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Sources 101: Audio Current Regulator Tests for High Performance

Part 2: Precise High Current/Voltage Operation

By Walt Jung

Measurement tests can help reveal which configuration is best for your power supply application.

I will conduct many additional measurements here. Within this phase, the focus is on current regulators that operate at higher voltages, at higher currents, and do so with a higher degree of precision. This implies higher initial accuracy, as well as good temperature stability, for all circuits discussed hereafter, with the exception of those MOSFET based.

LM317 CURRENT SOURCE/SINK

One of the easiest ways to make a quite good audio current source is to simply connect an LM317 IC with a current set resistor (**Fig. 10A**, left). This circuit, which is simplicity personified, cannot be reduced further in functionality. Details of the LM317 operation are described in References 7 and 8 (highly recommended reading). The wide availability of this useful part in a variety of packages at low cost makes it attractive.

The LM317 is a *floating* three-terminal regulator, meaning it can be applied quite flexibly, and no pin inherently needs to be grounded. When operated in a current mode, the internal 1.25V reference voltage appears between the

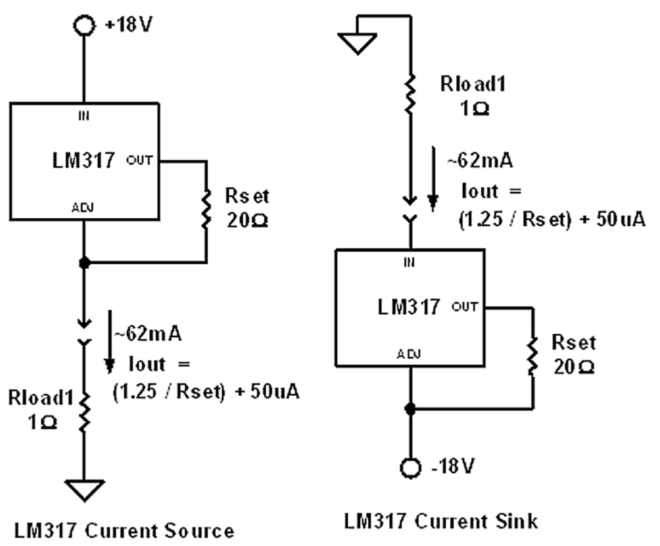

FIGURE 10A: Basic LM317 current source (left) and sink (right).

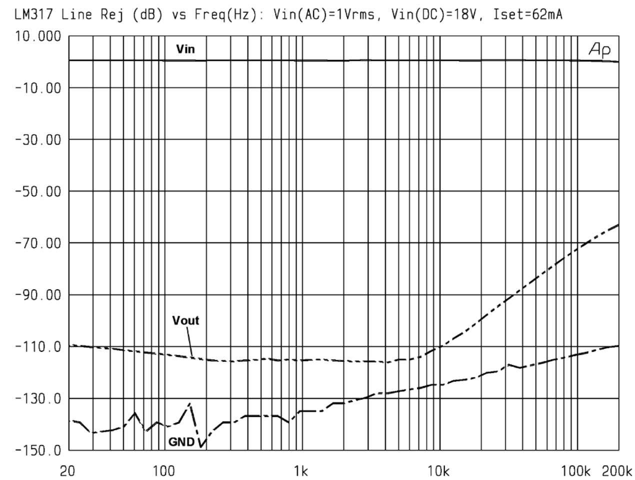

FIGURE 10B: Performance of the LM317 as a 62mA current source shows 110dB or more rejection below 10kHz, but rapid deterioration at higher frequencies.

OUT and ADJ pins, so a simple resistor Rset programs the current into a load. In this case a fixed 20Ω value sets up a 62mA load current. The 1.25V is held to ±50mV, and is stable over temperature.

Thus, an LM317-based current source will be one of the more predictable and stable types for DC. Of course, at such higher currents power dissipation will be an issue, so you should use a TO-220 package part at these current levels, along with the appropriate heatsink.

It may not be obvious at first, but the LM317 can function as both a current source (as in the left case) and as a current sink, shown at the right. In either case, the IC and its Rset resistor are treated as a two-terminal circuit, which is applied between the source and the load. The LM317 current sink is implemented with similar connections shown at the right, with the load connected to the IC's IN pin, and using a negative power supply. Note that in such cases a small AC bypass capacitor may be necessary at this pin, ~1µF.

The LM317 working in this current output mode will require about 2.5V across the IC, plus the 1.25V, for a total of nearly 4V to make it operate. The IC also needs a 10mA minimum of output current for regulation. Practically speaking, this means that Rset should never be any higher than about 125Ω.

Once biased properly, the IC operates reasonably well, as shown in **Fig. 10B**, an AC rejection performance plot of the output. Here the low frequency (LF) rejection is about 110dB, equivalent to an impedance of 316kΩ. There is, however, noticeable deterioration at higher frequencies.

This is one aspect of the LM317's performance that would be desirable to improve, because the rejection at 200kHz is only about 60dB, meaning potentially increased sensitivity to high frequency (HF) intermodulation. A couple of the following circuits address this aspect of the LM317's operation.

