SECTION 1-6

High Speed Op Amps

Walt Kester

Introduction

High speed analog signal processing applications, such as video and communications, require op amps that have wide bandwidth, fast settling time, low distortion and noise, high output current, good dc performance, and operate at low supply voltages. These devices are widely used as gain blocks, cable drivers, ADC pre-amps, current-to-voltage converters, and so forth. Achieving higher bandwidths for less power is extremely critical in today's portable and battery-operated communications equipment. The rapid progress made over the last few years in high speed linear circuits has hinged not only on the development of IC processes but also on innovative circuit topologies.

The evolution of high speed processes using amplifier bandwidth as a function of supply current as a figure of merit is shown in Figure 1-96. (In the case of duals, triples, and quads, the current per amplifier is used.) Analog Devices BiFET process, which produced the AD712 (3 MHz bandwidth, 3 mA current) yields about 1 MHz per mA.

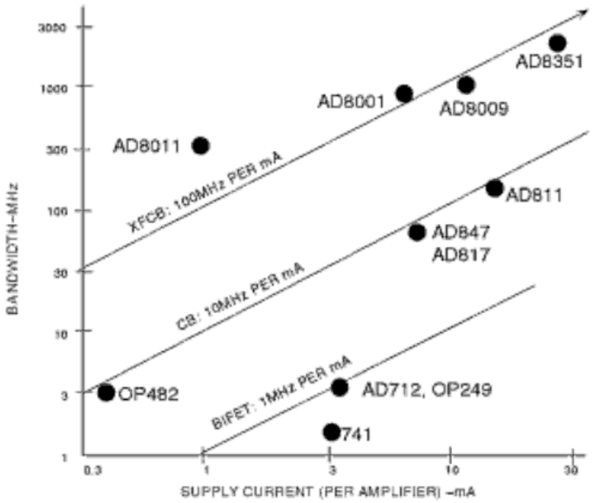

Figure 1-96: Amplifier bandwidth versus supply current for Analog Devices' processes

The CB (Complementary Bipolar) process (AD817, AD847, AD811, and so forth) yields about 10 MHz/mA of supply current. The f_ts of the CB process PNP transistors are about 700 MHz, and the NPNs about 900 MHz. The CB process at Analog Devices was introduced in 1985.

The next complementary bipolar process from Analog Devices was a high speed dielectrically isolated process called "XFCB" (eXtra Fast Complementary Bipolar) which was introduced in 1992. This process yields 3 GHz PNPs and 5 GHz matching NPNs, and coupled with innovative circuit topologies allows

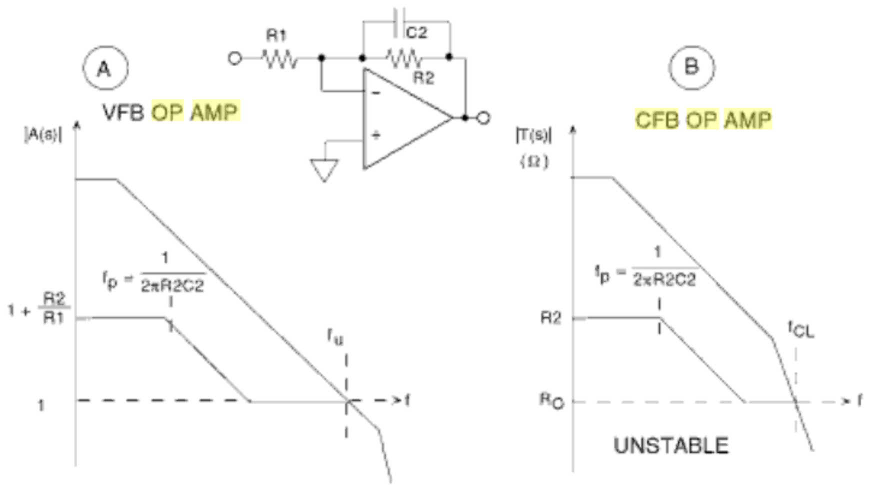

Figure 1-113: Noise gain stability analysis for VFB and CFB op amps with feedback capacitor

In the case of the CFB op amp (Figure 1-113B), the same analysis is used, except that the open-loop transimpedance gain, T(s), is used to construct the Bode plot.

