## 4x.6 High-speed Op-amps II: Current Feedback

As explained in the previous section, a current-feedback op-amp consists of a high-impedance noninverting *voltage* input, and a low-impedance inverting *current* input. The op-amp's output is a voltage. It's a strange beast, acting as a transimpedance amplifier (current in, voltage out) with respect to its inverting input, and simultaneously a voltage amplifier with respect to its noninverting input. Figure 4x.50 showed it in its most basic form, with Figure 4x.63A revealing the most common implementation: the input stage is a zero-offset unity-gain follower whose "output" is the op-amp's inverting *input* terminal!

### 4x.6.1 Properties of CFBs

Current-feedback op-amps are most often used as closed-loop noninverting voltage amplifiers, for example as seen in the inset of Figure 4x.64. In this configuration the closed-loop bandwidth is primarily set by $R_f$ (as the graphs in Figs. 4x.65 and 4x.66 show), with $R_g$ setting the voltage gain.

#### A. Closed-loop bandwidth

Before going on, it's worth pausing to develop some understanding why the closed-loop bandwidth of a CFB voltage amplifier is relatively constant, unlike the situation with a VFB (with its fixed gain–bandwidth product), where the closed-loop bandwidth decreases inversely as the gain is increased (i.e., BW$\approx f_T/G_{CL}$).

Here's a way to think about it: (a) From Figure 4x.50, you see that the current into the inverting terminal, set by the feedback resistor, is mirrored to the output buffer stage, where it sees a fixed load capacitance $C_C$ (the compensation capacitance); so the amplifier's closed-loop bandwidth (and slew rate) is determined by $R_f$. (b) Now, adding the gain-setting resistor $R_g$ sets the voltage gain ($G_{CL}=1+R_f/R_g$, just as in a VFB amplifier); but it also causes the source impedance seen at the inverting input (which is what creates the input current) to decrease, increasing the gain–bandwidth product comparably, thus preserving the closed-loop bandwidth. (c) This holds only to the extent that the CFB's inverting-terminal input resistance is small compared with the Thévenin resistance ($R_f \parallel R_g$); this fails for large gains, nicely seen in the graphs of Figures 4x.64–4x.66. Of course, this kind of qualitative intuition cannot replace an honest analysis; for that, take a look at the postscript section 4x.6.5 ("Bandwidth and gain in CFBs").

#### B. Slew rate and output current

As noted earlier, CFB op-amps deliver impressive slew rates, when compared with VFB op-amps of comparable supply current or bandwidth. That's because the slew rate is not limited by the rate at which the input-stage's quiescent current can charge the compensation capacitor, as it is in a conventional VFB op-amp (see for example Fig. 4.43); instead, in the standard CFB op-amp the feedback current driven into the inverting input (which can be much larger than the stage's quiescent current) is mirrored to slew the compensation capacitance.

This can be seen nicely in the tabulated specifications in Table 8.3c: comparing the groups labeled "HV bipolar VFB" and "HV bipolar CFB," the average ratio of slew rate (in units of V/$\mu$s) to supply current (in mA) is 21 and 570 (V/mA·$\mu$s), respectively; i.e., the CFBs beat the VFBs by a factor of 25 in that figure of merit. In those same two groups of op-amps, the slowest-slewing CFB is more than triple the fastest-slewing VFB. These puppies can really slew!

Interestingly, CFB op-amps tend to have significantly higher output current ratings. Comparing the same groups in Table 8.3c, the $I_{out}$(min) of the CFBs average 190 mA, versus 48 mA for the VFBs. Current-feedback op-amps are good when you need lots of bandwidth, slewing, and output current.

#### C. The feedback network and stability

The closed-loop bandwidth increases as you decrease the feedback resistor $R_f$, until you reach some minimum value beyond which the amplifier becomes unstable. Most CFB datasheets give plenty of guidance on this, including graphs of response peaking (see for example Fig. 4x.67). Although there are no issues of stability if you choose to use a far larger value of feedback resistance (as we've hinted at in Figures 4x.65 and 4x.66), in most cases the datasheet will tell you what $R_f$ should be, with graphs like Figure 4x.67; evidently chip designers want their customers to get maximum performance. Some datasheets include a table of recommended $R_f, R_g$ pair values for each of a list of closed-loop gain values, including corresponding bandwidths; see Figure 4x.68 for a nice example, where the optimum resistances are given for each of the three available packages.