LM337 CURRENT SOURCE

A companion device to the LM317 positive regulator IC is the LM337, designed to operate from negative sources. It also has a 1.25V reference voltage and can be configured to regulate current (**Fig. 11A**). The LM337 uses a similar set resistor (Rset) to set up an output current Iout, but it also requires an output capacitor for frequency compensation, C1. A typical value for this capacitor is shown.

While the LM317 and LM337 have complementary functionality, they achieve radically different degrees of rejection versus frequency as operated in a current mode. This is best appreciated by the LM337's AC performance (**Fig. 11B**). While the LM337 rejection is good below a few hundred Hz, it degrades steadily above this, to the point where the rejection is less than 30dB above 100kHz. This is an example of the type of rejection *not* sought for higher performance audio circuits!

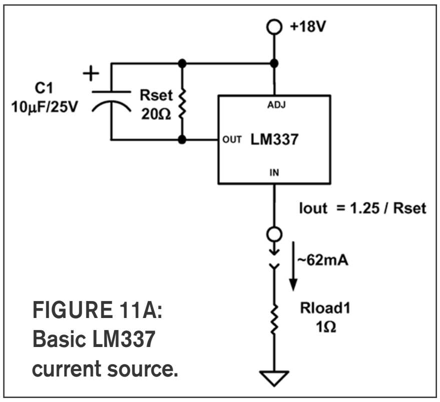

FIGURE 11A: Basic LM337 current source.

A detail worth noting at this point: If complementary source and sink circuits are needed for an application, it is actually better performance-wise to use a pair of LM317s as in **Fig. 10A** left and right, than it would be to use an LM317 and an LM337.

Caveats: A further special point on three-terminal regulator types is to simply be cautious about replacement or "improved" 317-type regulators, especially those designed for low dropout. As a byproduct of their design for low DC dropout voltage, these regulator types can have much worse AC rejection characteristics vis-à-vis the original. For example, two low dropout versions of the 317 were tested for rejection in a current regulator mode similar to **Fig. 10A**, and had responses more like that of **Fig. 11B** than the more desirable LM317 response of **Fig. 10B**. So, this is definitely a case of caveat emptor!

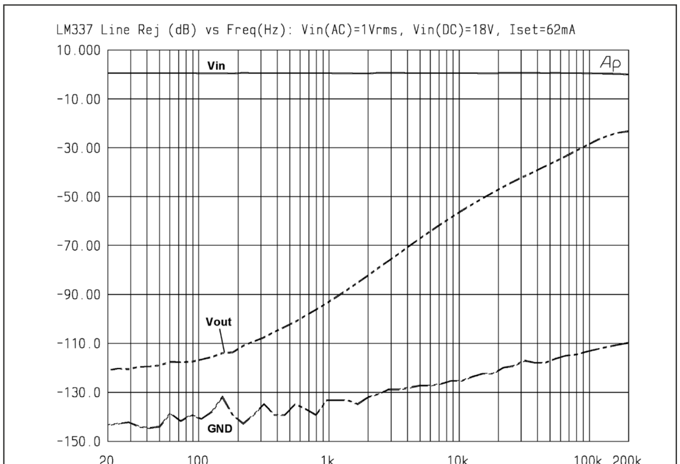

FIGURE 11B: Performance of the LM337 as a 62mA current source shows 110dB or more rejection—but only at the lowest frequencies.

DEPLETION MODE MOSFET CURRENT SOURCE/SINKS

Power MOSFETs are both extremely popular and widely available, and for many years have seen widespread use in audio amplifiers. Typically, these have been the original format, which is that of *enhancement mode* devices. This means simply that they require an applied gate voltage to conduct.

More recently, *depletion mode* MOSFETs have become available, which enables easier use of such parts in audio power supplies. Like the small signal JFETs, a depletion mode MOSFET is fully on with 0V bias, and is controlled to lower degrees of conduction with the applied bias voltage. Thus far the depletion mode MOSFETs that have appeared are N-channel parts. Two TO-220 packaged examples are the DN2540 from Supertex and the IXCP 10M45 from Ixys. See References 10 and 11 for further information.

These TO-220 devices can operate at voltages up to 450V, and at currents from the low mA range up to about 100mA. They are already being found in vacuum-tube-based audio projects where high voltage capability is required. Examples can be found via Reference 12.

In application, a basic current source using either part can be accomplished (**Fig. 12A**). This circuit is exactly the same as with a JFET device, save the addition of the gate-stopper resistor R1, and the important fact that the applied voltage can go up to 450V. And, like the JFET counterpart current regulator, this circuit is two-terminal, and so can be used either as a source (shown here), or as a sink, where the load is in the drain lead and negative voltage is applied to the bottom of Rset and R1. The tests described here used an 18V power supply.

For a load current of 30mA, I found that the two resistor values noted for Rset were appropriate. This underscores a basic point: These depletion mode MOSFETs aren't precision devices like the LM317 and other ICs with their fixed reference voltage(s). Rather, the gate bias for these MOSFETs sample to sample will vary, just as it does for other JFET and MOSFET parts. Nevertheless, this circuit still has the utility of extreme simplicity, and Rset is simply chosen to get the required current.

Operated within the test circuit of **Fig. 12A**, the two sample parts produced the data of **Fig. 12B**. Both devices show LF rejections of around 110dB (~316kΩ), with a gradual degradation beginning in the 5–10kHz range. The DN2540 is measurably better in terms of AC rejection at the higher frequencies. This is apparently due to the lower parasitic capacitance of the DN2540 versus the IXCP 10M45, but I cannot precisely confirm this (the latter isn't specified for capacitance).