The definition of *noise gain* (for the purposes of stability analysis) for a CFB op amp, however, must be redefined in terms of a *current* noise source attached to the inverting input as shown in Figure 1-114. This current is reflected to the output by an impedance, which we define to be the "current noise gain" of a CFB op amp:

$$\text{"CURRENT NOISE GAIN"} \equiv R_O + Z2\left(1 + \frac{R_O}{Z1}\right) \qquad \text{Eq. 1-50}$$

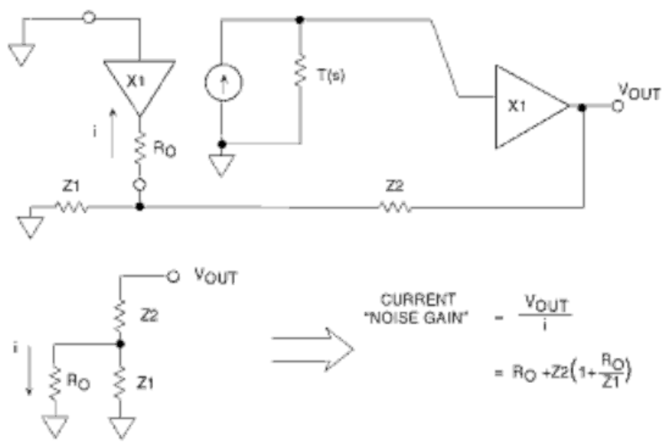

Figure 1-114: Current "noise gain" definition for CFB op amp for use in stability analysis

This value of C2 will yield a phase margin of about 45°. Increasing the capacitor by a factor of 2 increases the phase margin to about 65° (see Reference 3).

In practice, the optimum value of C2 may be optimized experimentally by varying it slightly, to optimize the output pulse response.

A similar analysis can be applied to a CFB op amp as shown in Figure 1-118. In this case, however, the low inverting input impedance, R_O, greatly reduces the sensitivity to input capacitance. In fact, an ideal CFB with zero input impedance would be totally insensitive to any amount of input capacitance.

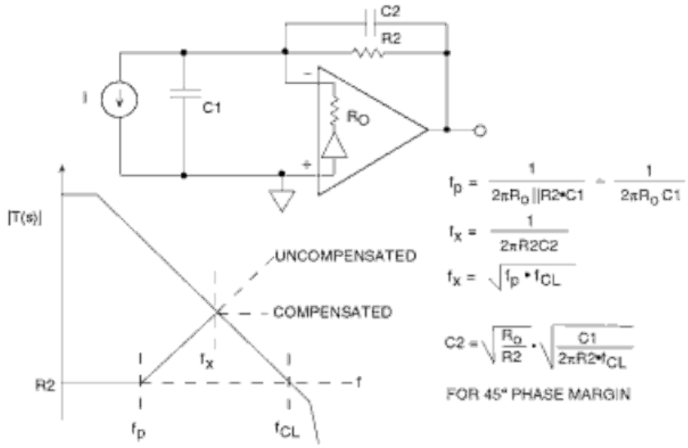

Figure 1-118: Current-to-voltage converter using a CFB op amp

The pole caused by C1 occurs at a frequency f_P:

$$f_P = \frac{1}{2\pi(R_O \| R2)C1} \approx \frac{1}{2\pi R_O C1} \qquad \text{Eq. 1-55}$$

This pole frequency will generally be much higher than the case for a VFB op amp, and the pole can be ignored completely if it occurs at a frequency greater than the closed-loop bandwidth of the op amp.

We next introduce a compensating zero at the frequency f_x by inserting the capacitor C2:

$$f_x = \frac{1}{2\pi R2C2} \qquad \text{Eq. 1-56}$$

As in the case for VFB, f_x is the geometric mean of f_p and f_{cl}:

$$f_x = \sqrt{f_P \cdot f_u} \qquad \text{Eq. 1-57}$$

Combining Eq. 1-56 and Eq. 1-57 and solving for C2 yields:

$$C2 = \sqrt{\frac{R_O}{R2}} \cdot \sqrt{\frac{C1}{2\pi R2 \cdot f_{cl}}} \qquad \text{Eq. 1-58}$$

There is a significant advantage in using a CFB op amp in this configuration as can be seen by comparing Eq. 1-58 with the similar equation for C2 required for a VFB op amp, Eq. 1-54. If the unity-gain bandwidth product of the VFB is equal to the closed-loop bandwidth of the CFB (at the optimum R2), then the size of the CFB compensation capacitor, C2, is reduced by a factor of $\sqrt{(R2/R_O)}$.

