Op-Amp Audio

Realizing High Performance: Buffers (Part II)

Taking up where last month's column left off, here's the second part of our discussion on output-buffer techniques as part of audio op-amp applications.

A flexible Class A buffer: To fulfill the function of the discrete version of a unity-gain buffer, consider the schematic in the figure. A number of features lend this circuit utility, and can either be built as-is or modified for specific needs. Functionally speaking, this buffer's intended to drop directly into the U2 stage of last month's general diagram.

The hookup's basic function is that of a complementary buffer, with a nominal input/output dc offset near (but not exactly at) zero. Actually, this is quite a common circuit type. It's often realized with a complementary output transistor pair, biased in turn by a pair of forward-conducting diodes driven at their midpoint by the input op amp. I used such a circuit years ago in my op amp book.[1]

Here, replacing the two diodes with complementary transistors still has the same basic advantage of near-zero input/output offset. But, it lowers input bias current substantially, due to the transistor gain. It can also reduce distortion due to better load isolation.

The cancellation of the forward V_{BE}s of Q1-Q3 and Q2-Q4 is somewhat imperfect, however, as these are different device pairs. Output transistors Q3 and Q4 are 1-A types, for best gain linearity at 100 mA or more current peaks. Driver-stage devices Q1-Q2 are general-purpose types, suitable for currents of up to 100 mA and more (much higher than used here). A version of this general complementary topology was used in the classic LH0002 buffer, where the Q1-Q2 emitter currents were set simply by resistors to the supplies. A discrete version, the "0002," was also offered.[2]

In this case, the respective Q1-Q2 emitter currents are set up by current sources, Q5 and Q6. Their output current levels, along with the use of emitter-stabilization resistors R3-R4, work to indirectly set up the output-stage quiescent current. With about 4.5 mA of current flowing in R3, Q1 is biased stably. With the V_{BE}s of Q1-Q3 nominally equal, it can be seen that R3 and R6 will drop comparable voltages. This means that Q3 will conduct about twice the current in Q1, for the 2:1 ratio values. Thus currents set by Q5 and Q6, along with the relative resistance ratios, determine the output quiescent current.

Here, the V_{BE}s aren't exactly equal between complements Q1-Q2, or for Q1-Q3, and the idle current in Q3 is more than 10 mA (about 13 mA). Similar reasoning applies to Q2-Q4. Either more or less output-stage current through Q3-Q4 can easily be affected, simply by adjusting the relative values of R3/R6 and R4/R7 together. This is best done via the choice of R3-R4 value, leaving R6-R7 fixed.

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At 13 mA of current in Q3-Q4, they operate rather rich in Class A mode—at least until heavier loads should appear. For this bias level, departure from Class A will occur somewhere around 1.5 V, for a 150 Ω load.

The Q3-Q4 dissipation is about 200 mW each on ±15-V supplies, which will be OK for plastic-packaged devices like the original TO-237 devices, or the Zetex "E-line" version. Either of these packages should be used with ample pc-board copper area on the collector leads to aid in heat transfer. All circuit parts are available from international suppliers, such as Digi-Key.[3]

If much higher sustained currents are needed, even lower-thermal-resistance device packages can be used with Q3-Q4, such as the MJE171/181 or D44/D45 families. And, a lower-output-current version can be implemented by using PN2222A and PN2907A types for Q3-Q4.

Protection of this circuit is provided by several means. Without D3 and D4, the upper current limit for Q3-Q4 is set either by the limited-drive current (5 mA) times the gain (50 to 250), or by the R6-R8 values and the supplies. This current can easily reach several hundred mA, so active current limiting is very useful. The optional Red LEDs D3 (D4) provide this, clamping the drive to Q3 (Q4) when the emitter current reaches about 1.2/R6, or ~240 mA as shown. For lower levels, the LEDs don't conduct and signals pass normally. The LEDs are Panasonic types as noted.

When used within an overall feedback loop with an op-amp driver feeding R1, this buffer might need protection from overvoltage. The optional diode clamps D5-D6 provide this function. They clamp the drive to Q1-Q2 when and if the R8 output is shorted—so large reverse voltages aren't seen in the circuit. With normal signals, there's just a few mV across the diodes and they don't conduct.

