The Filter Wizard
issue 20: Filter DC Voltages Outside Your Supply Rails
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Want to filter a bias, reference or even power supply voltage effectively, but only using circuitry that runs off a much lower supply rail? Might sound impossible, but it's not. The Filter Wizard shows how it's done, with some theory in this article and a practical design in a forthcoming piece.

Active lowpass filters can have a wide range of AC response characteristics but they all have one thing in common, and that's that they pass DC. Like other analogue processing blocks, they can therefore introduce errors in both the DC offset and the gain or span. Most filter configurations introduce DC offset error due to the offset voltages of the amplifiers used. We saw, in "Lowpass filters That Don't", an approach that can mitigate this to some extent. In the final circuit presented there (shown again as figure 1 below) the heavy lifting of frequency response management is done by an active "sidechain", and the main signal just passes along a resistor network from input to output. The only contribution to offset error comes from amplifier input leakage currents dropping voltage across this resistor network. In modern MOS amplifiers these leakage currents are tiny (at least at room temperature).

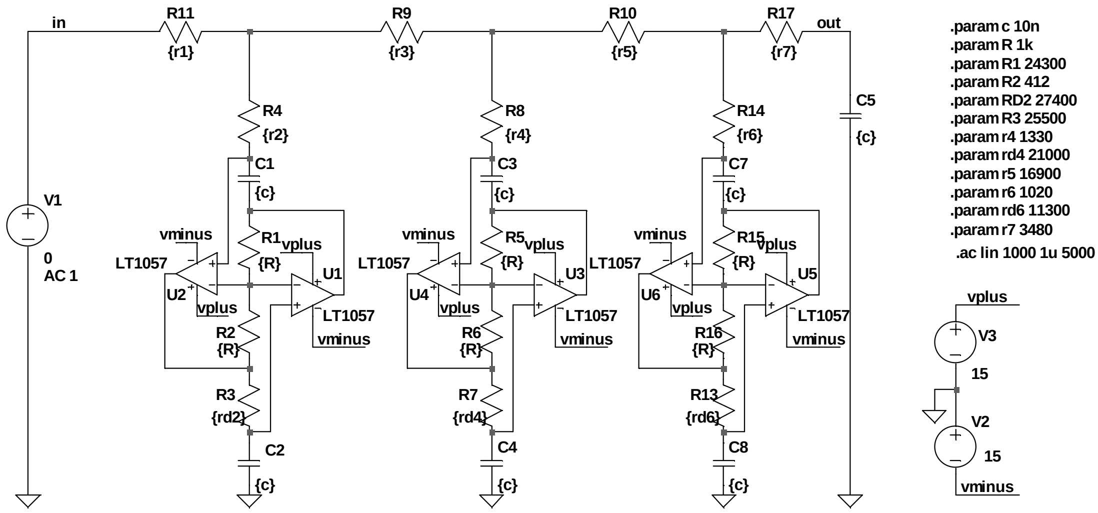

Figure 1: A DC-coupled lowpass D-element filter with low offset voltage.

There are some use cases that this configuration still doesn't support, though. One is where you can't rely on the amplifier input currents being low enough to neglect. This might be the case, even with MOS amplifiers, if the filter is inside a seismic sensor sitting at the bottom of a very deep hole in the ground. The other case might not seem like a legitimate case at all at first glance. That's where the voltage you want to filter is *outside* the supply voltages that you have available to run your active circuitry. For instance, say you've got a high-value bias voltage of tens or hundreds of volts, and you're trying to lowpass-filter it to remove some ripple, but you only have a 5 volt power supply on your

circuit board. Attenuating the voltage to ‘fit’ is out of the question, since you want the filtered voltage to be the same value as the input – just cleaner.

In these circumstances, don’t we usually just use a series resistor (of suitably low value) and a shunt decoupling capacitor? For sure, no matter what the ripple level is, we can suppress it to negligible levels by sufficiently increasing the time constant of the resulting single-pole passive lowpass filter. But – and you may have already encountered this in your own designs – you can suffer the undesirable double whammy of capacitor-size-too-big and step-settling-too-slow, if you just rely on this simple method.

