OP AMP TOPOLOGIES

As Excerpted From *Op Amp Applications*

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8/31/2017

This article has been excerpted from *Op Amp Applications*, CR 2002 by Analog Devices, Inc., ISBN 0-916550-26-5. The material following is adapted from: **SECTION 1-2: OP AMP TOPOLOGIES,** as originally authored by *Walt Kester, Walt Jung, and James Bryant.*

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SECTION 1-2: OP AMP TOPOLOGIES

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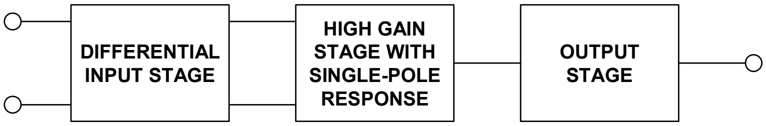
The previous section examined op amps without regard to their internal circuitry. In this section the two basic op amp topologies—voltage feedback (VFB) and current feedback (CFB)— are discussed in more detail, leading up to a detailed discussion of the actual circuit structures in Section 1-3.



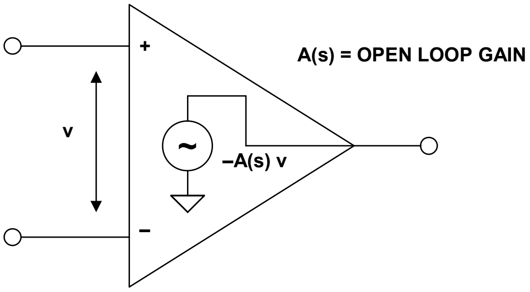
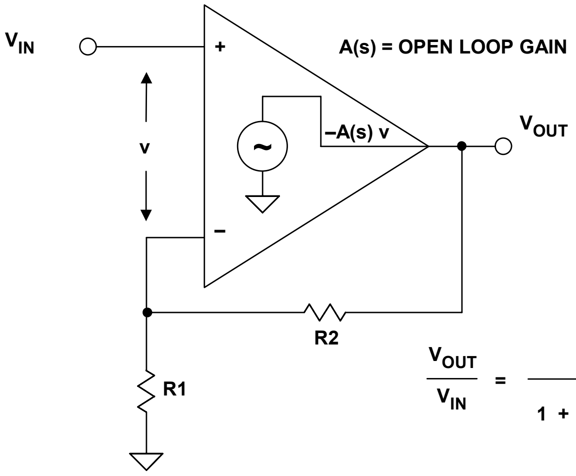


Figure 1-12: *Voltage feedback (VFB) op amp*

Although not explicitly stated, the previous section focused on the voltage feedback op amp and the related equations. In order to reiterate, the basic voltage feedback op amp is repeated here in Figure 1-12 above (without the feedback network) and in Figure 1-13 below (with the feedback network).



$$\frac{V_{OUT}}{V_{IN}} = \frac{1+\frac{R2}{R1}}{1+\frac{1}{A(s)}\left[1+\frac{R2}{R1}\right]} = \frac{1+\frac{R2}{R1}}{1+\frac{1}{A(s)\,\beta}}$$

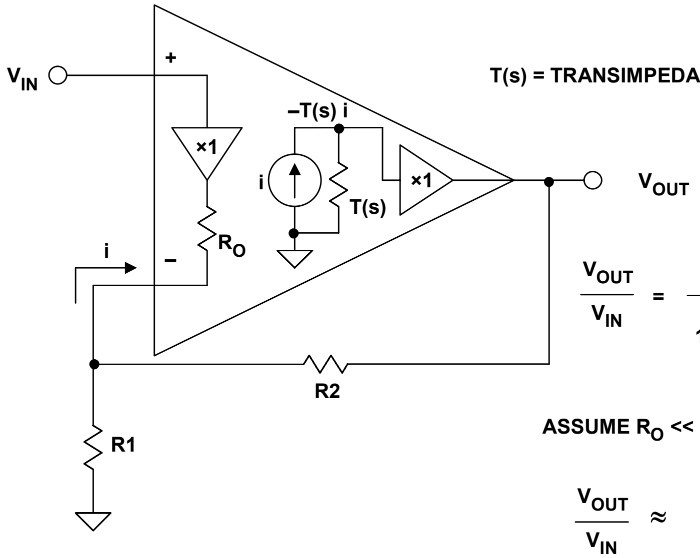
Figure 1-13: *Voltage feedback op amp with feedback network connected*

