Op-Amp Audio

Realizing High Performance: Buffers (Part I)

In this and the next few columns, we will take a departure from the immediate past, and focus some overdue attention on real circuits. We'll cover some op-amp issues related to realizing high performance in audio and other ac applications. This venture has been inspired in part by reading some USENET newsgroup postings, with such confidence-boosting headers as: *"Op Amps always inferior to discrete?"* and others equally as upbeat in tone.

While I can't promise any panaceas, I do have confidence that a greater understanding can come from some focused discussions of op-amp audio pitfalls. Topics to be covered are: buffering, the IC op amp's best friend (this and next installment); matching an op amp to an audio application; and op-amp wisdom and witchcraft.

How many inputs does an op amp have? I find it useful to look at op-amp performance in terms of errors in response to various inputs. These inputs can come via the normal differential ones at pins two and three, *plus at least three others*. Aha! Stumped on that one? So, what else constitutes an input, beyond the two familiar power-supply-rejection-ratio (PSRR) errors for an amp's $+V_S$ and $-V_S$ terminals, disregarding any offset pins?

Well, it may or may not be obvious, but the *output* terminal of an IC op amp can actually be the source of the fifth *input* error, one which results in load-induced changes in offset voltage. Although all modern, single-IC op amps are designed with thermally symmetric, input-stage layouts vis-a-vis the output (for minimum thermal feedback), life isn't completely perfect here. Consider the fact that just microvolts of undesirable offset change can be significant at low audio frequencies. Take a 5-MHz bandwidth op amp as one example, where a 1-V p-p/100-Hz output swing requires an effective 20-µV p-p differential input.

So, whatever their source, extraneous signals might easily be comparable to actual signals of this magnitude. In a low-noise, bipolar-input op amp, a thermal change resulting in a few degrees Celsius temperature differential to the input stage might induce a fraction of a microvolt or more offset shift. Although such an error seems numerically small, it's still relatively large with respect to a 20-µV p-p, real signal. The point is not that this example represents any real device or conditions. It is more to frame some perspective and sensitivity for monolithic-IC-based technology, and the resulting application implications.

The figure shows a typical op-amp gain stage, configured here as an example application with an ideal gain of 5x, driven by a signal V_{IN}. The previously mentioned op-amp error sources are as noted, represented by sources V1 to V5. The dotted lines are intended to convey a general relationship of a given error to the source.

For example, the output-power-dissipation-related errors are reflected back to the op-amp input as a thermally coupled offset change, V5. For this installment of the overall discussion, I'll concentrate on this error, picking up the others further down the road.

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Both single, as well as multiple, op amps built on common monolithic substrates can be susceptible to thermal errors. This is simply because a potentially high-dissipation output stage and the error-sensing input stage are part of the same basic monolithic IC chip. In the classic reference, thermal effects in IC op amps were discussed, and modeled as an additional feedback path, which can limit available gain.[1]

It is worth noting that IC designs are a diverse extreme away from conventional pc-board discrete circuits, which are by definition, loosely-coupled thermally. *Hybrid* op amps may or may not be thermally sensitive, depending on their specific substrate and layout details. *Modular* op amps should be relatively insensitive to thermal effects, unless potted with a thermal compound.

Testing for thermal errors: Quantifying op-amp input-offset errors due to output loading isn't totally straightforward, but it isn't impossible either. For audio-oriented use, one straightforward technique is to measure output THD+N and/or other distortions under both heavy and light output-loading conditions. This will reveal degradation due to thermal-coupling effects. However, dc and low-frequency testing may actually give some greater insight into what happens to an op amp as it undergoes heavy loading. This is because one can literally *see* the changes in transfer function, as output loading changes.

Relatively simple, dc X-Y plots can give visual indications of amplifier linearity under load. See Reference 2 for an example of a single-op-amp test circuit for plotting amplifier input drive on the Y axis vs. loaded ± output swing on the X axis. This test is easily expanded to include loaded and unloaded comparison conditions, which can then reveal dynamic-thermal-error components, as well as transfer nonlinearity.

For this article, I modified the test circuit as follows. I changed the summing-node attenuation resistors from 1MΩ/10 Ω to 100 kΩ/10 Ω, added a 10-Ω balancing resistor in the positive input, and made the total load resistance 530 Ω. To test various op amps, I made the offset trim universal by summing a stable, variable ± voltage into the 10-Ω summing resistor via 100 kΩ. If you repeat this setup, use clean, well-balanced layout techniques and stable supplies, and you'll be able to observe 1 µV/division on your scope.

These steps make the new V_Y error scaling 100 µV/V, which is easily sensitive enough to see µV-level input changes with 10-mV/division scope scaling. The display allows you to measure loaded and unloaded gain, as well as associated changes in slope, which represents device nonlinearity.

With a ±10-V output, and 530-Ω loading, nonlinearity is readily evident with standard 5534 audio IC op amps. In one sample, the offset shift and slope changes from low load to full load. This results in about 60 µV of offset change, with a steep slope change with polarity reversal (although this is a large shift in terms of the error change, it is still relatively small vis-a-vis the ±10-V output).

Precision low-noise op amps such as the AD797 and LT1115 are much more well-behaved for this test, with similar-

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conditions errors of about 1 μV, and no radical slope changes. Look for low- and linear-slope errors, which represent linear gain, as opposed to radical changes and transfer function kinks.

