SOURCES 101 TESTS

With regard to Walt Jung's recent article ("Sources 101: Audio Current Regulator Tests for High Performance," April '07 *aX*, p. 10), I am curious how he managed to get a one Vbe current source to perform worse than a two Vbe current source. My hand calculations and SPICE simulation show the one Vbe source to be 5 to 6dB better than the two Vbe source. In addition to having better power-supply rejection, the one Vbe source has higher output impedance for signals originating at the collector of the output transistor. The one Vbe source also lends itself well to simple modifications that can put both its power-supply rejection and output impedance below the noise threshold of Mr. Jung's test.

It is important to note that while power-supply rejection *may* indicate high output impedance, there is no guarantee that it is so. To fully characterize something as simple as a current source would require much more detailed testing. Some of the later examples in part two of the article (May '07), specifically Fig. 13C, look good for power-supply rejection because the source of M1 is bypassed to ground by stability capacitor C1. However, I believe that the output impedance of U1 will be quite a bit lower for signals originating in the output leg.

Thomas Bohley
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Walt Jung responds:

To first respond to paragraph one of this letter, it should be noted that others have already pointed out the poor-performance discrepancy of the Fig. 3A circuit. Chris Paul had first noted this to me in an e-mail; namely, that the "One Vbe" circuit has a theoretical advantage, vis-à-vis the "Two Vbe" type of Fig. 4A. We have since had several back-and-forth exchanges on this topic, aimed ultimately toward some sort of clarifying piece. The request from *audioXpress* for a published response to this letter warrants a reply, even if more information comes later. There is simply no way all of the pertinent technical points can be adequately addressed in a short form.

The essence of Chris' point was that the basic reference impedance of Fig. 3A should be lower than that of Fig. 4A, by a factor of two. Thus it should theoretically and practically be better than Fig. 4A, as is also noted by Mr. Bohley. And, a SPICE simulation does support this point using the values of the respective figures—the Fig. 3A circuit is about a factor of two better than that of Fig. 4A. For SPICE, that is.

Unfortunately, lab measurements don't show this advantage for the Fig. 3A circuit, vis-à-vis the Fig. 4A circuit, at least not using the example values. When recently repeated, the lab data for the "One Vbe" current source were found as published. But, it should be noted that higher values used for R1 might yield better results (by operating Q2 at less current). When R1 is set to 100kΩ, about 10dB better results were noted, as illustrated in the plots following below.

So, it is thus suggested that users of the Fig. 3A circuit might wish to operate Q2 at lower current relative to Q1, for two reasons. One is potential improvements in rejection, as noted. A second is for stability reasons, as originally noted.

So, my brief answer to Mr. Bohley about how I managed to get worse results for the Fig. 3A circuit is that I just plugged in the specified values, and I observed the cited results. Both originally, and also more recently. I agree that these results aren't spectacular, so I may have been bitten by a poor example. Mea culpa. Raising R1 does help the performance of the circuit as originally published. But, there is much more to be said on this circuit.

I received a further e-mail exchange on this part of the article from John Popelish, with a suggestion of a performance enhancement. I note from the above that while Mr. Bohley alludes to improvement modifications to this circuit, he offered no specific information. But John Popelish did, as follows:

"I am wondering if you have tested the simple enhancement to the two-transistor source shown in Fig. 3A. It is based on adding a second driving resistor, with a current approximately proportional to the total supply, but connected to cancel most of the effect of supply voltage variation, over some small range.

"For instance, if you reduce the Rset resistor from 332Ω to 316Ω (to compensate for the small current reduction this change causes) and connect 174kΩ between ground and the bottom of Rset, you get much higher output impedance over the whole audio spectrum, but especially at the low end.

"Adding this compensating resistor, R3, makes the circuit a little less general, because its value must be optimized for each application, depending on the expected range of the supply. But if well chosen, the improvement in supply rejection can be impressive—about 60dB improvement at low frequencies. I am pretty confident that this version can compete with any non-cascoded design on which you reported."