Nevertheless, these general patterns of AC rejection seemed to be typical for the two devices, and were observed with tests of other samples. The DN2540 is preferred for operation in this circuit, not only because of the better AC rejection at high frequencies, but because the Idss of this part is 150mA, making it more widely applicable.

CASCODE LM317 CURRENT SOURCES

These higher current regulators, like the low-level circuits described in Part 1, can also be enhanced for AC performance by means of cascoding. As the DC current carried by the regulator is increased, the rejection performance inevitably degrades, making the value of an effective cascode circuit more and more important toward good results.

A circuit that can be used to cascode the operation of an LM317 is shown in **Fig. 13A**. This is similar to the basic regulator of **Fig. 10A**, with an additional regulator added—stage U2. The U1 LM317

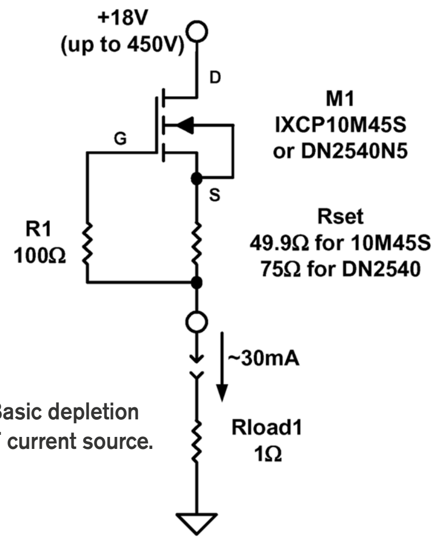

FIGURE 12A: Basic depletion mode MOSFET current source.

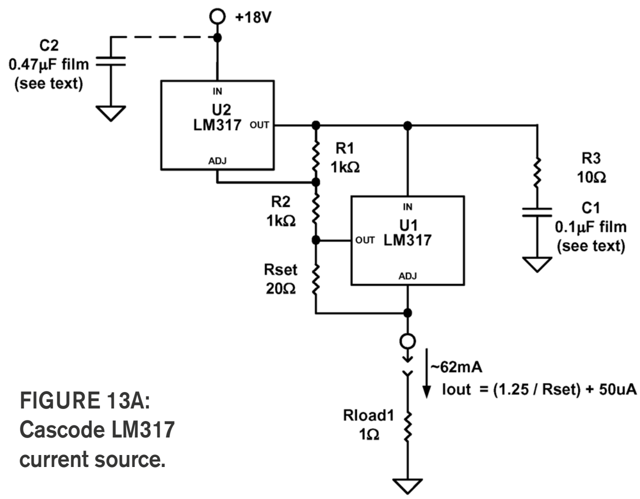

FIGURE 13A: Cascode LM317 current source.

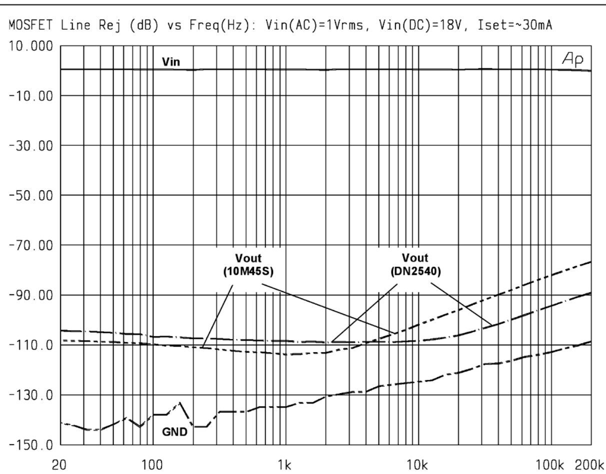

FIGURE 12B: Performance of two depletion mode MOSFET 30mA current sources shows ~110dB rejection below 5-10kHz, then deterioration as frequency increases.

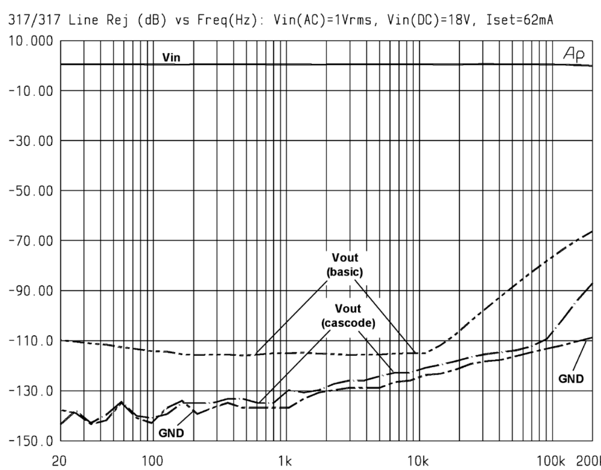

FIGURE 13B: Performance of the LM317/LM317 as a cascode 62mA current source shows much greater rejection than in basic mode, at all frequencies.

operates just as previously, producing an output current as noted, which is proportional to 1.25V and inversely proportional to Rset. The input drive for U1 is derived from cascode IC U2, which floats atop U1's output, 2.5V higher by virtue of resistors R1 and R2. C1 and R3 provide necessary stabilization for the cascode.

