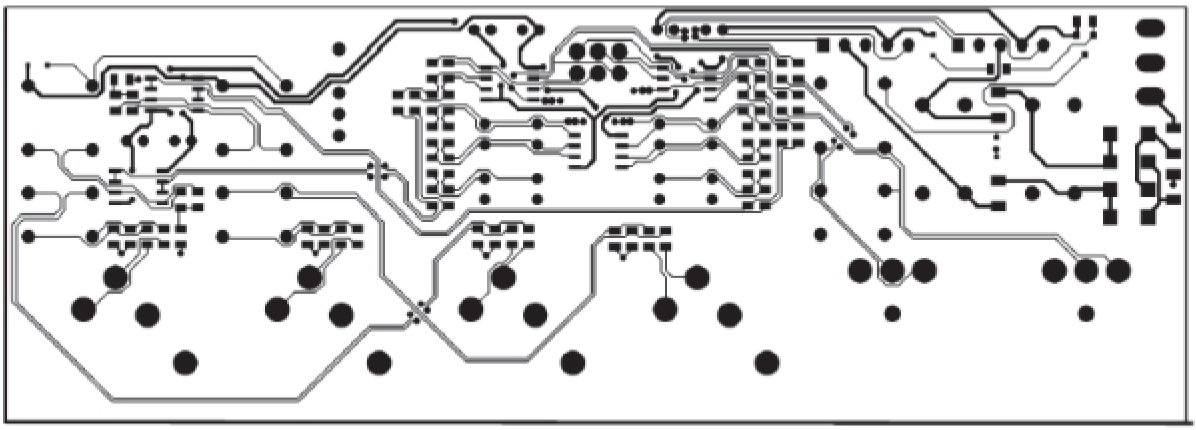

Figure 26c: PCB top copper

Test results

Test results
I tested the circuit with a 600-ohm load and started with a 1-kHz THD+N level sweep (**figure 27**). Both at unity gain and -20dB, onset of clipping is just above 19dBu (6.9Vrms). Clearly the difference amp stage clips first.

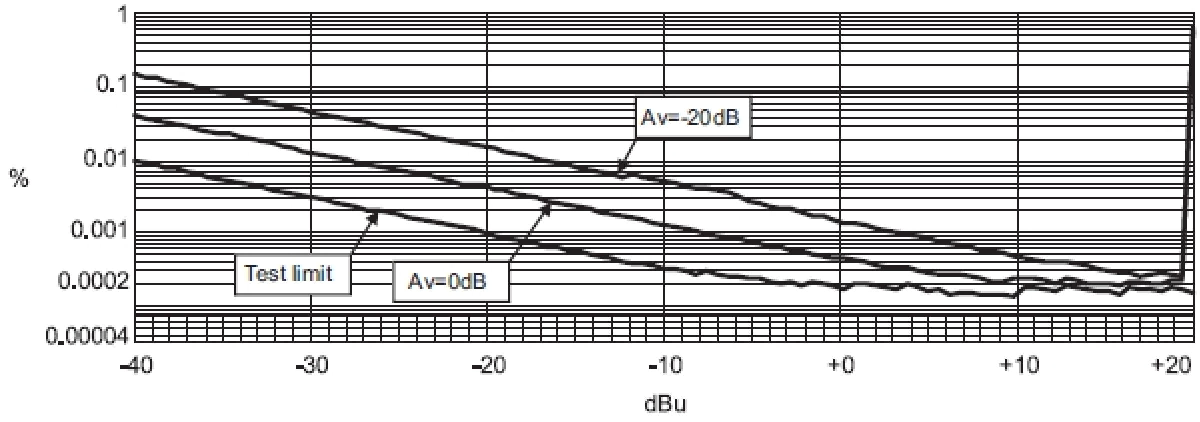

Figure 27: Distortion+Noise as a function of input level at 1kHz

Other than indicating the maximum signal level this plot doesn't say much. Noise is clearly visible at lower levels but at higher levels the reading is dangerously close to the noise floor of the analyser. A THD vs frequency sweep was more revealing (**figure 28**). For this test I set the analyser to measure just the harmonics and ignore the noise. The input level was set to 18dBu which is pretty close to the clipping point and quite a common choice in professional equipment.

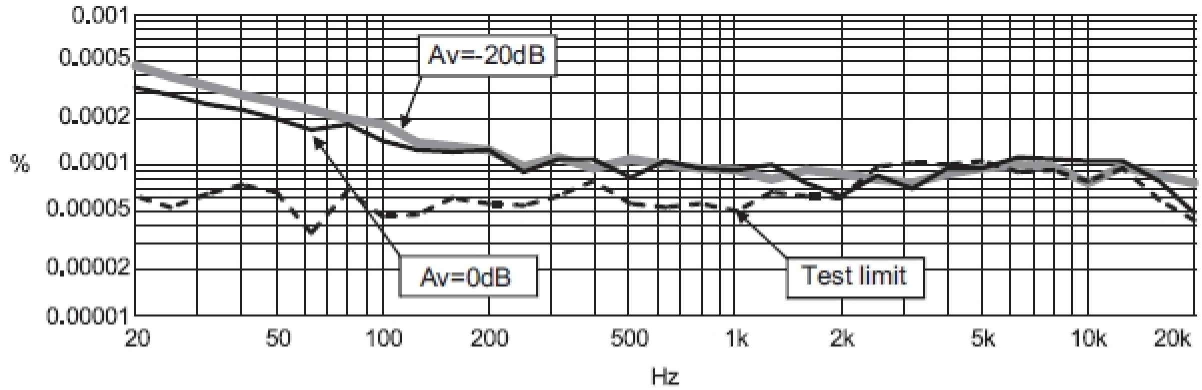

Figure 28: THD without noise as a function of frequency at 18dBu

The rise at low frequencies is attributable to uneven thermal modulation of the resistance track. In retrospect I should have picked something like a Cermet pot. In spite of this, you will find it very difficult to find a cleaner preamp, regardless of price or fancy parts. Note the absence of distortion at the top end of the audio band. Any form of capacitance variation would have resulted in a rise with frequency.

There was no measurable difference between 100k loading and 600-ohm loading, even though the latter forces the op amp far into class B. This demonstrates the complete indifference of the circuit to distorted currents returning through the supply lines and the ground plane.

Sensible listening tests

When you decide to build this preamp, build two. That way you can use the second preamp as a volume controlled A/B switch to compare, variously, an expensive high-end preamp (set to unity gain), this little preamp (also at unity gain), and a direct connection to the source. Listen to which of the two preamps' outputs resembles the input signal most. You may find the experience enlightening.

More about Bruno Putzeys.