I tested John's suggestion for performance enhancement both with SPICE and in the lab. The SPICE analysis was done with Linear Technology's "LTSpice" package (www.linear.com/designtools/software/switchercad.jsp/). The schematic of the circuit is similar to the original Fig. 3A, but with the addition of R3 to ground, at 174kΩ, and the slight adjustment of Rset. R1 is set to 100kΩ, for the reasons cited previously. This modified circuit is shown in **Fig. 2**, as it was lab tested.

Figure 1 is a plot of a DC simulation in LTSpice, with the supply swept from 16–20V, while R3 is stepped through a range of values, to illustrate the nulling properties. Note that there is a null in output change with supply voltage, which is here centered within a range around 18V for the 185kΩ trace. This null range constitutes a region of very high supply rejection, as can be seen from the data. A value for R3 which minimizes sensitivity for a given supply voltage can be used as a starting point for lab tests.

The **Fig. 2** lab results also illustrate relevant points about the enhancements to the "One Vbe" circuit discussed. With R1 set to 100kΩ and R3 open, a modest improvement is made over the originally published data of Fig. 3B. This is about 10dB, as can be noted on the intermediate curve.

When R3 is added and optimized with an in-situ trim, the errors fall down to the residual noise level at low frequencies. If this trim is done, it should consist of multiple steps. The first would be to use a high-resolution multi-turn film trimmer as a portion of R3, so as to find the exact null point. This would be using a low frequency measurement point, while measuring the null. In this case, the null observed was -142dB at 100Hz. Then, the closest value film resistor can be used in circuits built, i.e., 150 or 154kΩ. Note that although this example was tested with the Audio Precision system, an ordinary shop audio source and a high gain AC preamplifier could also be used to find this null point.

Note also that even if an exact equivalent value resistor isn't available, substantial improvement can still be obtained, vis-à-vis R3 open. This preliminary run with SPICE may or may not be helpful toward narrowing down the truly optimum R3, depending upon the specific type and vendor of transistors and models used. But, in any event, it should give some insight into the mechanism causing the very high supply rejection properties.

Leaving the Popelish enhancements, this brings us to the points raised in paragraph two of Mr. Bohley's letter. He says: ". . . while power-supply rejection may indicate high output impedance, there is no guarantee that it is so." I simply disagree with this, for most of the intended measurement context. Are we really on the same page here? Virtually all of the Sources 101 tests have been specifically aimed toward uses in power systems, as, for example, the shunt regulator cited. This was discussed under "Whys and Wherefores," and "What Tests." I don't believe that a valid critique of this content should be extended to include all of the many more general usages possible. In designing these tests, I was aware of the limitations in testing for fixed loads, but decided that, even with this constraint, the information would still be very worthwhile. After all, who could argue with the merits of audio power supply systems with low RFI sensitivity?

Such applications use a series-connected current source of some impedance, Z, and drive a shunt-connected load. This situation is emulated in these tests with the 1Ω load and the various circuit impedances tested, with calibration data shown. So, I believe the tests are valid for the conditions cited. But there can be exceptions to this—see "intrinsically high impedance output nodes" discussion below.

All that said, I think I do understand what Mr. Bohley is getting at as a potential weakness of some of the circuits. So, in principle I'd grant the general point that, yes, the behavior of some of these current source circuits can be application dependent. Many current source circuits behave differently if fed to medium or high impedance loads with voltage swings present, as opposed to the virtual short of the Sources 101 test cases.

As far as other possible tests, I did allude to this, under "Measured Noise," so no one should interpret these results to be a final word on audio current source circuits. Of course, I do agree with Mr. Bohley that many other useful tests are possible. Perhaps he could explore some of these points in a future article.

Finally, on the performance of Fig. 13C. Yes, this circuit will act differently if the Rset output node is allowed to move in voltage terms. This current source circuit (and many others, I should add) can show different behavior depending on which node is used as the load, and the relative impedances seen there. Few current source circuits have completely symmetric two-terminal behavior, but as was noted in the article, if that's what you need, the JFET (or MOSFET, for higher current) types should be tried. See "Current Source or Current Sink?".

