easily implemented trick then allows the series regulator to both source *and* sink output current, with a sink capability up to the level of the bleed current. The test condition examples discussed here used a relatively high bleeder current of 100–140mA, but obviously you can use lower levels.

- A general point to be made is that Figs. 8a and 8b are *optimized* circuits, and as such, you should think long and hard before attempting to "tweak" them—they've already been tweaked! Don't change the op amp from an AD848 or AD797, unless you don't care about retaining all aspects of performance (if you don't care about full performance, why build it at all?). Besides the degradation likely with other devices, there is also the real possibility of oscillation. The passive parts are much less critical, but again, why run a risk of degradation?

The selection between the AD848 and AD797 is best made in terms of polarity, dependent upon the specific application. While a good all-around choice, the AD848 has lower LR at low frequencies, particularly for negative operation. The AD797 is also preferable for lowest noise and highest DC stability (see below, although the latter of these points may be moot for audio uses).

- A subtlety which may or may not be obvious is that these regulator circuits operate the op amp in a *single supply mode.* By definition, this eliminates noise from the opposite polarity unregulated supply, and also aids in start-up to the desired output state. For these reasons, I do not recommend that you operate the Fig. 8 circuits from dual unregulated supplies.
- The low dropout feature of the new circuits can be optionally disabled, by deleting the current source components and the diode in series with R2 (for stability, R2 should be retained in any case). However, you should carefully consider before you exercise this option. It simplifies the circuit, but at the expense of higher dropout, obviously. A more subtle point of this mode of operation is that it might sacrifice the robust startup characteristic provided by the current source (which tends to automatically force the circuit to the desired output state).
- A major caveat is to watch the capacitive bypassing details at the regulator output. Note that in Figs. 8a, 8b, and 9 there is no output film capacitor shown, which is done purposely. High-Q (low ESL/ESR) capacitors such as stacked films or ceramics should *not* be connected directly across the regulator output! This caveat is nonnegotiable because of the wide regulator bandwidth, which reacts negatively with the rapid phase changes produced by a high-Q cap load, and as a result oscillates merrily. Film capacitor types, if used, are better applied right at the load decoupled by low DCR chokes or ferrite beads, or even just normal wiring of a few inches or more. The electrolytic bypass C5 *is* desirable, but its value is not highly critical.
- DC stability of the Figs. 8a and 8b circuits can be made quite high if desired, even though this is an unlikely audio priority. Using an AD797 amplifier with R1 and R3||R4 matched resistances, drift can approach that of the reference device used (many others offer lower TC than the 329DZ's 100ppm).[6] This also assumes due attention to operating C4 in a low leakage condition.[14] The ½W resistor types specified for R3 and R4 also aid DC stability.
- Master/slave (same polarity) regulators can be operated, using the common reference of the "master" stage. In such a setup, a single reference source feeds the master regulator R1-C4 filter and error

amp/pass device, plus additional slave RC filter networks and error amp/pass devices. This allows the additional slave regulators to be added without the full complexity of 100% parts duplication, at little or no performance trade-off. To ensure proper startup, the reference current of D1 should be increased, by lowering R6.

• Preregulation is possible in principle, but I didn't explore it in this article. My goal was to achieve as high a LR and low a dropout voltage as possible, within a single relatively simple stage. With typical broadband LR of 80dB or more and dropout voltage of 1.2V, the goal was met. I will be interested to hear reader enhancements which extend these performance areas.

• Setting up other output voltages of the general-purpose Figs. 8a or 8b regulators is simply a matter of selecting R3/R4 value(s) to provide a V_{OUT} level different than the 13.8V shown. *Table 1* simplifies this process for 10–18V outputs, and is used as follows:

With the Fig. 8a (8b) circuit's reference voltage V_R set at 6.9V by D1, the output voltage V_{OUT} is generally:

$$Vout = Vr\left(1+\frac{R4}{R3}\right)$$

The ratio of 1+ R4/R3 scales the 6.9V up to the output level, with R1 nominally equal to R3||R4. In this table, R1 is kept at 499Ω for simplicity's sake, and the R3-R4 values are adjusted to provide both the desired ratio shown in column 2 and the nominal 500Ω equivalence. The suggested R3-R4 values of columns 4 and 5 for a range of popular voltages are preferred 1% value selections, with the key word here being "suggested." Note that since the 329 diode's nominal 6.9V output can vary ±5%, exact output voltages should not be expected (without trimming). However, this should really not be necessary, as absolute accuracy is probably not required. This table works for either the Fig. 8a or the 8b circuit, as long as you use a 6.9V reference voltage.

• Although performance for these circuits should be generally repeatable for similar conditions in relative terms, *the data here is based on a small number of samples.* You should expect some deviation due to sample-sample variation, which is not shown for the broader spectrum of circuits tested. Statistical sample studies for a given circuit, while quite worthwhile in their own right, are unfortunately beyond the scope of this article.