It seems obvious to consider using a higher order filter to solve this problem. If the ripple frequency is quite low, a passive filter may require inconveniently large inductors. There’s more about passive approaches, and picking an actual filter response, in the next article. Right now let’s concentrate on inductorless solutions – i.e. active filters.

Can we use the D-element ladder filter technique shown in figure 1 to create a suitable high order filter? Well, not as it stands. You can see from the schematic that the amplifiers are connected to the input voltage through a resistive path, and this sets the static voltage at each of the op-amp terminals. There’s no practical way round that. What we need is a D-element topology that doesn’t actually ‘see’ the DC voltage that it’s attached to. And, while we’re at it, wouldn’t it be a good idea if it used fewer amplifiers? (Op-amp manufacturers need not answer that question). To get us started, let me reintroduce you to a filter configuration with which you may well be quite familiar:

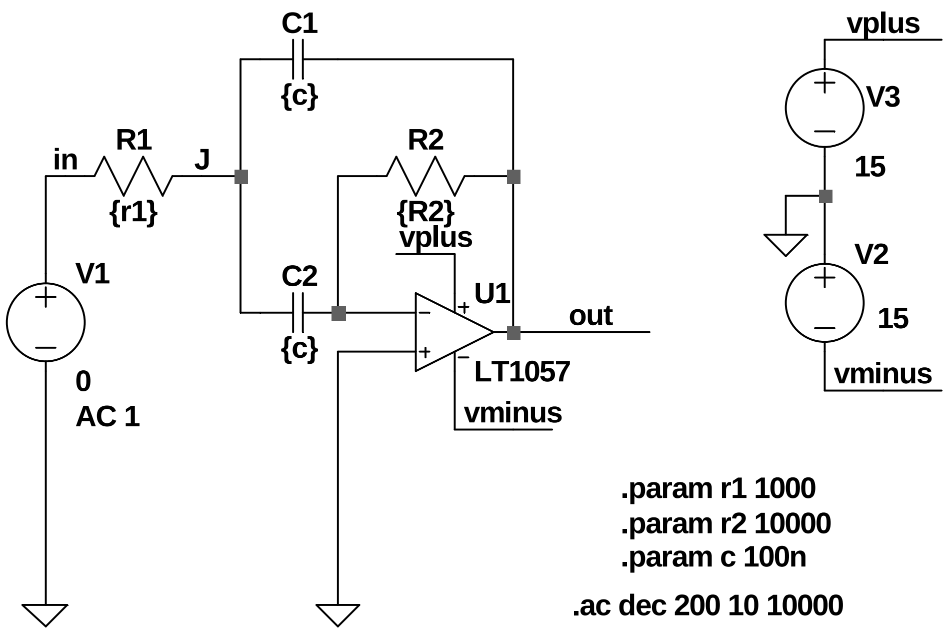

Figure 2: The ever-popular multiple feedback bandpass filter.

This is probably most popular second order bandpass filter circuit around, and the web is awash with information on it. Now as it stands this doesn’t look like it’s much use here,

because it's a bandpass filter, and the filtered signal appears at the amplifier output. That's a bit, well, conventional, and we need to take another look.

Think about what's happening at the point labeled J in figure 2. Can you see by inspection what the frequency response at that point will look like, referred to the input? Well, we know that the voltage at the amplifier output has a bandpass characteristic. And we can also see that the block formed by C2, R2 and amplifier is just a differentiator, with a +6 dB per octave rising slope. So, the voltage at J, when multiplied by this +6 dB/octave slope, looks like a bandpass. For that to happen, J's voltage must actually have a second order **lowpass** response with respect to the input, as shown in figure 3:

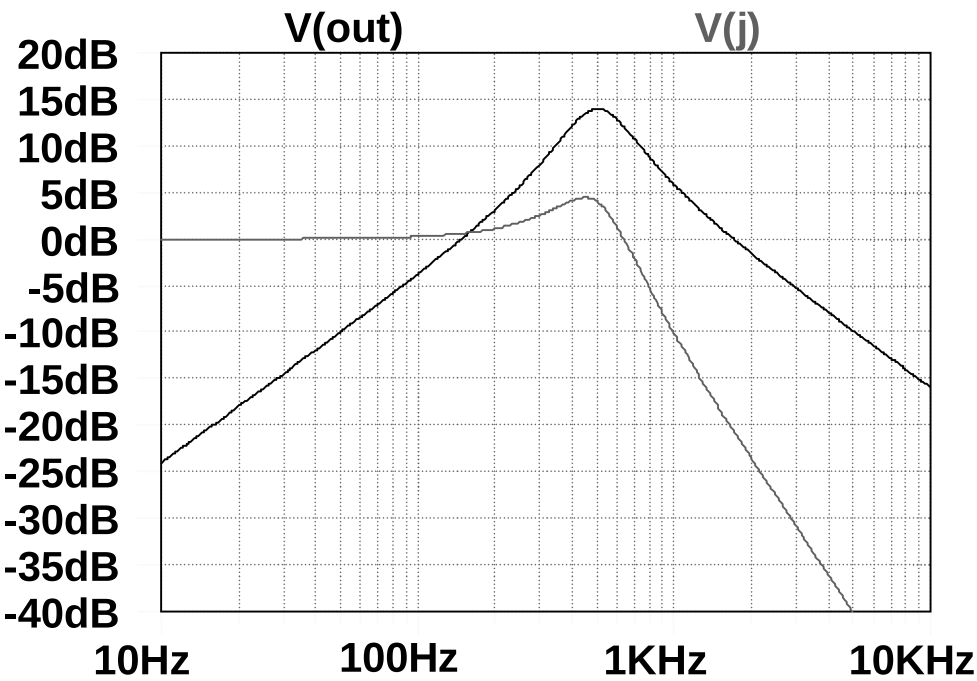

Figure 3: Voltages at nodes out and J in figure 2. V(j) is a lowpass response.

Why is that useful? Well, it shows that we can make a circuit that we can tack onto a resistor to give us more stopband rejection than just using a shunt capacitor alone. You might think of this as a 'super capacitor'. But hang on, isn't that another of the nicknames for the D-element introduced in "Bruton Charisma" and "Gee, I See!"? You bet! It turns out (and you can show this easily with a bit of hand analysis) that at the junction of C1 and C2 our circuit 'looks like' the parallel combination of a capacitor of value C1+C2 and a D-element of value C1C2R2. It's a bit easier to see if you look at the circuit sideways, as in figure 4:

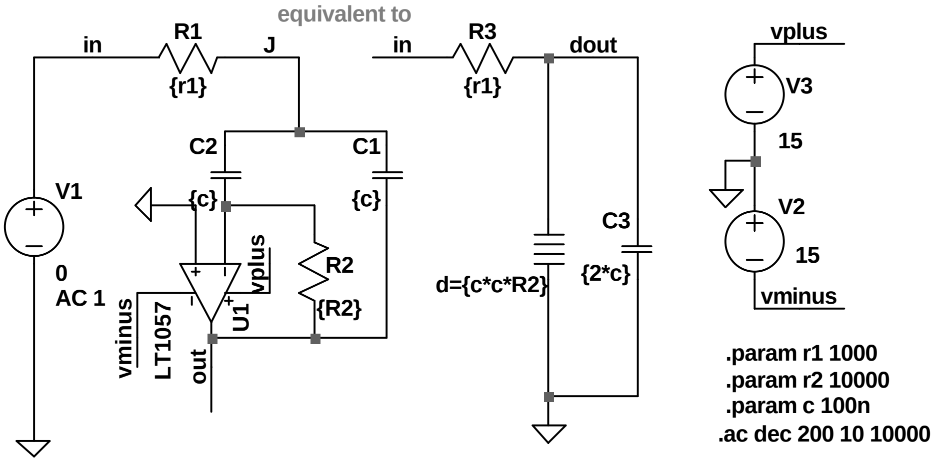

Figure 4: A sideways look at figure 2, showing the ‘hidden’ D-element.

What’s more, both the output and the inverting input of the amplifier are connected to resistor R1 through capacitors. There’s no galvanic connection between the input voltage and the active part of the filter electronics. And that means that we can put whatever voltage we want on that resistor (subject to capacitor breakdown ratings, naturally), independent of the amplifier supply voltage.