Other current sources useful where load dynamic swings are required would be ones with intrinsically high impedance output nodes (transistor collectors, FET drains, and so on). Examples here include the much discussed Fig. 3A (with variants), as well as Figs. 4A, 5A, 6A, 9C, and so on. For these types of applications at the lower current levels, I will admit that my Sources 101 test methodology doesn't necessarily show an entire picture, as Mr. Bohley says.

Such as they are, the tests nevertheless still give indications which circuits are useful! The tests show that they differ in basic performance; they demonstrate cascode effectiveness, the importance of low-C, and the deterioration with current, and so on. The better performing ones (for example, Fig. 6A, using 2SA1016K transistors) should also do well in amplifier signal paths, either as an input diff pair tail current source, or as a driver stage dynamic load.

But, the above caveats weren't a consideration for the Fig. 13C circuit as originally used with a shunt regulator, with the output fixed at 12V or 21V. So, for these conditions, the test data can be considered valid. This circuit can also be used as either a source or a sink, and will be featured as part of a future shunt regulator article.

Other errata: There are references in the text and figures to the MOSFET circuits using the IXYS IXCP10M45S and the Supertex DN2540, with operation "up to 450V." To clarify this point, readers should note that only the IXCP10M45S has the 450V rating; while the DN2540 is rated at 400V. My apologies for any confusion this may have raised.

Finally, my thanks to readers Bohley, Paul, and Popelish for sharing their thoughts on these articles, allowing an opportunity for further discussions. I have particularly enjoyed interacting with John Popelish on his enhancements to Fig. 3A. Also, John Larkin posted comments about similar enhancements to the "Two Vbe" type of current source on the USENET forum sci.electronics.design (message ID 1q3013huejba8d51v9kgn9n2spjgl96dbh@4ax.com) and also in an e-mail to me.

It is hoped that a future "Sources" update can address some further circuit developments along these lines.

Walt Jung's recent articles (April and May '07 *aX*) were very informative. I only wish there had been space to explore a couple of additional areas.

First, a few years back Doug Self briefly touched on small signal current sources and concluded that the differences in rail rejection would largely be mooted by use of a decoupling cap across the current source. I would have been interested to see whether the conclusion was repeatable and what benefit, if any, there might be when applied to the other current sources schemes described by Walt Jung.

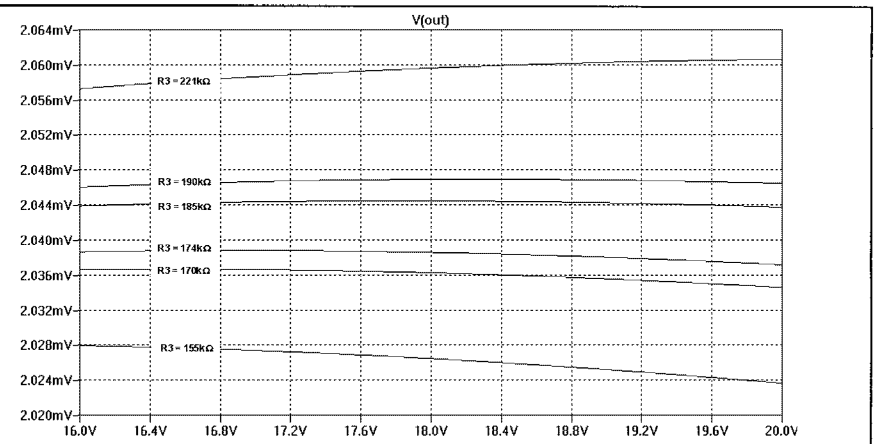

FIGURE 1: A DC SPICE simulation of the enhanced circuit shows low errors, with an optimized null that occurs at one R3 value, here 185kΩ. Note that this null centers on a narrow range of supply voltage, in this case 18V. Note also that R3 values too low (155kΩ) result in a downward error slope, while values too high (221kΩ) result in an upward slope.