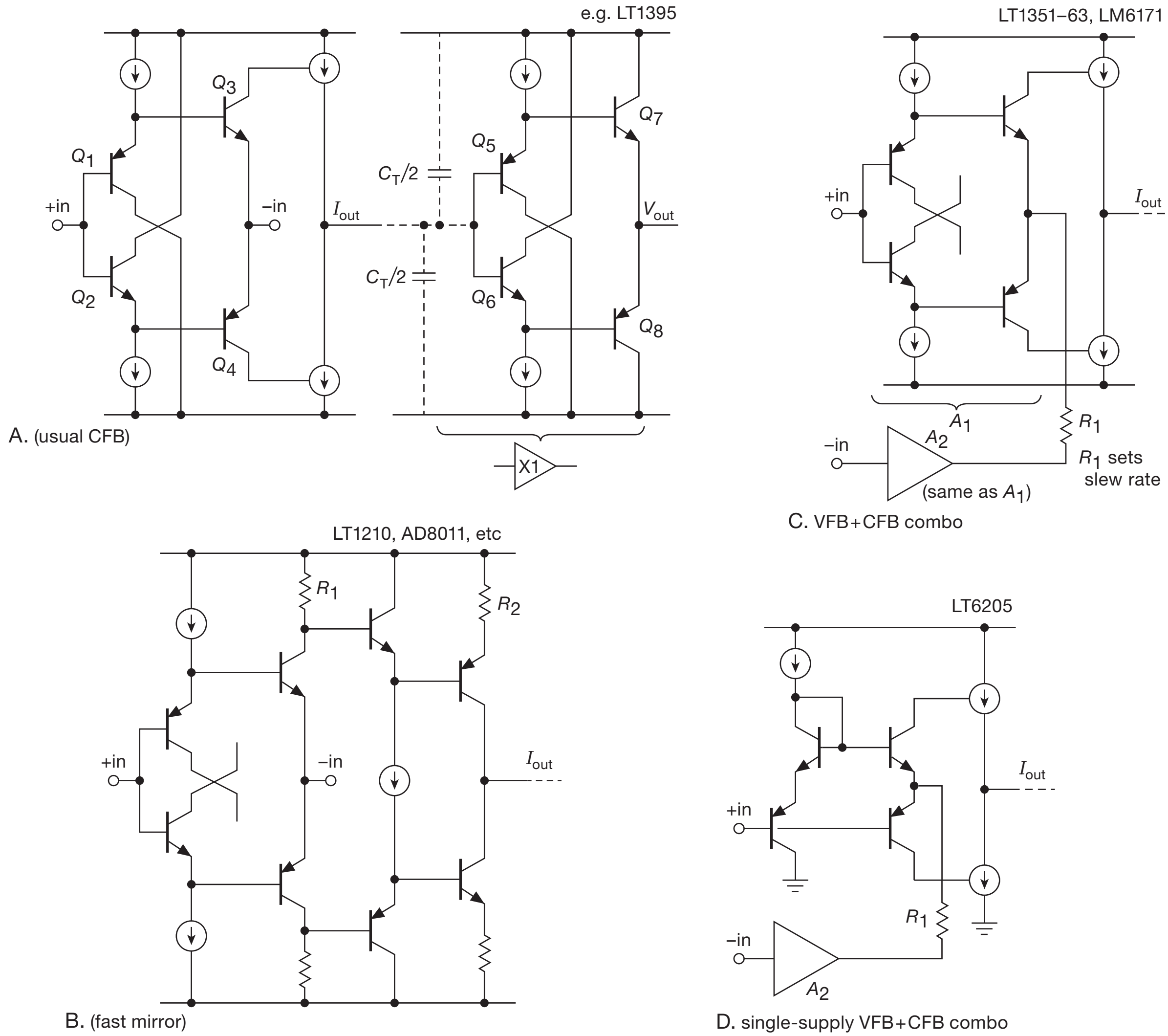


**Figure 4x.63.** Current-feedback op-amp topologies. Configuration A is the basic form; in B the input-stage current is mirrored with gain $R_1/R_2$; configuration C buffers the inverting input, creating a high-impedance voltage-input pair that looks like a normal VFB; the variant D is similar, with single-supply operation down to the negative rail (the latter two are marked with **Z** in the VFB table). For all configurations the intermediate current $I_{out}$, loaded by internal capacitance $C_T$, is converted to an output *voltage* by the follower stage shown explicitly in configuration A.

Unlike VFBs, where stability is enhanced with a small capacitor across the feedback resistor (see for example Fig. 4.104), CFBs react strongly (and unhappily) to such medicine: it takes only a small capacitance across $R_f$ (or, similarly, from the inverting terminal to ground) to push them into instability and oscillation. See the impressive results in Figures 4x.69 and 4x.70 produced by just a few picofarads. A personal anecdote: in making the measurements for Figure 4x.66, the unity-gain datapoints showed anomalously large bandwidths – even with $R_f = 30\,k\Omega$ the bandwidth was suspiciously "too good." Turns out capacitance at pin 2 of the DIP was the culprit, tamed by bending it up and away from the board, then connecting $R_f$ to the flying lead.

### D. Input current and precision

Current-feedback op-amps, with their asymmetric input structure, are generally mediocre in precision ($V_{os}$), and of course the inverting input presents a low impedance and significant input current. Looking again at the LT1223, we

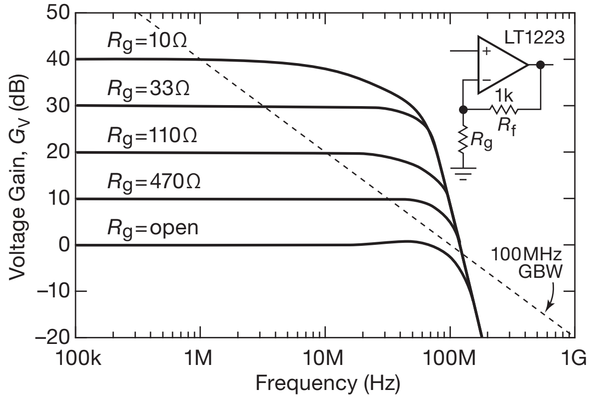


**Figure 4x.64.** The closed-loop bandwidth of current-feedback op-amps is relatively insensitive to closed-loop voltage gain, as shown in the LT1223's datasheet. For comparison the dashed line represents a constant 100 MHz gain–bandwidth product.

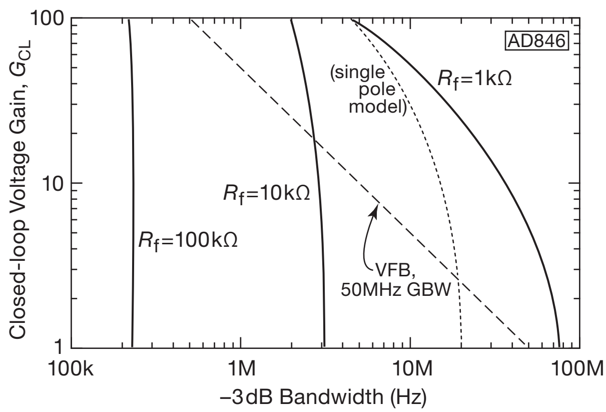


**Figure 4x.65.** Whereas the bandwidth of a VFB amplifier (dashed line) varies inversely with closed-loop gain, the closed-loop bandwidth of a CFB is determined primarily by the feedback resistor $R_f$. Additional poles in the AD846 cause peakiness in the 1 kΩ curve at low gains; the dotted curve illustrates ideal behavior, see §4x.6.5. (Adapted from the AD846 datasheet.)

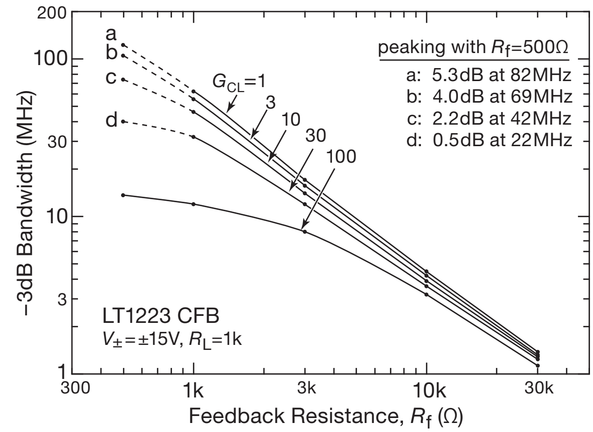


**Figure 4x.66.** Another way to show the closed-loop gain dependence on $R_f$ and $G_{CL}$ is to plot a family of bandwidth curves versus feedback resistance, shown here with data measured on our bench.

