Yet More On Decoupling, Part 2: ring the changes, change the rings

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Previously on “Yet more...” we built up a pair of regulators with output capacitors, and connected them to some decoupling caps with a short length of copper trace. We looked at the impedance at these decoupling caps, and saw some peaks. What happens when we start taking some current from these imperfect supplies?

Figures 2.1 and 2.2 show what happens in the time domain when we take a squarewave current switching between 0 and +10mA at 100kHz from the positive regulator, and one switching between -10mA and 0 on the negative regulator. The rationale is that later on, we’ll either be taking current from the +ve rail, or dumping it into the –ve rail. Remember that the regulators have a static load of 20mA as well, so we are not taking regulator current down to zero. The swept parameter is once again the value of the local decoupling capacitor, 22nF (top trace, blue) to 470nF (bottom trace, pink), and the traces are offset from the top down by 10mV each time.

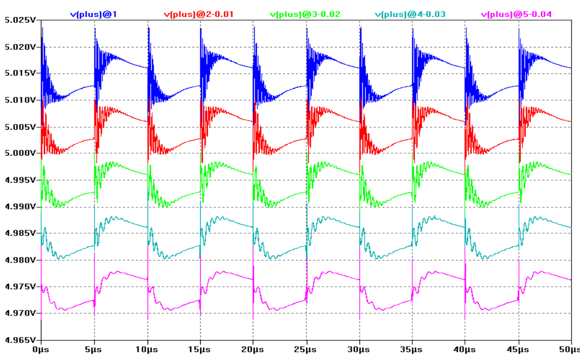

Figure 2.1(L): pinging the positive rail with 100kHz 0 to +10mA square wave, 5mV/div, traces spread by 10mV

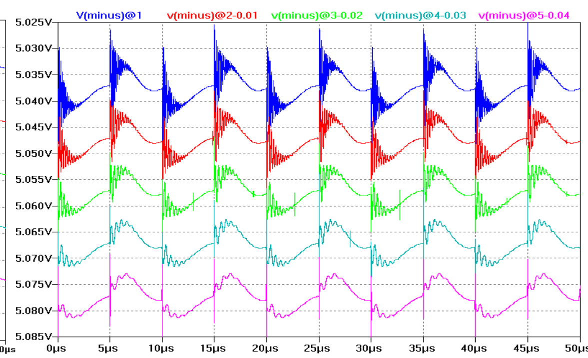

Figure 2.2(R): pinging the negative rail with 100kHz 0-10mA square wave, 5mV/div, traces spread by 10mV

As expected, the smallest capacitor shows the highest amplitude of additional ringing, occurring at the highest frequency. As the capacitor value goes up, the magnitude of the ringing falls. Constant in all this is the effective impedance at the 100kHz fundamental, which seems to be about 0.7ohms for either supply. Note that these voltages are *in phase*. The frequent assumption about the supply variations being symmetrical around ground is not true in this case; indeed, hardly ever true.

The high frequency ringing looks unsightly and may well impact our circuits – what could we do about that? We need some damping somewhere, perhaps by adding some series resistance to one of the capacitors. This will help to dissipate stored energy in the resonant circuits more rapidly, reducing the ‘Q’. Now, with other regulator designs we might have been *forced* to have this extra series resistance, because some LDO designs are not stable when the main output capacitor has too low an ESR. Often in those designs a tantalum capacitor is used, so let’s pick one.

AVX have another useful utility on their download page, SpiTanII, which assists with the selection of tantalum capacitors, and the associated SPICE library contains models which accurately portray the frequency-dependent loss of that type of cap. This should lead to much more accurate simulation than just guessing a resistive ESR value. A 2.2uF 1206-sized part (TPSA225K016R1800, same footprint as the ceramic previously deployed, and with 16V working voltage) was chosen; it has a rated maximum ESR of 1.8ohms at 100kHz, which is about as good as it gets for a small tantalum. Important tip: fit this capacitor the right way round in your simulations. In the simulation world as well as in the real world, the tantalum capacitor doesn't work properly under reverse polarity!