I tested the **Fig. 13A** circuit at a current level of 62mA, to be consistent with the basic LM317 operation of **Fig. 10A**. The results are shown in **Fig. 13B** for both the basic and cascode modes of operation. Note that the addition of the cascode reduces the noise down to a level approaching the setup residual at all but the very highest frequencies. Although not shown here, for lower levels of current operation (i.e., ~15mA), this cascode scheme showed even lower noise levels.

Some caveats for the **Fig. 13A** *circuit:* Although the AC rejection properties of this relatively simple circuit could be considered exemplary in some regards, I cannot recommend it unconditionally for several important reasons. One, it has a rather high dropout voltage, requiring ~6.5V across it—just to function! This is due primarily to the basic characteristics of the LM317, and can't be easily reduced. Anticipating potential questions here, using low dropout 317 regulators isn't any real help, either. I tried this, and it does reduce the dropout—but at the expense of rejection.

A second caveat is that the basic LM317 dropout voltage is actually specified as 3V for currents up to 1.5A. Datasheet graphs show it to be typically ~1.7V at a current of 200mA at 25°C. So the scheme here won't really work well at high currents and/or low temperatures.

But, there is still much latitude for use at much lower currents and typical temperatures from 25° C and up. Here operation of U1 is at a fixed input/output voltage of 2.5V, and because this is still somewhat of a gray area, only load currents of <100mA are suggested. Finally, and perhaps most important, this setup can and will oscillate under certain conditions, so be wary. All cascode-type schemes using additional high gain, wide bandwidth parts have this potential and should be rigorously checked. Input bypassing should be used, with a film capacitor such as C2 close to U2, and the C1/R3 network always used.

Fortunately, for all of the cascode schemes tested for this series, only a couple of them showed oscillation tendencies, this one included. The absence of oscillation for an LM317 regulator can be checked by the presence of a stable 1.25V ±50mV output (or, the exact target DC current for this or other precision regulators). If a scope is used, the output should be clean on a scale of a few mV.

For some more carefully selected operating conditions, a cascode LM317 arrangement can be implemented using an LM317 as the control IC and a depletion mode MOSFET as the cascode part. This variation (**Fig. 13C**) can use either the DN2540 or the 10M45 as the cascode device M1. *Note that this circuit will simply not work with a conventional MOSFET!* For the two M1 device types, it has the advantage of workability at very high voltages, up to 450V, making it quite attractive as a simple and precise current source for tube circuits.

This circuit also has some caveats, including the general ones for the 317. For the LM317 to properly function as a regulator, the input/output voltage, labeled here as V317, *must meet the LM317 device dropout limits*. In this circuit V317 is the Vgs of M1, and this should be 2.5V or more. Both the devices listed for M1 typically meet this requirement at lower currents of 10–20mA, and the DN2540 holds up even higher. And, don't forget the RC stabilization network, R2/C1.

AC rejection performance of this circuit operating at 16mA is shown in **Fig. 13D**, and for either of the cascode devices it is nearly ideal. Only a tiny deviation above the noise level at the very highest frequencies can be noted. This exceptional performance makes this a very attractive circuit for such lower currents.

At the higher current of 38mA (**Fig. 13E**), the 10M45 begins to approach the sample device Idss. Therefore, V317 is lower than the minimum required for effective LM317 operation, and as a result, the data for the 10M45 shows noticeable deterioration vis-à-vis lower currents. By contrast, the DN2540, a higher current

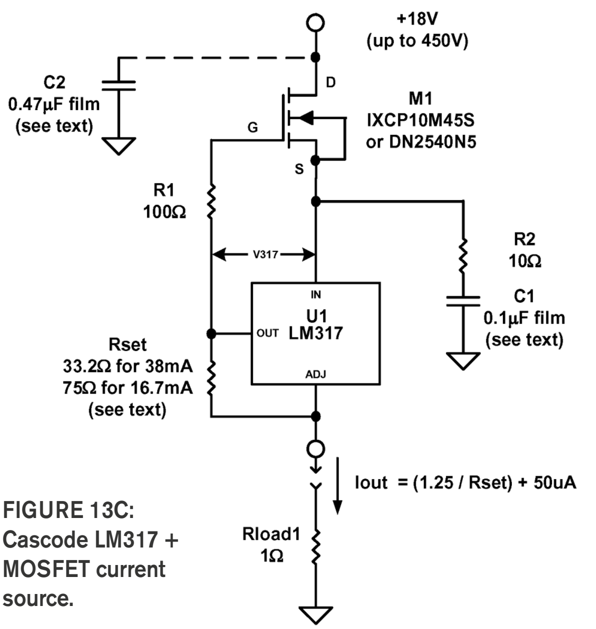

FIGURE 13C: Cascode LM317 + MOSFET current source.