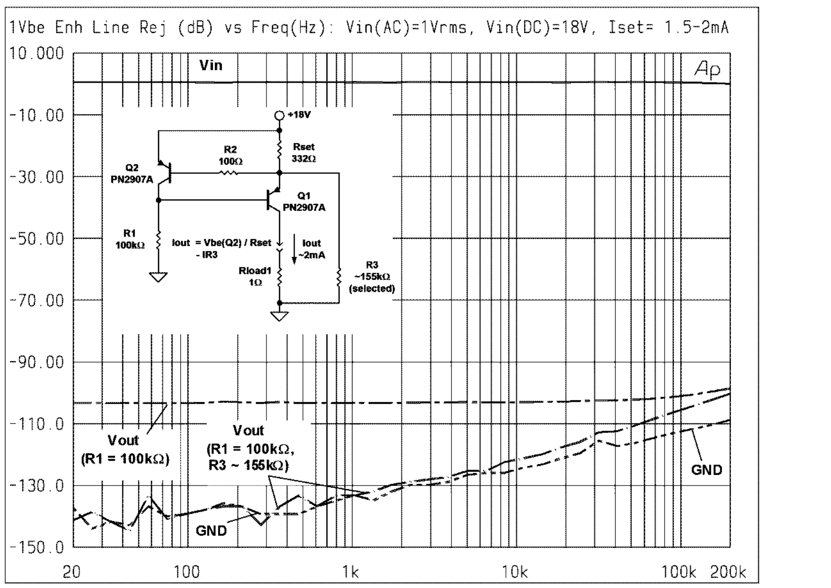

FIGURE 2: A lab test of the enhanced circuit (see inset) shows performance for Rset = 332Ω, R1 = 100kΩ, and R3 open, then with R3 added at 155kΩ. There is a distinct setting for R3 that results in the lowest errors, but unfortunately one not exactly predicted from SPICE.

Second, his measurement setup used a fixed load. Perhaps in a future article, he could explore the performance of the various current sources with variable or even reactive loads. This, too, may be a concern when selecting one approach over another requiring a decision to trade off some of one benefit to get more of the other.

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Walt Jung responds:
First, my thanks to Mr. Whitney for his interest in the articles.

To respond to the first item on Doug Self's form of the "One Vbe" current source, let me say that this is a worthy point. As it turns out, his variation, similar to the circuit shown in **Fig. 1**, really has excellent performance for line rejection. Readers of the original "Sources 101" articles will recognize this circuit as another variant of the "One Vbe" circuit, which was originally published as Fig. 3A in Part 1 of the article.

For specific details of Self's circuit and his overall context, I refer readers to his *Audio Power Amplifier Design Handbook*, Fourth Edition, Newnes, 2006, ISBN: 978-0-7506-8072-1. A circuit which contains the current source in question can be found as Figure 7.5 (Note: this is available online from http://books.elsevier.com/companions/9780750680721).

In the circuit of **Fig. 1** shown here, Q1 and Q2 are 2SA1016K transistor types, which have a 150V rating. These transistors are not only suitable for power amplifiers in terms of this voltage rating, but, importantly, they also feature better performance in this circuit, vis-à-vis the PN2907A general-purpose counterparts. Self's circuit uses MPSA56 types for Q1-Q2, which have noticeably higher capacitance than do the 2SA1016Ks (about a factor of 3 or more at Vcb = 10V). Lab measurements were done on this circuit operating at a supply of 18V, under conditions otherwise similar to the previous tests, with the Rset value shown, producing an output current just under 2mA.

Note that when applying this circuit to power amplifiers operating at voltages higher than 18V, the R1 value(s)/operating point of Q2 may need attention. For reasons cited previously, the higher values for R1 might yield better results, by virtue of operating Q2 at less current. Here, the target is about 160μA. Self's Figure 7.5 circuit operates the transistor comparable to Q2 (his TR14) at

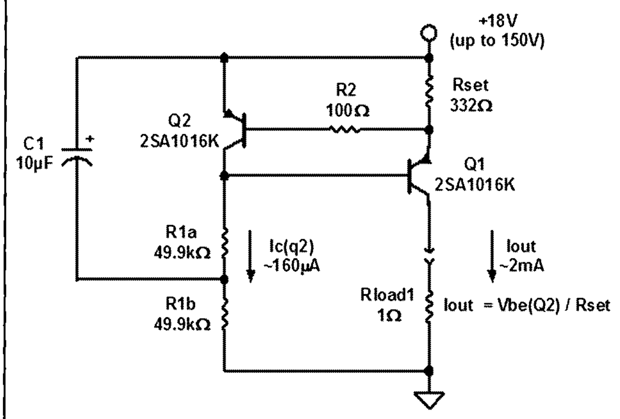

FIGURE 1: A "One Vbe" type current source using a C1 bootstrap capacitor, similar to the form used by Doug Self.