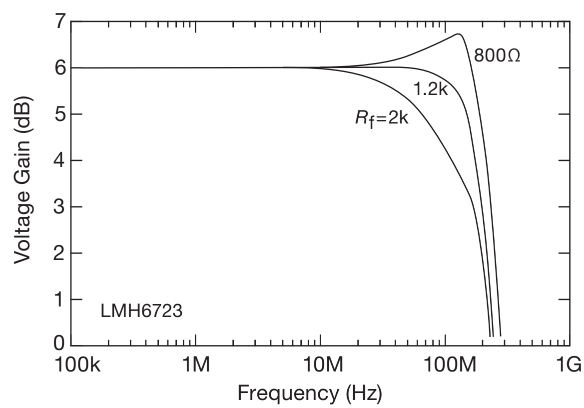


**Figure 4x.67.** For sufficiently small values of $R_f$ the response becomes peaked, as seen in these datasheet curves for the LMH6723. A small amount of peaking extends the bandwidth, but don't overdo it!

see $V_{os} = \pm 1$ mV (typ), $\pm 3$ mV (max); and both inputs have quiescent bias currents of $\pm 1\mu$A (typ), $\pm 3\mu$A (max). The input impedance of the noninverting input is 10 MΩ (typ), but the inverting input looks like some tens of ohms (not specified on the datasheet).

Quite apart from low offset voltage, a good precision op-amp should have large open-loop voltage gain. The exemplary OPA277 VFB precision op-amp ($V_{os}$=20$\mu$V max) has a typical open-loop voltage gain of 140 dB ($10^7$), compared with 89 dB ($3\times10^4$) for the LT1223 CFB op-amp. Owing to the low gain of the latter, it requires 300 $\mu$V of input difference to swing its output 10 V, compared with just 1 $\mu$V for the high-gain VFB.

### 4x.6.2 Care and feeding of CFBs

Current-feedback op-amps can be fussy things, primarily perhaps because their wide bandwidth makes them susceptible to instability if they are not treated with respect. That respect begins with following the datasheet's recommendations for resistor values, as just described. But you have to be particularly careful (*obsessive* might be a better description) about bypassing; we mistakenly soldered 10 nF chip bypass caps (plus larger tantalums) at the supply pins of an

**Recommended Component Values**

| Package | AD8001AN (PDIP) | | | | | AD8001AR (SOIC) | | | | | AD8001ART (SOT23-5) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gain** | –1 | +1 | +2 | +10 | +100 | –1 | +1 | +2 | +10 | +100 | –1 | +1 | +2 | +10 | +100 |
| $R_F$ (Ω) | 649 | 1050 | 750 | 470 | 1000 | 604 | 953 | 681 | 470 | 1000 | 845 | 1000 | 768 | 470 | 1000 |
| $R_G$ (Ω) | 649 | | 750 | 51 | 10 | 604 | | 681 | 51 | 10 | 845 | | 768 | 51 | 10 |
| **small-signal BW** (MHz) | 340 | 880 | 460 | 260 | 20 | 370 | 710 | 440 | 260 | 20 | 240 | 795 | 380 | 260 | 20 |
| **0.1dB flatness** (MHz) | 105 | 70 | 105 | | | 130 | 100 | 120 | | | 110 | 300 | 300 | | |

**Figure 4x.68.** Op-amp manufacturers are not shy when it comes to telling you what resistor values to use with their CFBs, even specifying it separately for each package style (data from AD8001 datasheet).

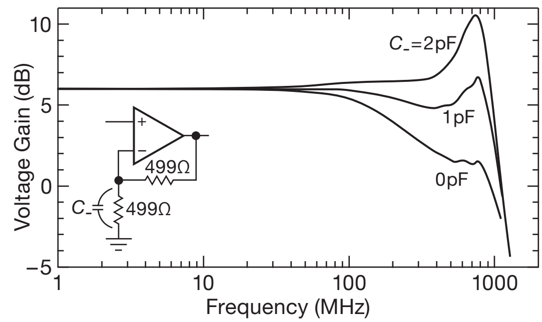


**Figure 4x.69.** Current-feedback op-amps are sensitive to capacitance at the inverting input, as shown in the AD8009 datasheet. If you're careful, this can be used to extend amplifier bandwidth (see the LT1228 datasheet, for example). But don't put a capacitor across $R_f$ in CFB circuits.

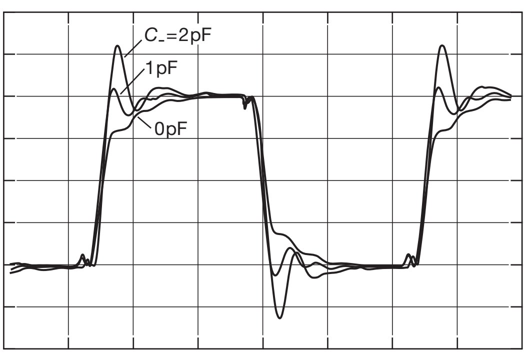


**Figure 4x.70.** An amplifier with peaking in its frequency response will exhibit transient overshoot, as seen here for the same AD8009 circuit as in Fig. 4x.69. Vertical: 50 mV/div; Horizontal: 2 ns/div.

AD846 (the datasheet[48] said to use 100 nF, but we forgot), which proceeded to oscillate around 100 MHz. The problem is widespread enough to merit bragging rights about forgiving CFBs, for example "The LT1223 is very stable even with minimal supply bypassing, however, the transient response will suffer if the supply rings."

Another fussiness is the sensitivity to capacitance at the inverting input, as seen in Figures 4x.69 and 4x.70. Just a few picofarads can kill you, and you'll find advice like this on some datasheets: "The [PCB] ground plane should be removed from the area near the input pins to reduce stray capacitance."