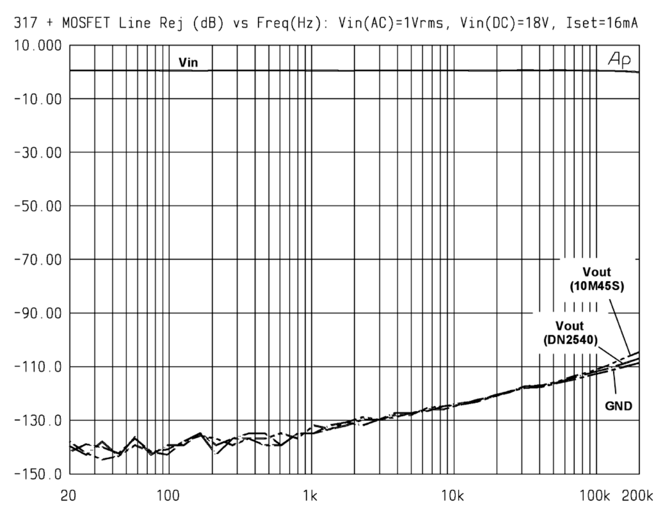

FIGURE 13D: Performance of the LM317 + MOSFET cascode 16mA current source shows excellent rejection compared to basic mode at all frequencies.

device, still shows excellent rejection for these conditions.

A power caveat: While you should always be aware of power dissipation limits for any of these circuits, this boundary can quickly sneak up on you within tube circuits—even at relatively low current levels. For example, a 10mA current in M1 of **Fig. 13C** with 150V across it implies an M1 dissipation of 1.5W, which will definitely require a heatsink. Don't operate under the assumption that a datasheet rating of 1W at 25° C for a TO-220 will guarantee a safe and long life of the part, if it sees 1W of constant power while the room is 25° C. Internally, the part will be much hotter, and it is highly likely a hefty heatsink is in order for a truly reliable design. See Reference 13 for further heatsink information.

TLV431 CURRENT SINK

The TLV431 is a three-terminal IC designed to be used as a programmable shunt regulator, from 1.24 to 6V[14]. It has an uncommitted feedback path, meaning that external active parts can be used with it to extend the basic current and voltage range. As you will see, this part operates as a current regulator referred to the negative rail, thus it is most suited to make current sinks.

The TLV431 reference voltage of 1.24V has a tolerance of ±18mV (1.5%), but A and B suffix parts tighten this to 12mV (1%) and 6mV (0.5%), respectively. The TLV431 is related to the very popular TL431, which offers similar functionality at a reference voltage of 2.5V. Because the TLV431's lower voltage of 1.24V is more desirable for a current regulator (it means lower dropout), I chose it for this test. But note that the same principles applied here for the TLV431 also work for the TL431, except for the higher reference voltage of 2.5V.

Figure 14A is a basic TLV431 current sink that you can use over a range of voltages up to 40V, and currents up to several tens of mA. The final voltage/current rating for this circuit is a function of the transistor type used for Q1 and the heatsinking. Typically the load would be applied between the OUT1 and OUT2 terminals. Note that the OUT1 terminal need *not* be common to the +18V supply as shown; it can (and often will) be a higher voltage.

The U1 IC, a TLV431, regulates with a 1.24V developed between the R and A terminals as noted, so the Rset resistance determines the current flowing into Q1-Q2 and the external load. The feedback path is via terminal K and the base-emitter path of Q1–Q2. Z1 performs as load impedance for IC U1, and can be one of three options, all of which should provide for a current of 100µA, minimum. The simplest option is a 100kΩ resistor (A); next most simple a current source such as the J507 (B); and finally, for highest performance from the circuit as a whole, functioning as a current source, a J202 operating at ~280µA and cascoded with a 2N5486 (similar to *Fig. 8A*, right option, Part one).

Because this circuit is more aptly used as a current sink, the measure of how it performs would best be told by a sense resistor placed at OUT1-OUT2. But, as noted, the test setup here measures current in Rload1, which is tied to ground. Interestingly, however, you can still infer some degree of performance of the circuit by observing the total current in Rload1.

The current in Rload1 has two components, the output current flowing in Rset-Q1/Q2, and Iz1, the bias current of U1, which flows in Z1-U1. When the current in Rload1 is monitored, both of these currents are, in fact, being measured. It would be desirable that only Iz1 be dominant, because this would mean that the Rset-Q1/Q2 current path is noise free.

To a great extent this is indeed true, and is reflected by a related change in Iout rejection, because Z1 is varied. This is shown in **Fig. 14B** for various Z1 conditions. Note that for a finite resistance value for Z1, the net impedance is shown by the Vout (100k) plot (as was true for the calibration plots of Part one of this article). And, as Z1 takes on higher impedance characteristics, such as with the Vout (J507) plot, this condition is reflected in a higher impedance display (i.e., more rejection). The greatest rejec-

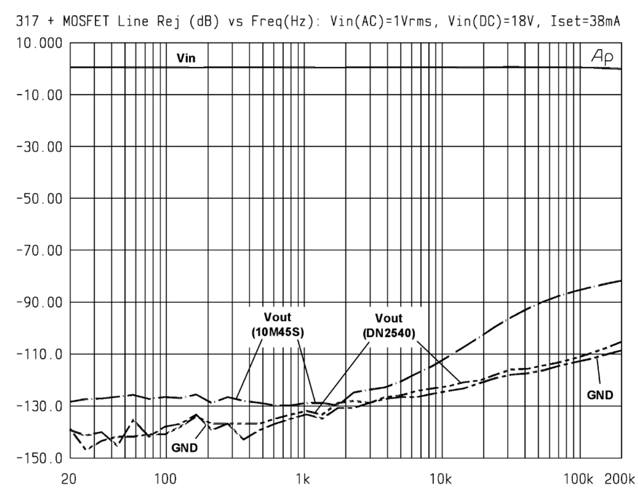

FIGURE 13E: Performance of the LM317 + MOSFET cascode 38mA current source still shows excellent rejection for the DN2540, but deterioration for the 10M45S.