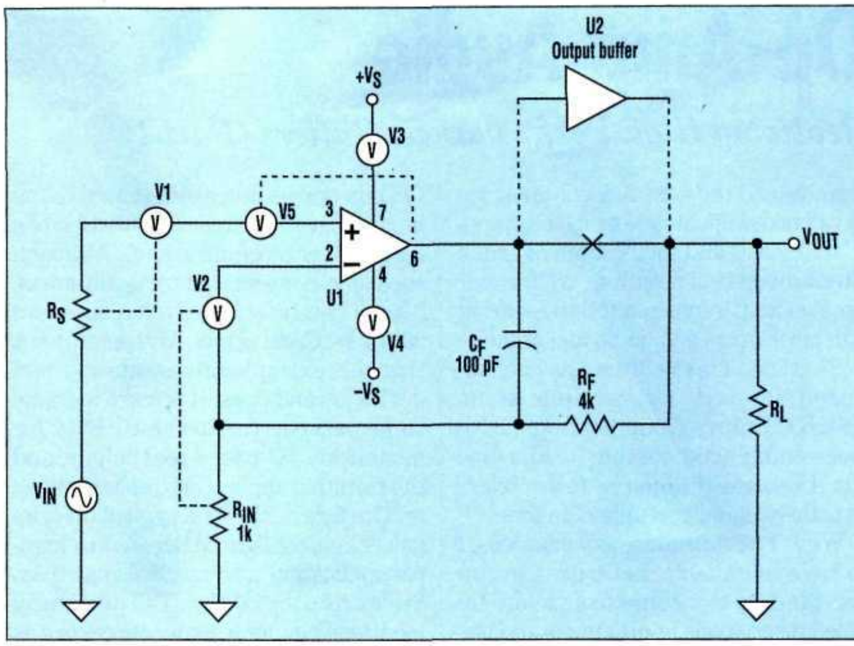
Dual IC op amps are very popular, and can also be easily tested for power-dissipation-related crosstalk.[3] One of the more simple, yet useful tests, is to connect channel A of a dual op amp as a grounded-input follower, with channel B configured in a closed-loop, gain-of-1000 circuit. By driving current into the A side, A-B thermal coupling can be measured at the B output. By controlling the polarity, frequency, and duty cycle of the driving current, useful information on a device's channel-to-channel thermal coupling can be obtained.

What may be surprising about some thermal errors is the relatively high frequencies at which they can be noticed. For example, a dual-output power-driver circuit, using a composite topology can be monitored for the effects of thermal crosstalk between the driven and undriven channels.[4] Crosstalk components were noted up to several kHz.

Minimizing thermal errors: By using one or more of the tests above, various amplifiers can be exercised for thermal errors, and comparisons can be made to find types with the lowest thermal errors for loaded conditions. But, audio op amps tend to be more specialized, and it may be that your favorite chip just doesn't look so good for thermal errors. Not to worry, there is still a worthwhile *system* solution, one which really turns out to be optimized for solving thermal problems and maximizing performance.

As shown in the figure, the answer is to simply split the voltage amplification (U1) and power-delivery functions (U2) by *buffering* the output of an IC op amp with a dedicated circuit, chosen (or designed from scratch) for more-than-sufficient drive current. The burden of current delivery and associated power dissipation is simply (entirely) removed from op amp U1. This is shown conceptually as the optional (dotted connection) buffer stage in the figure. The buffer is activated by breaking the output line at "X," and connecting the unity-gain buffer U2 as noted.

With the buffer used, the main feedback path through R_F is taken after the buffer, and across the load, R_L. The buffer circuit proper may include some specific details, such as bypassing, parasitic suppression resistances, etc.; this will be an individual thing. There should almost always be some sort of isolation impedance between the buffer output and the output terminal, to isolate any cable capacitance. This can either be a small, 20- to 100-Ω resistor, or the LR network described in Reference 4.



There is also a high-frequency, ac-feedback path through C_F, which has the effect of removing the buffer from the circuit at very high frequencies, in this case at $1/(2\pi R_F C_F)$. This also aids with stability when driving long cables or other difficult loads.

Choosing a buffer circuit: One has a basic two-path choice—an IC or a discrete circuit. ICs tend to be more desirable from points of size and efficiency, but they may not be lower in cost, or useful beyond about several hundred mA in non-heatsink packages. Discrete circuits can be tailored for any current level, but they tend to be quite busy in terms of component count, especially with such bells and whistles as current limiting and protection circuits.

Performance-wise however, both of these circuit approaches to buffering can be used, and either will allow the highest realizable performance for a given op amp. If an IC buffer is used, one can almost have the cake while eating it, too. This is done by packaging a simple, four-lead IC buffer like the BUF04, and a highly linear IC op amp such as the AD744, together as a (isolated) two-chip solution in a common package. Other dedicated IC buffers I have used successfully in the past have been the OPA633, EL2003, LT1010, LH0002, and LH0033, all of which deliver ±100 mA (or more). Video op amps like the AD811 and AD817, also work well as buffers, due to their good linearity and high-current output stages.

The U1 op-amp-circuit part can really be left to optimize from other standpoints. Whatever it is, it will be most happy when lightly loaded via a fast, linear, high-current buffer.

TIP: In the next installment we'll look at some more issues associated with buffering, and describe in detail a suitable discrete-circuit version.

References:
1. Solomon, J., "The Monolithic Op Amp: A Tutorial Study," *IEEE Journal of Solid State Circuits*, December 1974; Vol. SC-9, No. 6.
2. "Open-Loop Gain Linearity Test Circuit," Figure 3, Analog Devices OP177 data sheet.
3. "Crosstalk from Thermal Effects of Power Dissipation," Figures 24-26, Analog Devices AD708 data sheet.
4. Jung, W., "Composite Line Driver with Low Distortion," *ELECTRONIC DESIGN Analog Applications*, June 24, 1996, p. 78.

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