### 4x.6.3 "Hybrid" VFB+CFB op-amps

The drawbacks of the conventional CFB op-amp (Fig. 4x.63A) – namely its unfriendly inverting input and its mediocre input offset voltage – can be nicely circumvented by buffering the inverting input and including the current-feedback resistor $R_f$ within the chip, as in Figure 4x.63C. The resultant hybrid, which we might christen a "CFB in VFB's clothing," combines the best properties of CFBs and VFBs: high slew rate and bandwidth, with symmetrical high-impedance voltage inputs. The 100 MHz LM6171, for instance, appeals to designers with a banner proclaiming "Easy-To-Use Voltage Feedback Topology" followed by "Very High Slew Rate: 3600 V/$\mu$s." They

[48] "A 0.1 $\mu$F ceramic and a 2.2 $\mu$F electrolytic capacitor as shown in Figure 35 placed as close as possible to the amplifier (with short lead lengths to power supply common) will assure adequate high frequency bypassing, in most applications." They do not further expound on the meaning of "most."

don't brag about precision, however, probably because it's, uh, underwhelming ($V_{os}$ of 3 mV typ, 6 mV max). LTC's LT1351–63 series of successively wider bandwidth op-amps (also VFB+CFB hybrid) does considerably better in this regard, with typical offset voltages ranging from 0.2 mV to 0.5 mV for parts of bandwidths from 3 MHz to 70 MHz. Their LT6205–07 series uses the topology of Figure 4x.63D to create an analogous single-supply VFB+CFB part. See also the discussion in §4x.9.1.

### 4x.6.4 When to use CFBs

Current-feedback op-amps are good when you want high slew-rate, or plenty of voltage gain along with plenty of bandwidth. They tend to have lower distortion than comparable VFBs at high frequencies. And you can change gains without significantly changing the bandwidth, a useful property in a programmable-gain amplifier (PGA) that might precede an ADC system.

Voltage-feedback op-amps are more familiar, and they come in a bewildering variety (precision, low-bias, high-voltage, rail-to-rail, etc.). They're versatile, allowing great variety in the feedback network (think of active filters). Our general advice is to choose VFBs for pretty much everything other than the special applications for which CFBs excel.

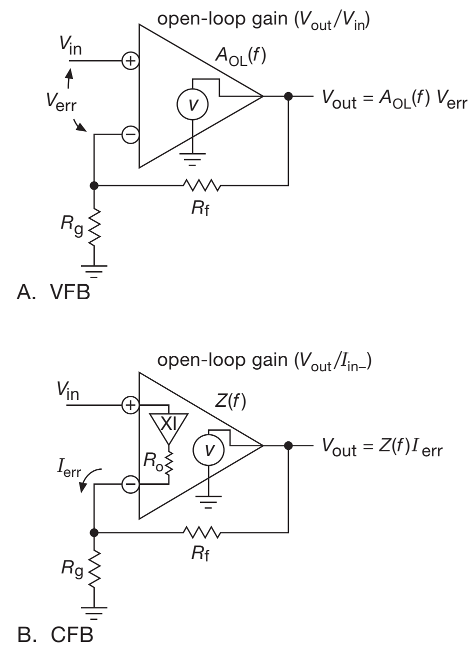


**Figure 4x.71.** VFB and CFB op-amps compared. A VFB amplifies the voltage error at its high-impedance input pair to produce a voltage output, with unitless gain $A_{OL}(f)$; a CFB converts a current ($I_{err}$) at its low-impedance inverting input to a voltage output, with transimpedance gain $Z(f)$.

### 4x.6.5 Mathematical postscript: bandwidth and gain in CFBs

It's instructive to see how the closed-loop voltage gain $G_{CL}$ of a given CFB depends primarily on the value of the feedback resistor $R_f$, and only weakly on the target closed-loop gain (as determined by the gain-setting resistor $R_g$). Although one may have some confidence in an intuitive understanding, there's no substitute for a proper analytic derivation, which we'll do here. Plus, some folks just love to see the math.

#### The familiar case: voltage-feedback op-amp

An "ordinary" (aka *voltage-feedback*, or VFB) op-amp, configured as a noninverting voltage amplifier with feedback resistor $R_f$ from the output to the inverting input, and gain-setting resistor $R_g$ from the inverting input to ground (Fig. 4x.71A), has an ideal voltage gain (in the limit of infinite open-loop voltage gain $A_{OL}=\infty$), which we'll call $G_\infty$, of

$$G_\infty \equiv 1 + R_f/R_g.$$

As we saw back in Chapter 2 (eq'n 2.16), in the realistic case of *finite* open-loop gain $A_{OL}$, the closed-loop voltage gain becomes

$$G_{CL} = \frac{A_{OL}}{1 + A_{OL}B},$$

which (because the ideal closed-loop gain $G_\infty = 1/B$) we can rewrite as

$$G_{CL} = G_\infty \frac{1}{1 + \dfrac{G_\infty}{A_{OL}(f)}}, \qquad (4x.4)$$

a form that shows in plain sight how the ideal gain is degraded, according to the ratio of target gain ($G_\infty$) to (finite) open-loop gain.[49] We've here written the open-loop gain as $A_{OL}(f)$, emphasizing that the latter depends on frequency, extrapolating to unit gain at the unity-gain bandwidth $f_T$. So, for a VFB voltage-amplifier circuit, the closed-loop bandwidth is approximately[50] the frequency at which the open-loop gain $A_{OL}(f)$ has fallen to the target gain $G_\infty$;

[49] Note that the term $G_\infty/A_{OL}$ in the denominator is just the inverse of the loop gain $AB$. A large loop gain ensures a closed-loop gain close to the ideal $G_\infty$.

[50] We say *approximately* because the gain $A_{OL}(f)$ is complex, and accompanied by a 90° phase shift over most of the interesting range of frequency, see §4.4.2A.

another way to say it is that the closed-loop bandwidth is approximately $f_T/G_\infty$.

### The unfamiliar case: current-feedback op-amp

Now let's look at the scene where we substitute a CFB op-amp, again in the noninverting voltage amplifier configuration (Fig. 4x.71B). We'll cast the closed-loop gain in a form similar to eq'n 4x.4, to make the differences evident.

Initially let's assume that the internal impedance $R_o$ of the amplifier is zero. Then the CFB op-amp produces an output voltage

$$V_{out} = I_{err}Z(f)$$

with

$$I_{err} = \frac{V_{in}}{R_g} - \frac{V_{out} - V_{in}}{R_f}.$$

Substituting and rearranging, we get

$$G_{CL} = \frac{V_{out}}{V_{in}} = G_\infty \frac{1}{1+\dfrac{R_f}{Z(f)}}, \qquad (4x.5)$$

where the target gain $G_\infty$=1+$R_f/R_g$, as before.