A comparison in an actual application is shown in Figure 1-119. The full scale output current of the DAC is 4 mA, the net capacitance at the inverting input of the op amp is 20 pF, and the feedback resistor is 500 Ω. In the case of the VFB op amp, the pole due to C1 occurs at 16 MHz. A compensating capacitor of 5.6 pF is required for 45° of phase margin, and the signal bandwidth is 57 MHz.

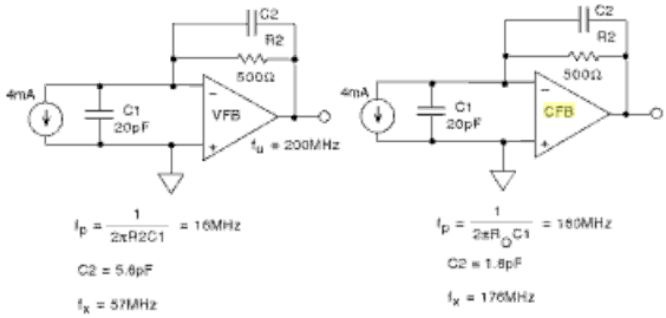

Figure 1-119: CFB op amp is relatively insensitive to input capacitance when used as an I/V converter

For the CFB op amp, however, because of the low inverting input impedance (R_O = 50 Ω), the pole occurs at 160 MHz, the required compensation capacitor is about 1.8 pF, and the corresponding signal bandwidth is 176 MHz. In practice, the pole frequency is so close to the closed-loop bandwidth of the op amp that it could probably be left uncompensated.

It should be noted that a CFB op amp's relative insensitivity to inverting input capacitance is when it is used in the inverting mode. In the noninverting mode, however, even a few picofarads of stray capacitance on the inverting input can cause significant gain peaking and potential instability.

Another advantage of the low inverting input impedance of the CFB op amp is when it is used as an I/V converter to buffer the output of a high speed current output DAC. When a step function current (or DAC switching glitch) is applied to the inverting input of a VFB op amp, it can produce a large voltage transient until the signal can propagate through the op amp to its output and negative feedback is regained. Back-to-back Schottky diodes are often used to limit this voltage swing as shown in Figure 1-120. These diodes must be low capacitance, small geometry devices because their capacitance adds to the total input capacitance.

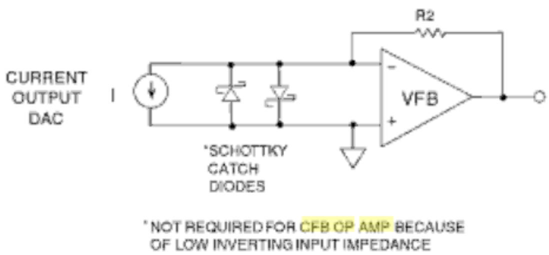

Figure 1-120: Low inverting input impedance of CFB op amp helps reduce effects of fast DAC transients

A CFB op amp, on the other hand, presents a low impedance (R_O) to fast switching currents even before the feedback loop is closed, thereby limiting the voltage excursion without the requirement of the external diodes. This greatly improves the settling time of the I/V converter.

Noise Comparisons between VFB and CFB Op Amps

In most applications of high speed op amps, it is generally the total output RMS noise that is of interest. Because of the high bandwidths involved, the chief contributor to the output RMS noise is therefore the white noise, and the 1/f noise is negligible.

Typical high speed op amps with bandwidths greater than 150 MHz or so, and bipolar VFB input stages, have input voltage noises ranging from about 2 nV to $20\ \text{nV}/\sqrt{\text{Hz}}$.

For a VFB op amp, the inverting and noninverting input current noise are typically equal, and almost always uncorrelated. Typical values for wideband VFB op amps range from $0.5\ \text{pA}/\sqrt{\text{Hz}}$ to $5\ \text{pA}/\sqrt{\text{Hz}}$. The input current noise of a bipolar input stage is increased when input bias-current compensation generators are added, because their current noise is not correlated, and therefore adds (in an RSS manner) to the intrinsic current noise of the bipolar stage. However, bias current compensation is rarely used in high speed op amps.