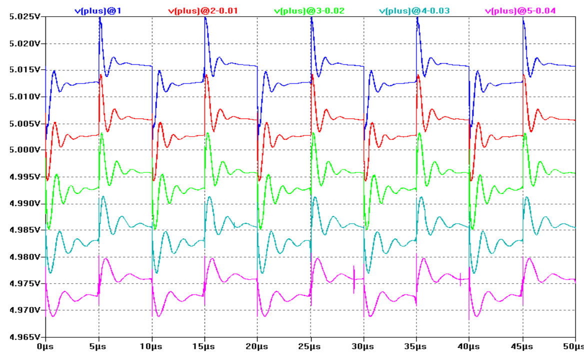

Figure 2.3(L): *same as fig 2.1 but using a 2.2uF tantalum output cap on the +ve regulator*

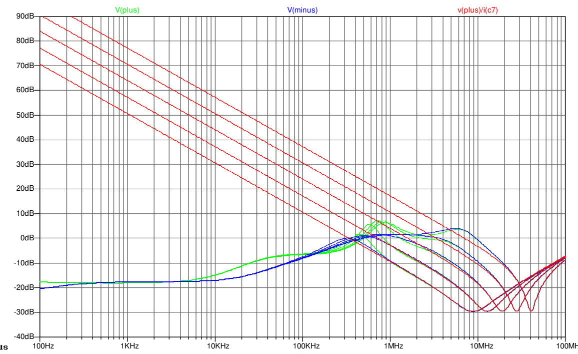

Figure 2.4(R): impedance plots of the supply rails with tantalum capacitors. Contrast with figure 1.2 in part 1

What a difference; a lot less high frequency rubbish (especially on the –ve rail which is not shown). The impedance curves show why; with the tantalum capacitor, the +ve regulator particularly is still showing some peaking just below 1MHz. Still, looks like an improvement, but we will keep testing this choice in the work to come, to see what consequences the ringing has.

Can you hear me?

Most of this work is concerned with effects in the MHz region, but in passing, let's look at what happens with lower frequency stimulation of the rails. This may be interesting for people working on audio applications.

Figure 2.5 shows the rail impedances as we step up the regulator output capacitor from our current 2.2uF up to a whopping 2200uF (ESR was set at 0.1ohm for all of them, as might come from a physically large aluminium electrolytic used in audio circuits). The decoupling capacitor was fixed at 100nF; none of the high frequency effects pointed out earlier are relevant at this timescale. As the capacitance value increases, the audio band impedance becomes flatter, then finally rather less flat as the very largest capacitor does a better job than the regulator does. Figure 2.6 shows the voltage response of the +ve rail to a test current of 0-10mA at 333Hz.

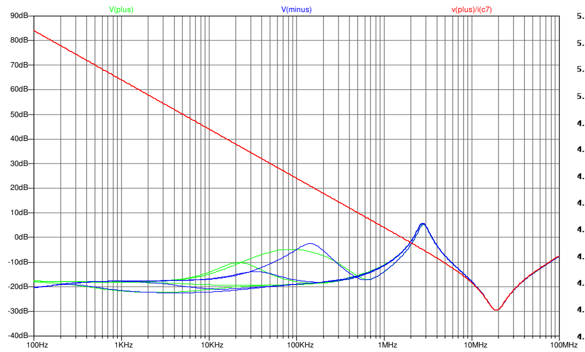

Figure 2.5(L): rail impedance as we increase the regulator output cap from 2.2uF up to 2200uF, decade steps. This is with the noise bypass caps.