Unlike the case with the VFB, the bandwidth-limiting term in the denominator depends only on the amplifier's native bandwidth (set by the roll-off of its transimpedance gain $Z_f$) and on the value of the feedback resistor $R_f$. It does not depend on the gain-setting resistor $R_g$. This behavior is seen, approximately, in Figure 4x.64.

Notice, though, that the bandwidth *does* decrease at the highest gains in that figure, and in others (e.g., Fig. 4x.66). To finish the discussion we have to take into account the non-zero impedance $R_o$ seen at the CFB's inverting input. When that is included, the voltage at the inverting input becomes $V_-$=$V_{in}$−$I_{err}R_o$, so the input error current is

$$I_{err} = \frac{V_{in} - I_{err}R_o}{R_g} - \frac{V_{out} - V_{in} + I_{err}R_o}{R_f}.$$

With a bit of fiddling you arrive at the grand finale

$$G_{CL} = \frac{V_{out}}{V_{in}} = G_\infty \frac{1}{1+\dfrac{R_f + R_oG_\infty}{Z(f)}}. \qquad (4x.6)$$

With $R_o$ included, the closed-loop gain includes an additional bandwidth-limiting term $R_oG_\infty$ in the denominator; for a given feedback resistor $R_f$, the bandwidth will decrease with increasing target gain when the product of the op-amp's $R_o$ and the target gain $G_\infty$ is comparable to or greater than $R_f$. That is the cause of the dropoff in Figures 4x.64, 4x.65, and 4x.66. (It is not hard to show that the extra term $R_oG_\infty$ becomes important when $R_o$ is not small compared with $R_g$, as we expect from the qualitative argument in §4x.6.1.)

Let's try this out, for some CFB op-amp. It's not so easy, though because many CFB op-amp datasheets omit a value for $R_o$, and those that do include it (Analog Devices is exemplary in this regard) do not usually list bandwidth versus gain for a given $R_f$. Happily the AD846 (no longer in production ... but datasheets live forever!) lets us test eq'n 4x.6. The datasheet specifies $R_o$=50 Ω; so voltage gains of 1 and 100 correspond to values of $R_oG_\infty$ of 50 Ω and 5 kΩ. With a feedback resistor of 1 kΩ the closed-loop bandwidths should be approximately in the ratio of 5:1, which is in good agreement with the dotted curve[51] in Figure 4x.65. And for a 10 kΩ feedback resistor, eq'n 4x.6 predicts a ratio of 1.5:1, in good agreement with the $R_f$=10 kΩ curve.

## 4x.6.6 Remarks on the table

We've scoured manufacturers' CFB offerings, collected together in Table 4x.3 on the following page, analogous to the four-pages of fast VFB op-amps listed in the previous section. Some general comments follow:

### Bandwidth

As discussed earlier (see Fig. 4x.65 if you've forgotten), CFB op-amps (unlike VFB) cannot be characterized by a gain–bandwidth product. In the table we list more useful bandwidth specs: the −3 dB frequency for unity gain (or the lowest usable gain), and for $G \geq 5$, which gives some idea of the high-gain capability. We also list (where available) the frequency at which the low-gain configuration rolls off by 0.1 dB; this is useful for precision applications, such as an ADC driver. Be aware that small changes in op-amp compensation can cause large changes in the bandwidth; see, for example, the MAX4223 and 4224. Note, also, that op-amps with bandwidths greater than about 100 MHz often have greatly reduced −3 dB frequencies for large output swings (such a 1 V); be sure to read the datasheet carefully! Another speed-related parameter is overload recovery time, which we've not listed, but which can usually be found on datasheets.

### Limited specifications

Many CFB op-amps provide no specifications for gains other than $G$=1 or 2. These are aimed at the cable-driver market, where you need to drive a back-terminated and

[51] A complication: with small $R_f$, CFB amplifiers exhibit peaked response at high frequencies, as seen for example in Fig. 4x.67; that's generally not a good thing, but it does extend the official −3 dB bandwidth. The AD846 acknowledges this artifact, and adds the dotted curve with the notation "single-pole model, AD846."

Table 4x.3: High-Speed Op-amps II: CFB[a]