The input voltage noise in CFB op amps tends to be lower than for VFB op amps having the same approximate bandwidth. This is because the input stage in a CFB op amp is usually operated at a higher current, thereby reducing the emitter resistance and hence the voltage noise. Typical values for CFB op amps range from about 1 nV to $5\ \text{nV}/\sqrt{\text{Hz}}$.

The input current noise of CFB op amps tends to be larger than for VFB op amps because of the generally higher bias current levels. The inverting and noninverting current noise of a CFB op amp is usually different because of the unique input architecture, and are specified separately. In most cases, the inverting input current noise is the larger of the two. Typical input current noise for CFB op amps ranges from 5 pA to $40\ \text{pA}/\sqrt{\text{Hz}}$. This can often be dominant, except in cases of very high gain, when R1 is small.

The noise sources that dominate the output noise are highly dependent on the closed-loop gain of the op amp and the values of the feedback and feedforward resistors. For high values of closed-loop gain, the op amp voltage noise will tend be the chief contributor to the output noise. At low gains, the effects of the input current noise must also be considered, and may dominate, especially in the case of a CFB op amp.

Feedforward/feedback resistors in high speed op amp circuits may range from less than 100 Ω to more than 1 kΩ, so it is difficult to generalize about their contribution to the total output noise without knowing the specific values and the closed-loop gain.

The best way to make the noise calculations is to write a simple computer program that automatically performs the calculations, and include all the noise sources. The equation previously discussed can be used for this purpose (see Figure 1-74). In most high speed op amp applications, the source impedance noise can often be neglected for source impedances of 100 Ω or less.

Figure 1-121 summarizes the noise characteristics of high speed op amps.

- Voltage Feedback Op Amps:
  - Voltage noise: 2nV to 20nV/√Hz
  - Current noise: 0.5pA to 5pA/√Hz
- Current Feedback Op Amps:
  - Voltage noise: 1nV to 5nV/√Hz
  - Current noise: 5nV to 40pA/√Hz
- Noise Contribution from Source Negligible if < 100Ω
- Voltage Noise Usually Dominates at High Gains
- Reflect Noise Sources to Output and Combine (RSS)
- Errors Will Result if there is Significant High Frequency Peaking

Figure 1-121: High speed op amp noise summary

DC Characteristics of High Speed Op Amps

High speed op amps are optimized for bandwidth and settling time, not for precision dc characteristics as found in lower frequency precision op amps. In spite of this, however, high speed op amps do have reasonably good dc performance.

Input offset voltages of high speed bipolar input op amps are rarely trimmed, since offset voltage matching of the input stage is excellent, typically ranging from 1 mV to 3 mV, with offset temperature coefficients of 5 μV to 15 μV/°C.

Input bias currents on VFB op amps (with no input bias current compensation circuits) are approximately equal for (+) and (–) inputs, and can range from 1 μA to 5 μA. The output offset voltage due to the input bias currents can be nulled by making the effective source resistance, R3, equal to the parallel combination of R1 and R2.

As previously discussed, this scheme will not work with bias-current compensated VFB op amps that have additional current generators on their inputs. In this case, the net input bias currents are not necessarily equal or of the same polarity.

CFB op amps generally have unequal and uncorrelated input bias currents because the (+) and (–) inputs have completely different architectures. For this reason, external bias current cancellation schemes are also ineffective. CFB input bias currents range from 5 μA to 15 μA, being generally higher at the inverting input.

Figure 1-122 summarizes the offset considerations for high speed op amps.

- High Speed Bipolar Op Amp Input Offset Voltage:
  - Ranges from 1mV to 3mV for VFB and CFB
  - Offset TC ranges from 5μV to 15μV/°C
- High Speed Bipolar Op Amp Input Bias Current:
  - For VFB ranges from 1μA to 5μA
  - For CFB ranges from 5μA to 15μA
- Bias Current Cancellation Doesn't Work for:
  - Bias current compensated op amps
  - Current feedback op amps

Figure 1-122: High speed op amp offset voltage summary