We can chain a bunch of these together to get an RDC ladder filter, as shown in figure 5:

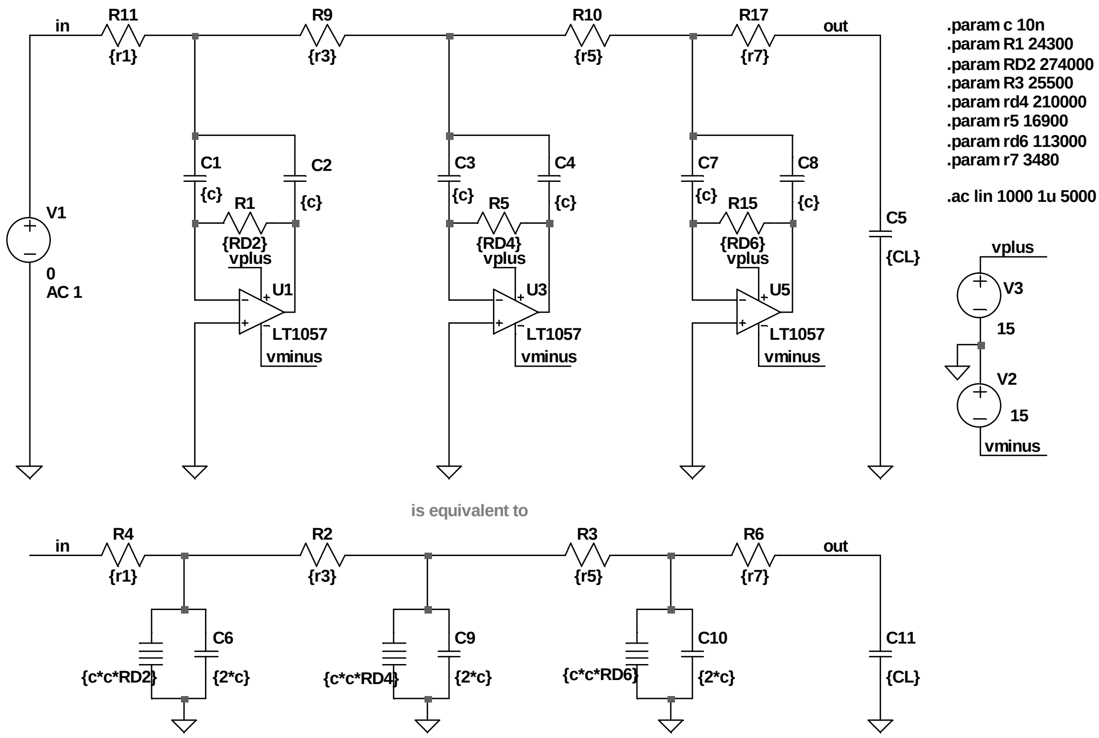

Figure 5: Stringing our new circuits together to make a higher order filter.

Now, we've not made a pure D-element, but one with a capacitor in parallel. When we use these in our ladder filter circuits instead of pure D-elements, we get a filter circuit that's not covered by the standard design methods. The equivalent LCR passive filter (before we apply the Bruton transform) contains capacitors that each have a resistor in parallel. How do we take this into account? Well, you'll remember my attachment to the Million Monkeys Method – using a spreadsheet solver to manhandle a filter circuit to have the right response. We'll see again next time how those monkeys can indeed do a good job, and create useful filter designs.

What's more, you can see that we've only had to use one amplifier for each branch in the filter. Figure 5 is a seventh order filter and it uses only three amplifiers instead of the six required by the regular singly-terminated D-element design in figure 1.

This might all seem rather theoretical and lacking in "how do I use this?" information. Next time I'll describe a worked example of a higher order filter for a high bias voltage that's well outside available DC power supplies, using this approach to meet tight component size and settling time constraints that simply can't be met by just "slapping a capacitor on". This will also involve a deeper look at how cutoff frequency, stopband rejection ands settling time interact, and how we can optimize the values in these non-standard circuits for best performance. Meanwhile, why not look sideways at some of **your** other circuits? Happy (DC-free) filtering! / Kendall