| Part # | qty per pkg[f] | Supply[p] Range (V) | Supply[p] $I_q$[t] (mA) | Bias Curr @25°C $I_{in+}$ typ (μA) | Bias Curr @25°C $I_{in-}$ typ (μA) | $V_{os}$ max (mV) | CMRR min dB | Noise[t] @10kHz $e_n$ $\left(\frac{nV}{\sqrt{Hz}}\right)$ | Noise[t] @10kHz $i_n$[x] $\left(\frac{pA}{\sqrt{Hz}}\right)$ | min gain[n] | Bandwidth −3dB G=1 (MHz) | Bandwidth −3dB G>5[g] (MHz) | Bandwidth -0.1dB[w] (MHz) | $I_{out}$ typ (mA) | Slew typ (V/μs) | Settle 0.1% (ns) | $C_{in}$[c] (pF) | null pins | comp pin | shdn pin | DIP avail | SOIC-8 | SOT-23 | Power pkg | Cost ($US) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *BJT, high-voltage* | | | | | | | | | | | | | | | | | | | | | | | | | | |
| LT1217 | **1** | 9-36 | 1 | 0.1 | 0.1 | 3 | 60 | 6.5 | 0.7 | 1 | 10 | 8 | | 50 | 500 | 280 | 1.5 | • | - | • | • | • | - | - | 4.42 | A |
| LT1210 | **1** | 10-36 | 9-35 | 2 | 10 | 15 | 55 | 3 | 2 | 1 | 53 | 48 | | 1100 | 900 | - | 2 | - | • | • | - | - | - | • | 8.93 | B,D |
| AD844 | **1** | 9-36 | 6.5 | 0.15 | 0.2 | 0.3 | 90 | 2 | 10 | 2 | 60 | 33 | | 60 | 2000 | 100 | 2 | • | • | - | • | u | - | - | 5.23 | |
| LT1206 | **1**,2 | 10-36 | 20 | 2 | 10 | 10 | 55 | 3.6 | 2 | 1 | 60 | 40 | | 250 | 900 | - | 2 | - | • | • | • | u | - | • | 5.70 | C,D |
| LM6181 | **1** | 9-36 | 7.5 | 0.5 | 2 | 5 | 50 | 4 | 16 | 1 | 100 | 80 | | 90 | 1400 | 50 | - | - | - | - | • | - | - | - | 2.67 | |
| THS3120 | **1** | 9-33 | 7 | 1 | 3 | 8 | 60 | 2.5 | 1 | 1 | 130 | 105 | 90 | 200 | 620 | 7 | 0.4 | - | - | • | - | • | - | • | 5.24 | E |
| AD812 | **2** | 3-36 | 4.5 | 0.3 | 7 | 5 | 55 | 3.5 | 1.5 | 1 | 145 | 40 | 30 | 30 | 1600 | 40 | 1.7 | - | - | - | • | • | - | - | 5.22 | F |
| THS3122 | **2** | 9-33 | 8.4 | 0.33 | 6 | 20 | 63 | 2.2 | 2.9 | 1 | 160 | 120 | 30 | 440 | 1550 | 53 | 2 | - | - | • | - | • | - | • | 9.24 | F |
| LT1223 | **1** | 9-36 | 6 | 1 | 1 | 3 | 56 | 3.3 | 2.2 | 1 | 200 | 10 | | 60 | 1000 | 75 | 1.5 | • | - | • | • | • | - | - | 5.17 | |
| THS3091 | **1** | 10-33 | 9.5 | 3.5 | 4 | 3 | 62 | 2 | 14 | 1 | 235 | 190 | 95 | 175 | 7300 | 42 | 0.1 | - | - | • | - | • | - | • | 8.21 | G |
| THS3095 | **1** | 10-33 | 9.5 | 3.5 | 4 | 3 | 62 | 2 | 14 | 1 | 235 | 190 | 95 | 175 | 7300 | 42 | 0.1 | - | • | • | - | • | - | • | 8.65 | H |
| LT1227 | **1**,2,4 | 4-36 | 10 | 0.3 | 10 | 10 | 55 | 3.2 | 1.7 | 1 | 280[k] | 80 | 60 | 60 | 1100 | 50 | 3 | • | - | • | • | • | - | - | 3.57 | J |
| THS3061 | **1**,2 | 10-33 | 8.3 | 6 | 2 | 3.5 | 72 | 2.6 | 20 | 1 | 300 | 260 | 120 | 145 | 5700 | 30 | 1 | - | - | - | - | • | - | • | 7.28 | K |
| THS6012 | **2** | 9-33 | 11.5 | 4 | 3 | 5 | 100[b] | 1.7 | 12 | 1 | 315 | | 40 | 500 | 1300 | 70 | 1.4 | - | - | - | - | - | - | • | 6.98 | L |
| THS3001 | **1** | 9-33 | 6.6 | 2 | 1 | 3 | 65 | 1.6 | 13 | 1 | 420 | 350 | 115 | 100 | 6500 | 25 | 7.5 | - | - | - | - | • | - | • | 6.93 | |
| THS3491 | **1** | 14-33 | 16.7 | 2 | 7 | 2 | 69 | 1.7 | 15 | 2 | 900 | 450 | 350 | 420 | 8000 | 7 | 1.2 | - | - | • | - | • | - | • | 11.49 | M |
| *BJT, low-voltage* | | | | | | | | | | | | | | | | | | | | | | | - | | | |
| AD8017 | **2** | 4.4-13 | 14[h] | 16 | 1 | 3 | 59 | 1.9 | 23 | 2 | 160 | | 70 | 270 | 1600 | 35 | 2.4 | - | - | - | - | • | - | - | 4.74 | N |
| AD8010 | **2** | 9-12.6 | 15.5 | 6 | 10 | 12 | 50 | 2 | 3 | 1 | 230 | 100 | 60 | 200 | 800 | 25 | 2.8 | - | - | - | • | • | - | - | 6.26 | N |
| AD8023 | **2** | 4.2-15 | 6.2 | 5 | 15 | 5 | 50 | 2 | 14 | 3 | 125 | 38 | 7 | 100 | 1200 | 30 | 2 | - | - | - | - | u | - | - | 9.19 | P |
| ADA4310 | **2** | 5-12 | 0.7-8 | 2 | 6 | 1[t] | 62[t] | 2.9 | 22 | 5 | 190 | 190 | | 120 | 820 | - | - | - | - | - | - | - | v | • | 2.10 | F,N |
| LT6211 | 1,**2** | 3-13 | 0.3-6 | 3.5 | 14 | 6 | 46 | 6.5 | 4.5 | 1 | 200[e] | | | 75 | 700 | 20 | 2 | - | - | p | - | - | • | - | 2.29 | B,Q |