Beyond the different regulator topologies, there are also the broader system level points of remote sensing and star power distribution. Optimum use of wiring and layout methods can make application of the new regulators most effective, so Parts 3 and 4 cover this in more detail. General background reading on power supply systems and regulators of various types can only enhance your overall understanding of the circuits and their operation.[19–21]

However, bear in mind that, even though sophisticated, these new regulators are simply one element of an overall AC ⇒ DC power conversion system. Optimization of the raw DC supply towards RFI/EMI suppression and other factors is equally critical to attain the highest performance levels.

A final caveat for the reader is not to overinterpret the absolute terms of performance data. Much of the regulator Z_O performance lies in implementation details, which is under your control. Take the time to do a good job with parts selection, the layout of your circuit, and wiring it into the system. You will be amply rewarded! □

STAY TUNED

I JUST FINISHED part 1 of "Regulators for High-Performance Audio" and wonder whether future articles will deal with higher power applications (i.e., power amps)? While not technically sophisticated enough to comment on the details of your article, I thank you for your contributions.

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Walt Jung responds:

I do not know of any plans for a higher voltage/current "power amp" article on regulators. I agree with you that it would be welcome, and hope someone will step forward to try it. I'd be happy to provide them with the Audio Precision software plus suggestions towards its use. Testing themes of the current series would also be applicable towards higher powered regulators, just as they would towards tube type regulators.

BREADBOARD SEARCH

I AM LOOKING for a source for the Ivanboard breadboards which Walt Jung refers to in his "Regulators for High-Performance Audio" article (*TAA* 1/95, p. 14).

MICHAEL J. AARVOLD
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Contact Mike Chittenden, 900 W. Grove Pky. #1101, Tempe, AZ 85283, (602) 345-8870.—Ed.

SUPER REGULATORS

THANK YOU FOR a very interesting article about regulators in *TAA* 1/95 ("Regulators for High-Performance Audio, Part 1," p. 8). I have also enjoyed earlier POOGE articles and some other articles. I'm currently working on a regulator mod for my X-DAC 3.0 from Audio Crafters Guild. My main interest is in regulators for the AD811-based output stages and the analog supplies for the CS4328 DAC circuit.

All these three "components" use ± supplies and can (very probably) benefit from good "common mode" supplies. Their worst case supply is when one rail is stable and the other one moves.

When supplies have such high quality as the ones you are writing about, how critical is common mode? Is it still a good idea to somehow make the regulators work together?

I have seen some different solutions for common mode regulators, but none have approached the quality of those in your article. They were built around NE5532 op amps and lacked very many discrete components.

Even so, the design in itself might save some components. If, for example, you require a positive regulator, you could perhaps design the negative regulator with the goal to "keep the negative voltage at the same distance from ground as the positive voltage is from the ground." That is, the ground becomes the negative reference point and the midpoint of the ± output becomes the measure point. That would save one voltage reference, and common mode operation ought to be improved.

Also, when using multiple regulators, such as one pair for each audio channel, is it a good idea to reuse the voltage reference and have it supply multiple regulators? That would also decrease regulator complexity (and cost).

Well, time to go parts hunting for the components you use in the article (Sweden is a black hole when it comes to advanced parts for audio amateurs).

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Walt Jung responds:

I know very little about your "X-DAC" or the CS4328. I do know about the AD811, and I can assure you that it simply loves these new regulators. I've built them up in about three different forms, within my preamp as well as a modified (POOGE 5.5 and then some) DAC960. These all use AD811s as line drivers, and in each case the improvement over the previous level of power supply was well worth the upgrade effort and cost.

I am not so sure about the common mode factor, in terms of being a critical issue. As published, the Fig. 8a and 8b regulators are optimized for single supply operation, which inherently eliminates noise injection from the opposite unregulated rail. Note that a tracking type regulator as you describe does not have this advantage, so this factor is a basic weak point of that approach.

You could, however, work around this issue by using the regulated opposite output as the supply feed for the error amp. This could be somewhat complicated by startup problems, which you may appreciate. I did have a tracking type regulator in my preamp for many years, and when it was abandoned for one of these new dual independent regulators, there was a net improvement. This may have been due to the relative sophistication of the older tracking regulator (similar to the POOGE 5.51 circuit) rather than the two different topologies themselves. In any event (in my opinion at least) you won't be wasting your time to try the new regulator.

Yes, you can operate multiple, same polarity regulators from a common reference, in a master/slave fashion. One example of this was the twin +5V supplies used in the AD1891 evaluation board upgrade described by Gary Galo ("Ask TAA: Analog Devices Chips/Super Regulators," TAA *4/94, p. 43). In the context of the* TAA *1/95 article, this would be equivalent to using Fig. 9 with a common AD680 reference but separate op* *amps and pass transistors for the analog and digital 5V outputs.*

I have not done this as yet for the Fig. 8a or 8b circuit, but this would be useful for left and right channels, as one example. You could even have different voltage outputs from the various stages, since they all will have separate feedback networks. However, use separate RC filtering for each slave, and it might be a good idea to bias the 329 heavier in current, to avoid any startup issues.

I'll be interested to hear of your experiences with the circuit(s) and how they work for your application. □