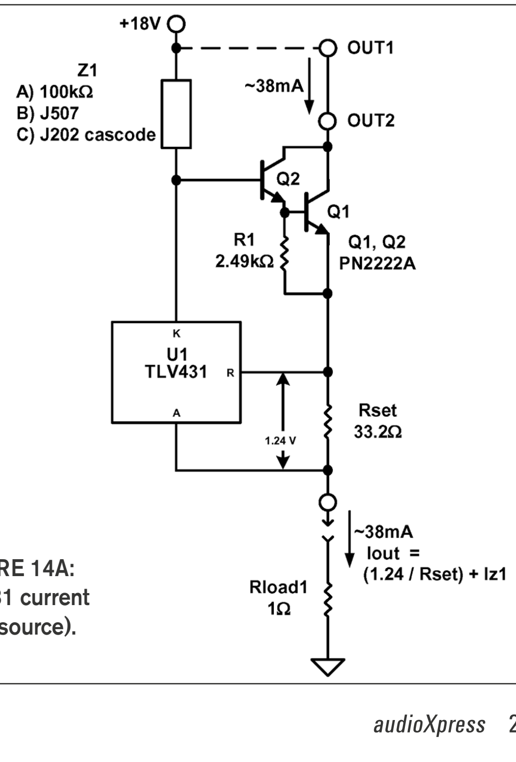

FIGURE 14A: TLV431 current sink (source).

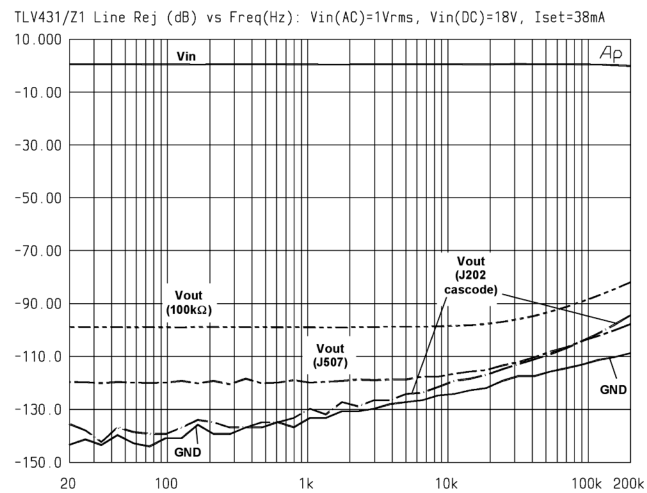

FIGURE 14B: Performance of the TLV431 as a 38mA current source depends upon Z1, but is excellent with a high-Z for Z1. See text on current sink operation.

tion at the lower frequencies is provided by the cascoded J202 setup, while the J507 provides the most rejection with a single component used for Z1.

So, while this test method doesn't directly measure just the current flowing in the collector of Q1/Q2, it still suggests some aspects of relative quality—a good thing, nevertheless. The bottom line is that you can use the circuit as either a current sink, in which case Z1 can likely be the simple 100kΩ resistor, or, alternately, as a current source, whereby the higher impedance choices for Z1 are suggested, such as the J507 or the cascoded J202.

You might ask what the need is for this type of current sink, when previous examples have provided good performance at these currents. The answer lies in the overall flexibility of **Fig. 14A**. Operated as a current sink, and with Q1 properly selected for power and voltage handling, this circuit can handle currents of amperes and voltages as high as the Q1 device rating. Although data isn't shown for this example, with a D44 series power transistor for Q1, output currents of 350mA have been witnessed. This is all available with relative simplicity—Z1 a 100k resistor (Z1) and Rset chosen for the current desired. Or, with Q1/Q2 2SC2362, the OUT1 terminal can operate up to 150V, at low currents, with proper heatsinking.

LM4041 CURRENT SOURCE

The LM4041-ADJ is a three-terminal IC designed to be used as a programmable shunt regulator, from 1.233 to 10V[15]. Like the counterpart TLV431 series, it also has an uncommitted feedback path. And, as with the TLV431, this means external active parts can be used with it to extend the basic current and voltage range.

A key difference in applicability is that the LM4041-ADJ operates with a positive rail common, as opposed to the TLV431, which uses a negative rail common scheme. The two devices can be viewed as complements, performing similar tasks. The basic LM4041-ADJ reference voltage is 1.233V, and the available grades of C and D for this version have initial tolerances of ±0.5% and ±1%, respectively, for Vout = 5V.

Inasmuch as the operation of the LM4041-ADJ is with the positive rail common, you can easily use it to make current sources operating over a wide range. An example is shown in **Fig. 15A**, which is a mirror image of the TLV431 circuit of **Fig. 13A**.