~2mA. For **Fig. 1**, the total R1 resistance is 100k. . . providing the 160μA. The equal values for R1a/R1b allow the AC bypass capacitor C1 to perform almost identically to the values of Self's circuit, where the cap value is 47μF and the total resistance is 20kΩ.

As can be noted from the data of **Fig. 2**, the presence/absence of C1 makes a remarkable difference toward operation. Without C1 (as in the intermediate curve), the line rejection is about 105dB, consistent with previous performance of this same circuit using PN2907As. But, with C1 active, the line rejection is on the order of 140dB at low frequencies, and actually challenges the test setup.

The C1 capacitance works to maintain high effective AC impedance for R1a, similar to the use of an active current source in place of R1a-R1b, but using passive parts only. It is worth noting that this technique also works with other current sources of this type; among these are the "Two-diode" and "LED" variants discussed in Figs. 4A and 5A of the original article. The key step is to split bias resistor R1 into two equal parts, and apply the coupling cap to the midpoint. I hope to discuss these circuit types in a follow-up article (see final point below).

As for Mr. Whitney's second query about other load conditions for current source tests, I can only hope that this has been at least in part addressed with my reply on this same point, within the reply to the Thomas Bohley letter.

My thanks again to readers Whitney, Bohley, Paul, and Popelish for sharing their thoughts on these articles, allowing opportunity for further discussions.

I hope that a future "Sources" update can address some further circuit developments along these lines, and bring these many-faceted points of audio current source performance into a more complete discussion.

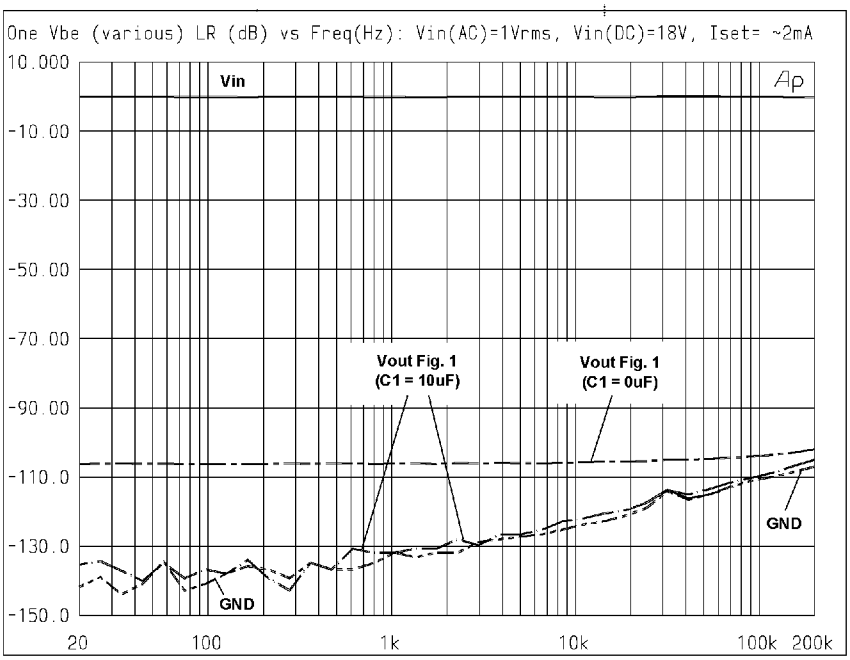

Figure 2: The addition of bootstrap capacitor C1 to the One Vbe current source circuit of *Fig. 1* provides a substantial line rejection improvement.