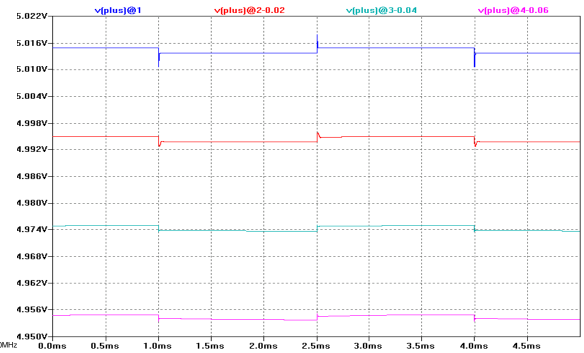

Figure 2.6(R): voltage on the rails when 0-10mA squarewave at 333Hz is applied. 2.2uF top, 2200uF bottom.

As the output capacitor increases, it provides progressively more ‘support’ for the regulator. Going only on the traces in figure 2.6, it looks like a 220uF capacitor would do a good job of delivering an ‘uncoloured’, frequency-independent output impedance in the audio band. The square-wave response for the 2200uF is actually less accurate, though judgements like these will depend on the actual test frequency and there’s no one “right answer”.

Remember that we suppressed some impedance peaking at 10kHz in part 1 by adding the noise bypass capacitors. What happens if we lift these off and run this test again?: The resulting rail impedance is shown in figure 2.7; the location of the peak falls as the output capacitor is increased, but even with an enormous 2200uF capacitor it’s still well into the audible band. The consequences of this peak are clear in the current transient test. Perhaps it’s not surprising that advocates of ultimate audio quality insist that capacitor selection can have an effect on a system’s sonic performance even where you’d think it couldn’t, like on the output of a regulator. Fit those noise bypass caps!

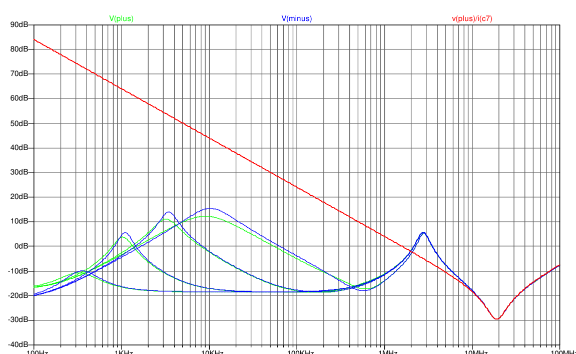

Figure 2.7(L): as figure 2.5 but with the noise bypass capacitors removed. Note the resonant peak in the audio band

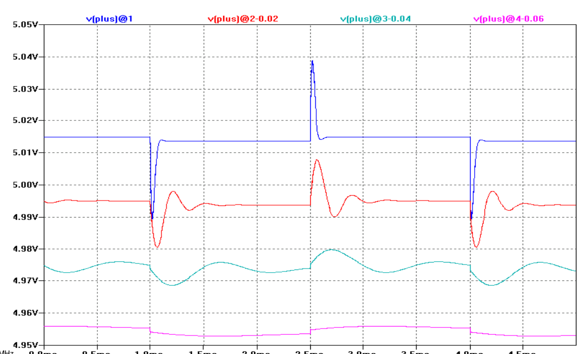

Figure 2.8(R): the response of figure 2.7 to the 0-10mA 333Hz square wave. Talk about ringing!

Still to come: we’ll look at ‘real’ operational amplifiers (well, models of them, anyway) and see what actually happens at their output when their supply pins are waved around.

And then we'll bring those amplifiers and the power supply from this part together. It won't be pretty! To be continued...

Takeaways from this part:

- Whatever the LDO datasheet says, high-ESR output capacitors give better control of high frequency supply resonances
- The smaller you make the main ceramic decoupling capacitor, the faster and larger will be the ringing that occurs on a load current step – this is a small-signal effect and occurs for *any* current change, not just large ones.
- If you are designing audio circuits which don't have impeccable power supply rejection, the LDO regulator impedance bump could cause coloration as it usually occurs within the audio band. Huge output capacitors don't cure it, in fact they could make it worse. Use that noise bypass connection.