In this current source circuit, the output current is measured in Rload1, which is in series with the Q1-Q2 collectors. There is no error current from the internal amp of the LM4041, thus the rejection characteristics measured at Rload1 are indeed what you get. This is shown in **Fig. 15B**, for conditions as shown and a current of 38mA. The LF rejection is approaching 130dB (3.16MΩ), which, while good, is still well above the noise level. However, the rejection deteriorates above 1kHz.

Cascoding of Q1-Q2 in this circuit did not improve the performance to any great degree, only 2-3dB. At lower cur-

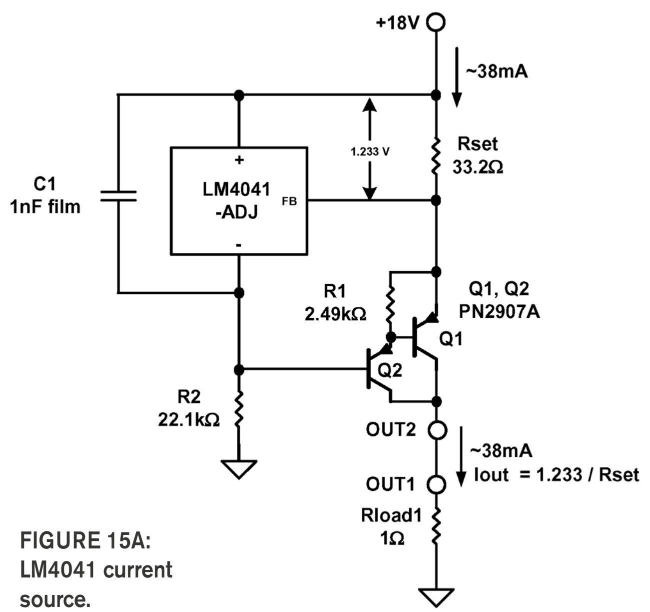

FIGURE 15A: LM4041 current source.

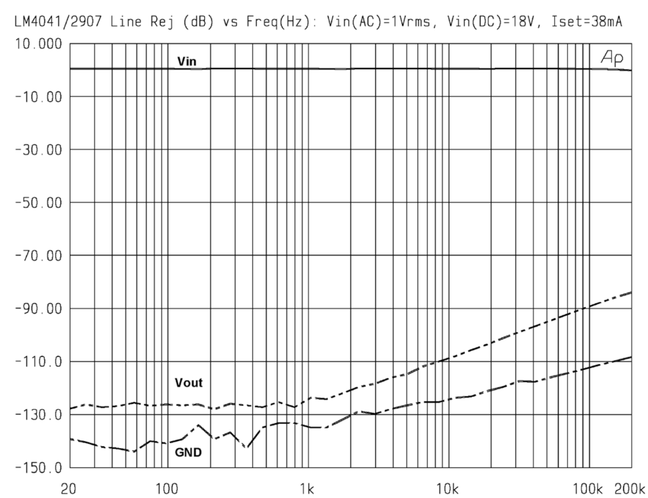

FIGURE 15B: Performance of the LM4041 as a 38mA current source is good, but falls short of excellent, particularly at the higher frequencies.

rent levels of a few mA, the rejection improved to just above the residual noise level. From this, you would conclude that this particular circuit is better used at the lower current levels.

TLV431 BOOSTED CURRENT SOURCE/SINK

As noted, the TLV431 circuits are better suited to use as current sinks, as opposed to sources. But, with some key changes, you can use a TLV431 current regulator either as a source or sink, and/or at high voltages. One scheme to do this is shown in **Fig. 16A**.

This circuit is like **Fig. 14A**, except Q1 uses a standard connection (non-Darlington), and the current source portion represented by Z1 of **Fig. 14A** is replaced by a high current or high voltage equivalent. This has the effect of regulating the current in R1, making the error current flowing from Rset and the TLV431-A pin constant. Therefore, this circuit, operating as a whole, can be used either as a source or as a sink.

With an LM317 for U2, R1 establishes a current of ~800μA, providing drive to Q1 for currents of 50mA or more. Q1 is bootstrapped by the LM317 at the collector and sees less than 2V C-E. It thus does not dissipate high power at 38mA of output or even higher currents. The LM317 will need the heatsink in this circuit long before Q1!

For operating voltages higher than the 40V LM317 rating, you can also use a depletion mode MOSFET by substituting an M1 device at the points marked X and Y. R1 can remain the same, and the current limit for this mode will of necessity be much less than 40mA. But, the voltage limitation becomes that of the M1 device used, or 450V as shown. Take care to use a proper heatsink for M1!

Performance in terms of AC rejection is shown in **Fig. 16B** for all three cascoding options, operating at 38mA. Overall, the best performance is achieved with the LM317, where the errors are only slightly more than residual noise, except for the very highest frequencies. The two MOSFET parts are nearly as good at LF, but deteriorate more rapidly above 1kHz. Of the two MOSFETs, the DN2540 is favored due to lower noise at all frequencies, plus its ability to handle more current. To get higher output currents, Q1 can be operated as parallel devices driven from R1-bottom end, with 10Ω current sharing resistors in the emitters.

CONCLUSIONS, CAVEATS, AND RECOMMENDATIONS

This concludes the testing portions of this series. A future article will explore some example applications of current sources and sinks within audio circuits, and discuss some general power supply system noise reduction techniques.