Performance: Ideally, a buffer such as this is transparent to signals with differing loads and with diverse levels. The circuit shown was tested standalone—that is, with no driving op amp. Tested for THD+N with both low- (150 Ω) and high-impedance (100 kΩ) loads, it holds up well over levels from 0.5 to 8 V rms. At the highest levels of 8 V into a low impedance, THD+N reaches a high of 0.15%. But, it quickly drops to 0.02% at 2V, and is appreciably less than .01% at 0.5 to 1 V, or within the Class A range.

For high-impedance loading, distortion for all levels is well below 0.01%, typically 0.002% for 1 V. And, for either load impedance, THD+N is also relatively independent of frequency (below 100 kHz). Harmonics within the distortion residual at the output are predominantly third at 1- to 2-V levels.

The circuit's output impedance is essentially resistive and about 15 Ω, most of which is the R8 value. Voltage offset of the buffer will be high, in the 20- to 30-mV range, due to the inexact V_{BE} cancellations. When used within an overall feedback loop, as illustrated last month, this offset isn't consequential. It's suppressed by the feedback loop.

Housekeeping details: Some parts of the schematic aren't directly involved with the buffer function, but nevertheless still have utility. An example is the optional npn current-source transistor, Q_X. This can be used to set up a fixed-

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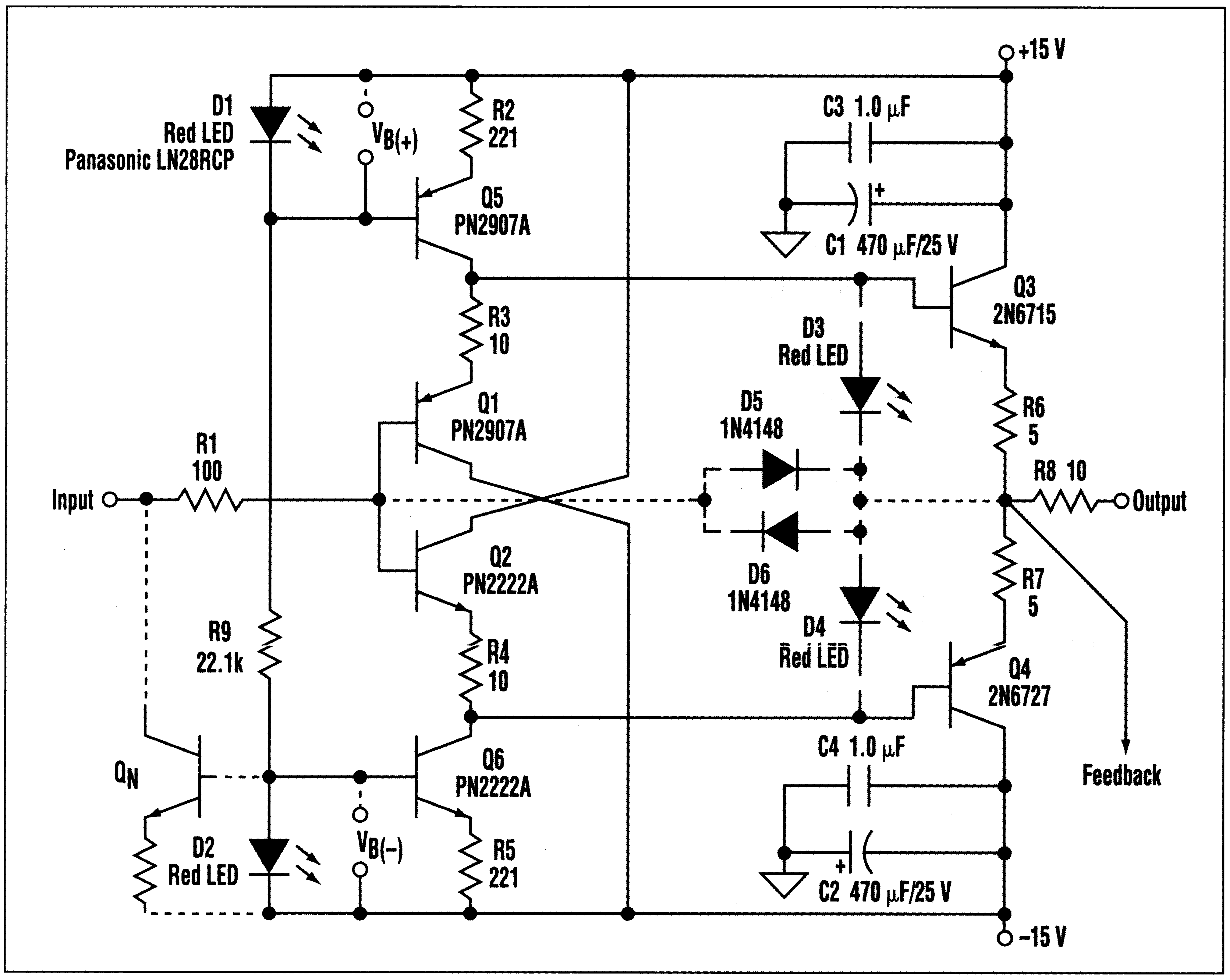