| OPA2677 | **2** | 5-13 | 9 | 10 | 10 | 4.5 | 51 | 2 | 16 | 1 | 220 | 250 | 80 | 500 | 2000 | - | 2 | - | - | • | - | • | - | • | 3.48 | S |
| OPA2674 | **2** | 5-13 | 2-9 | 10 | 10 | 4.5 | 51 | 2 | 16 | 1 | 250 | 220 | 100 | 500 | 2000 | - | 2 | - | - | • | - | • | - | - | 2.62 | B,T |
| AD8004 | **4** | 4-12.6 | 3.5 | 40 | 35 | 3.5 | 52 | 1.5 | 38 | 1 | 250 | | 30 | 50 | 3000 | 21 | 1.5 | - | - | - | - | u | - | - | 8.66 | |
| OPA691 | **1**,2,3 | 5-13 | 5.1 | 15 | 5 | 2.5 | 52 | 1.7 | 3.1 | 1 | 280 | 210 | 90 | 190 | 2100 | 12 | 2 | - | - | • | - | • | • | - | 2.41 | |
| LT6559 | **3** | 4-12.6 | 4.6 | 10 | 10 | 10 | 42 | 4.5 | 6 | 1 | 300 | | 150 | 100 | 800 | 25 | 2 | - | - | • | - | - | q | • | 1.39 | P |
| LT1399HV | 2,**3** | 4-15.5 | 4.6 | 10 | 10 | 10 | 42 | 4.5 | 6 | 1 | 300 | | 150 | 100 | 800 | 25 | 2 | - | - | • | - | u | - | - | 4.25 | P |
| AD8011 | **1** | 4-12.6 | 1 | 5 | 5 | 5 | 52 | 2 | 5 | 1 | 400 | 57 | 25 | 30 | 2000 | 25 | 2.3 | - | - | - | - | • | - | - | 5.32 | |
| LT1395 | **1**,2,4 | 4-12.6 | 4.6 | 10 | 10 | 10 | 42 | 4.5 | 6 | 1 | 400 | | 100 | 80 | 800 | 25 | 2.0 | - | - | • | - | • | • | - | 2.28 | |
| LMH6723 | **1**,2,4 | 4.5-13 | 1 | 2 | 0.4 | 3 | 57 | 4.3 | 6 | 1 | 370 | 150 | 100 | 110 | 600 | 30 | 1.5 | - | - | - | - | • | • | - | 2.03 | |
| LMH6720 | **1**,4 | 5-13.5 | 5.6 | 1 | 4.0 | 6 | 48 | 3.4 | 1.2 | 1 | 400 | | 120 | 70 | 1800 | 12 | 1.0 | - | - | - | - | • | • | - | 2.47 | |
| EL5162 | **1**,2,3 | 5-13.2 | 1.5 | 0.5 | 2.0 | 5 | 50 | 3 | 6.5 | 1 | 500 | 110 | 30 | 100 | 4000 | 25 | 1 | - | - | - | - | • | • | - | 2.39 | |
| MAX4223 | **1**,2 | 5.7-12 | 6 | 2 | 4 | 4 | 55 | 2 | 3 | 1 | 1000 | 230 | 300 | 80 | 800 | 8 | 0.8 | - | - | • | - | • | • | - | 8.36 | |
| EL5164 | **1**,2,3 | 5-13.2 | 3.5 | 2 | 2 | 5 | 50 | 2.1 | 13 | 1 | 500 | 230 | 30 | 140 | 4000 | 25 | 1 | - | - | - | - | • | • | - | 2.82 | |
| TSH350 | **1** | 4.5-6 | 4.1 | 12 | 1 | 4 | 56 | 1.5 | 20 | 1 | 550 | 125 | 120 | 205 | 940 | - | - | - | - | - | - | • | • | - | 2.61 | F |
| MAX4224 | **1**,2 | 5.7-12 | 6 | 2 | 4 | 5 | 55 | 2 | 3 | 2 | 600 | 230 | 200 | 80 | 1400 | 5 | 0.8 | - | - | • | - | • | • | - | 8.36 | |
| HFA1135 | **1** | 9-11 | 6.9 | 6 | 0.4 | 5 | 40 | 3.5 | 2.5 | 1 | 660 | | 25 | 60 | 1200 | 23 | 2 | - | - | - | - | • | - | - | 3.82 | V |
| AD8007 | **1**,2 | 5-12 | 9 | 4 | 0.4 | 4 | 56 | 2.7 | 2 | 1 | 650 | | 90 | 70 | 1000 | 18 | 1 | - | - | - | - | • | s | - | 3.05 | |
| LMH6702 | **1** | 5-13.5 | 12.5 | 6 | 8 | 4.5 | 45 | 1.8 | 3.4 | 1 | 720 | 140 | 120 | 80 | 3100 | 13 | 1.6 | - | - | - | - | • | • | - | 3.04 | |
| ADA4860-1 | **1** | 5-12.6 | 5.2 | 1 | 1 | 13 | 55 | 4 | 1.5 | 1 | 800 | 320 | 125 | 30 | 790 | 8 | 1.5 | - | - | • | - | - | • | - | 1.31 | W |
| HFA1130 | **1** | 9-12 | 21 | 25 | 12 | 6 | 40 | 4 | 18 | 1 | 850 | 200 | 80 | 60 | 2300 | 11 | 2 | - | - | - | - | • | - | - | 4.36 | V |
| AD8001 | **1**,2 | 6-12.6 | 5 | 3 | 5 | 5.5 | 50 | 2 | 2 | 1 | 880 | 200 | 145 | 85 | 1200 | 10 | 1.5 | - | - | - | • | • | • | - | 2.72 | |
| AD8009 | **1** | 5-12.6 | 14 | 50 | 50 | 5 | 50 | 1.9 | 46 | 1 | 1000 | 350 | 75 | 175 | 5500 | 10 | 2.6 | - | - | - | - | • | • | - | 3.19 | |
| EL5166 | **1** | 5-12.6 | 8.5 | 0.7 | 0.7 | 5 | 52 | 1.7 | 50 | 1 | 1400 | 260 | 100 | 110 | 6000 | 8 | 1.5 | - | - | • | - | • | • | - | 2.95 | |
| OPA694 | **1**,2 | 7-13 | 5.8 | 5 | 2 | 3 | 55 | 2.1 | 22 | 1 | 1500 | 250 | 90 | 80 | 1700 | 20 | 1.2 | - | - | - | - | • | • | - | 3.38 | |
| AD8000 | **1**,3 | 4.5-13 | 13.5 | –5 | –3 | 10 | 52 | 1.6 | 3.4 | 1 | 1580 | 330 | 190 | 100 | 4100 | 12 | 3.6 | - | - | • | - | • | - | • | 3.00 | |
| OPA695 | **1**,2,3 | 5-13 | 13 | 13 | 20 | 3 | 51 | 1.8 | 18 | 1 | 1700 | 450 | 320 | 120 | 4300 | 10 | 1.2 | - | - | • | - | • | • | - | 3.42 | |
| THS3201 | **1**,2 | 9-16.5 | 14 | 14 | 13 | 3 | 60 | 1.7 | 13 | 1 | 1800 | 565 | 380 | 100 | 10500 | 20 | 1.0 | - | - | - | - | • | • | • | 5.74 | |