Some general caveats are appropriate here, beyond those specifically stated. I believe the tests are valid for the conditions cited, and in general can be used to differentiate among the various circuits. Of course, there is an infinite set of different load, voltage, and current operating conditions that you may require. So, you should not expect to duplicate any measurements exactly for other conditions. But, in general the observations should hold up—cascodes work better, JFETs need proper voltages to work best, and so on.

To summarize, here are some principles to keep in mind:

- Select single JFET parts from families with lowest Vgs and thus highest rejection. An example would be the J201/2 series.
- Alternately, select from a specified JFET current regulator device family, such as the J507 series.
- Always operate current regulator circuits with sufficient voltage headroom to maximize rejection.
- Above 4-5mA of current, consider cascode type circuits. At several tens of mA, this should be considered mandatory for good performance.
- For any current regulator circuit, minimize capacitance in whatever active devices are used. This will enhance high frequency noise rejection and minimize the possibility of high frequency intermod.

If I were asked to recommend which of the many current regulators described here to use, I'd try to keep it as simple as possible. The maximum bang-for-the-buck is the cascode LM317 + MOSFET of **Fig. 13C**, assuming your current requirement is 40mA or less. This one

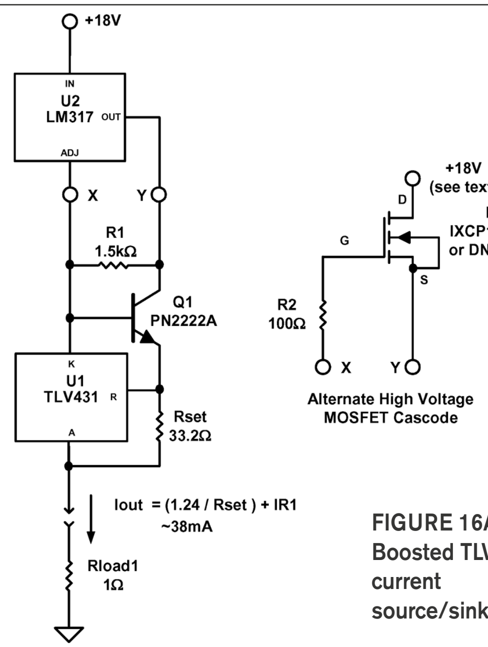

FIGURE 16A: Boosted TLV431 current source/sink.

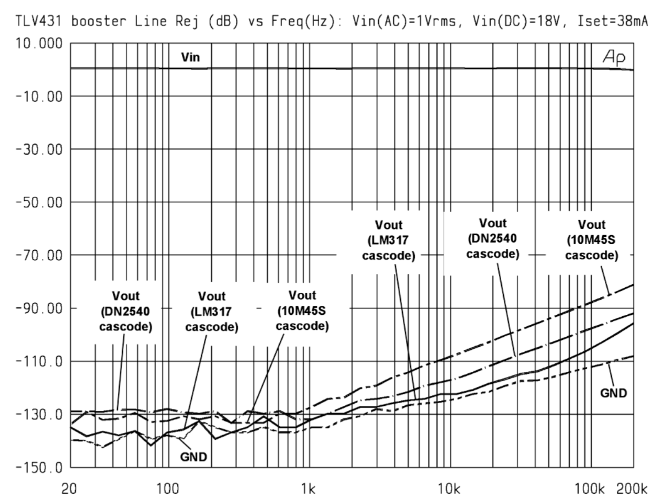

FIGURE 16B: Performance of the boosted TL431 as a 38mA current source or sink ranges from good to excellent, dependent upon the cascode device chosen.

worked great for me within a 12mA current feed for a 24V shunt regulator. For higher currents, the **Fig. 16A** circuit is both flexible as a source or sink and capable of much higher currents when Q1 is appropriately selected. For low currents of just a few mA, single and/or cascoded JFETs are likely best (*Fig. 8A*). Or, you could select the reference diode circuit of *Fig. 6A*.

SOME HOMEWORK ASSIGNMENTS

One manuscript reviewer asked about *very* high output currents, i.e., several amps. My general answer is that yes, this should be possible with minor revisions.

I said, "You could use **Fig. 14A** with a conventional N-channel MOSFET replacing Q1/Q2. The 1-2V Vgs of a MOSFET will bias the K pin of U1 roughly 1-2V above the R pin (but don't forget a 100Ω snubber in the MOSFET gate circuit). This should work OK for ampere outputs. Pick the FET for the required current, voltage, power, and, preferably, lowest C. I'm sure you have a favorite here. One possibility might be the Fairchild FQP4N20L, a TO-220 part, available from Mouser. I think I'll put this idea in at the end of the Part 2, as a reader 'Homework' assignment."

So there you have one assignment for some fun experiments. Let us know what you find out with this MOSFET-boosted current source idea!

Another assignment is to explore a hybrid vacuum tube/solid-state current regulator. For example, you could also use **Fig. 13C** with a power triode in place of M1 (grid to U1-OUT, cathode to U1-IN, and plate to the input voltage). The LM317L might be a possible candidate for U1.

I'd be very interested to hear about your results with these ideas. Write me at *audioXpress* via conventional mail, or contact me via my website, www.waltjung.org/index, and happy current sourcing and sinking! ***aX***

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