current drain directly from the driving op amp's output stage, thus operating it in a richer-than-normal Class A current range and minimizing any internal Class AB effects for alternating output-signal polarities. By using the high dynamic impedance of a transistor for this function, a fixed steady current can be taken from the op amp without loading it dynamically (and possibly increasing distortion). Q_N's LED bias scheme of $V_{B(-)}$ will cause a current of 1.2 V divided by the emitter resistance to flow in the collector. For example, 1 kΩ would source 1.2 mA. For opposite polarity (*current sink*) loading, a pnp current source "Q_P" is biased by D1, with a similar emitter resistance. If used, Q_N or Q_P are PN2222A or PN2907A types.

As noted, this buffer circuit functionally drops into the hookup of last month—that is, between the op amp and the load. The feedback path is taken *before* isolation resistor R8, providing simple, effective load isolation for the buffered op amp.

When driving low-impedance loads, decoupling of the high-load currents is accomplished with large, local electrolytic bypasses C1-C2, with their shared point returned to the load common. Because of the wide transistor bandwidths used, layout and wiring can also be critical. C1-C2 should be augmented by local, low-inductance high-frequency bypasses, such as 1-µF/50-V stacked-film types C3-C4, located physically near Q3-Q4.

It's worth noting that long lines, which appear as a capacitive load, are low-impedance loads. Even if terminated at the far end in a moderate resistance value (~10 kΩ)—for high frequencies, the effective load such lines present to the amplifier is still low (X_C for 10 nF looks like 800 Ω at 20 kHz). R8 is a load isolator, and can be increased if necessary.

Further suggestions: It should be obvious that this circuit is readily adaptable for various needs. If used on other supply voltages, the current in LEDs D1-D2 would benefit by being stabilized, perhaps by something as simple as a 1-mA JFET current diode in place of R9.

The output transistors (and their operating point) are best chosen to maintain the lowest distortion for the particular loads and operating level. Remember: The distortion figures quoted are for the buffer alone. A well-chosen driver can lower it even further.

TIP: These first two installments on high-performance audio with ICs and discretes have focused on choosing (or designing) a buffer stage for best overall performance. In IC op amps with poor thermal design, heavy output loading can cause shifts in effective input offset, as well as associated linearity changes. These load-dependent shifts can be identified with testing, allowing easier device selection to minimize this problem.

However, simply buffering the amplifier's output with an isolated-package circuit removes this source of error, and maximizes op-amp linearity. This step is recommended wherever it's practical and needed. Buffer circuits can be chosen from a number of ICs expressly designed for such tasks, as was noted last month. Or, they can be designed to match a given set of conditions, as in this example.

The ability to adapt and hone a circuit's operational characteristics precisely to an application is a major hallmark of discrete circuitry, as this example shows. In contrast, adaptability to different drive and bias levels isn't something IC buffers can do, at least not in the manner here. One needs to choose either the flexibility and diversity of the discrete approach (at the expense of component count), or the small size and component efficiency of the IC approach (at some expense of bias and drive flexibility). In any event, enjoy those low distortion, Class A sounds!

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References:

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2. Jung, Walt, and Childress, Hampton, 'Output Ills' and 'High Speed Buffers,' sections in "POOGE-4: Philips/Magnavox CD Player Mods, Part 2," *The Audio Amateur*, issue 2/1988.
3. Digi-Key Corp., 701 Brooks Ave. South, Thief River Falls, MN 56701-0677; (800) 344-4539; *www.digikey.com.*

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