**NOTES:** (a) ordered by increasing unity-gain –3dB frequency. (b) balanced differential. (c) input capacitance from noninverting input to gnd. (d) dual. (e) 10MHz and 170V/μs at $I_Q$=0.3mA. (f) bold is number of amplifiers in listed part number. (g) for $G$=5 to 10. (h) both amplifiers. (k) for $G$=2. (m) maximum. (n) min gain = 2 means $G \geq 2$ or –1. (p) programmable $I_Q$, range shown. (q) QFN pkg. (s) SC-70 available. (t) typ. (u) SOIC-14 or SOIC-16. (v) many-pin SOP or MSOP pkg. (w) at $G$=1 or 2. (x) non-inverting input.

**COMMENTS:** **A.** very low $I_Q$. **B.** programmable $I_Q$. **C.** Ccomp pin for optimum compensation to >1nF C-load. **D.** power pkgs: DD and TO220-7, 5°C/W. **E.** Winfield's fave. **F.** output swings to within 1 volt of the rails. **G.** Larkin uses this one, in DDA pkg. **H.** THS3091 with shutdown. **J.** video amp. **K.** Larkin shuns this one. **L.** balanced line driver, SOIC-20. **M.** upgrade for THS3091, -95. **N.** line driver. **P.** video driver. **Q.** rail-to-rail output! LT6210 is SOT23-6. **S.** OPA2674 has current lim, adjustable $I_Q$. **T.** no powerpad, use OPA2677. **V.**. Vout clamps! **W.** lowest cost.

end-terminated coax line (that attenuates the signal by a factor of two, thus the need for a $G$=2 buffer). Some of these parts are low cost, and may be suitable at higher gains, but the datasheets provide little guidance.

### Power dissipation

High-voltage parts with high quiescent current may need to be operated at lower voltage (say ±5 V to ±8 V) to prevent overheating. And supply current may increase with large output swings at high frequencies. Be generous with PCB copper, to carry off heat.

### Output swing

Most CFB op-amps require significant supply-rail headroom, which means that "low-voltage" op-amps (which can in principle run from a 5 V total supply) will often need more (e.g., ±5 V). Op-amps that can swing to within a volt of the rails are noted in the table (note F); the LT6211 is the unique exception with its rail-to-rail output.

### Packages

Smaller is usually better! The SOT-23 versions of wideband low-voltage parts, with their reduced lead inductance, often have less peaking and overshoot than the SOIC-8 versions. When selecting CFB (or other!) op-amps, be aware that the single (versus dual) versions are often not stocked at distributors. Duals also have different part numbers, not listed.

## 4x.7 Power Supply Rejection Ratio

We encountered PSRR in Chapter 5 (§5.7.5), when dealing with precision design, where we pointed out several important features (uh, maybe *warnings* is more accurate): (a) PSRR decreases with increasing frequency, in a manner similar to the open-loop gain; (b) PSRR is usually specified for a unity closed-loop gain configuration; (c) the PSRR is generally different with respect to the positive and negative supply rails.

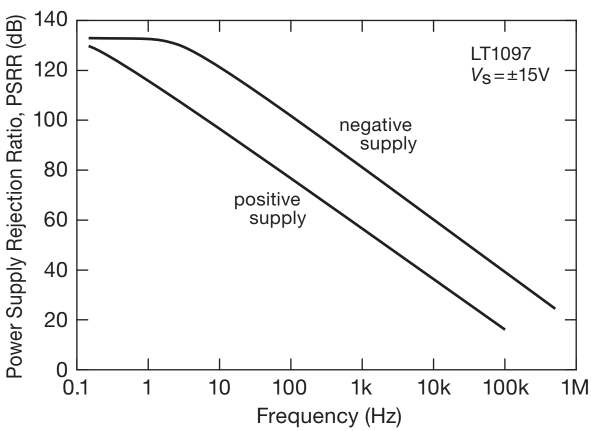


**Figure 4x.72.** LT1097 PSRR versus frequency, as shown in the datasheet plot.

Here we look a bit deeper into the latter effect. Figure 4x.72 shows the datasheet plot of PSRR versus frequency for the LT1097 precision BJT op-amp. At low frequencies the PSRR is comparable to the op-amp's open-loop gain (128 dB, typ), with the PSRR falling roughly at 20 dB/decade. Notice, however, that the PSRR with respect to the positive supply is some 24 dB worse than that with respect to the negative supply, for frequencies above about 10 Hz. (Interestingly, the tabulated data states only that the PSRR is 130 dB typ, 114 dB min, with no commentary about this disparity, nor about its behavior for closed-loop gains greater than unity.)

Why the difference? Look at the simplified circuit in Figure 4x.73. The input-stage *npn* BJT differential amplifier (with bootstrapped cascode) drives a second-stage *pnp* difference amplifier, with single-ended output to the unity-gain push–pull output follower. What spoils the symmetry of this neat picture is the compensation network, which couples back to one side of the input stage's collector pair; so voltage fluctuations on the positive rail see an unsymmetrical path to the first stage's output, being shunted (at high frequencies) by the $C_c$ path. So signals on the $V_+$ rail are coupled more strongly than those on the $V_-$ rail.

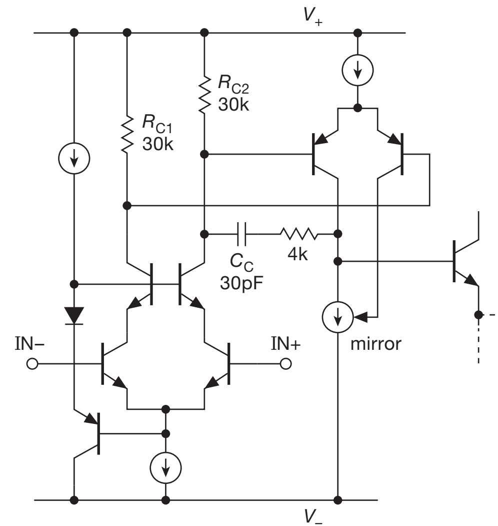


**Figure 4x.73.** Simplified schematic of the LT1097 op-amp, showing unbalanced paths of positive-rail fluctuations, owing to shunting of one side of the (otherwise symmetrical) input-stage differential output (collectors of the cascode) by the compensation capacitor at higher frequencies.

Depending on the details of the op-amp's internal guts, this effect can afflict either supply rail. Figure 4x.74 shows the datasheet plot of PSRR versus frequency for the LT1055 precision JFET op-amp.[52] Here it's signals on the *negative* rail that are more strongly coupled. Once again the simplified circuit (Fig. 4x.76) reveals the reason; this time the compensation network couples to one side of the *p*-channel JFET differential amplifier's drain pulldown. As with the LT1097, the tabulated PSRR for this op-amp is silent on the disparity, stating only that the PSRR is 106 dB typ, 90 dB min.

The poorer negative-rail PSRR of the LT1055 is typical of many op-amps, particularly those with the "Widlar architecture" (see Fig. 5.13), which use a feedback compensation capacitor to a negative-rail common-emitter stage; Figure 4x.75, a simplified circuit of our canonical

[52] Both examples are from Linear Technology (now part of Analog Devices); we like their products, but the reason we chose these examples is that LTC includes (simplified) schematics, a rarity in contemporary datasheets.