It is important to note that the error signal developed because of the feedback network and the finite open-loop gain A(s) is in fact a small voltage, v.

Current Feedback Amplifier Basics

The basic *current feedback* amplifier topology is shown in Figure 1-14 below. Notice that within the model, a unity gain buffer connects the non-inverting input to the inverting input. In the ideal case, the output impedance of this buffer is zero ($R_O = 0$), and the error signal is a small current, i, which flows into the inverting input. The error current, i, is mirrored into a high impedance, T(s), and the voltage developed across T(s) is equal to T(s)·i. (The quantity T(s) is generally referred to as the *open-loop transimpedance gain.*)

This voltage is then buffered, and is connected to the op amp output. If R_O is assumed to be zero, it is easy to derive the expression for the closed-loop gain, V_{OUT}/V_{IN}, in terms of the R1-R2 feedback network and the *open-loop* transimpedance gain, T(s). The equation can also be derived quite easily for a finite R_O, and Fig. 1-14 gives both expressions.



T(s) = TRANSIMPEDANCE OPEN LOOP GAIN

$$\frac{V_{OUT}}{V_{IN}} = \frac{1 + \frac{R2}{R1}}{1 + \frac{R2}{T(s)}\left[1 + \frac{R_O}{R1} + \frac{R_O}{R2}\right]}$$

ASSUME R_O << R1, AND R1 ≤ R2, THEN

$$\frac{V_{OUT}}{V_{IN}} \approx \frac{1 + \frac{R2}{R1}}{1 + \frac{R2}{T(s)}}$$

Figure 1-14: *Current feedback (CFB) op amp topology*

At this point it should be noted that current feedback op amps are often called *transimpedance* op amps, because the *open-loop* transfer function is in fact an impedance as described above. However, the term *transimpedance amplifier* is often applied to more general circuits such as current-to-voltage (I/V) converters, where either CFB or VFB op amps can be used. Therefore, some caution is warranted when the term *transimpedance* is encountered in a given application. On the other hand, the term *current feedback op amp* is rarely confused and is the preferred nomenclature when referring to op amp topology.

From this simple model, several important CFB op amp characteristics can be deduced.

- Unlike VFB op amps, CFB op amps *do not have balanced inputs.* Instead, the non-inverting input is high impedance, and the inverting input is low impedance.

- The open-loop gain of CFB op amps is measured in units of Ω (transimpedance gain) rather than V/V as for VFB op amps.

- For a fixed value feedback resistor R2, the closed-loop gain of a CFB can be varied by changing R1, without significantly affecting the closed-loop bandwidth. This can be seen by examining the simplified equation in Fig. 1-14. The denominator determines the overall frequency response; and if R2 is constant, then R1 of the numerator can be changed (thereby changing the gain) without affecting the denominator— hence the bandwidth remains relatively constant.

The CFB topology is primarily used where the ultimate in high speed and low distortion is required. The fundamental concept is based on the fact that in bipolar transistor circuits currents can be switched faster than voltages, all other things being equal. A more detailed discussion of CFB op amp AC characteristics can be found in Section 1-5.

Figure 1-15 below shows a simplified schematic of an early IC CFB op amp, the AD846— introduced by Analog Devices in 1988 (see Reference 1). Notice that full advantage is taken of the complementary bipolar (CB) process which provides well matched high f_t PNP and NPN transistors.

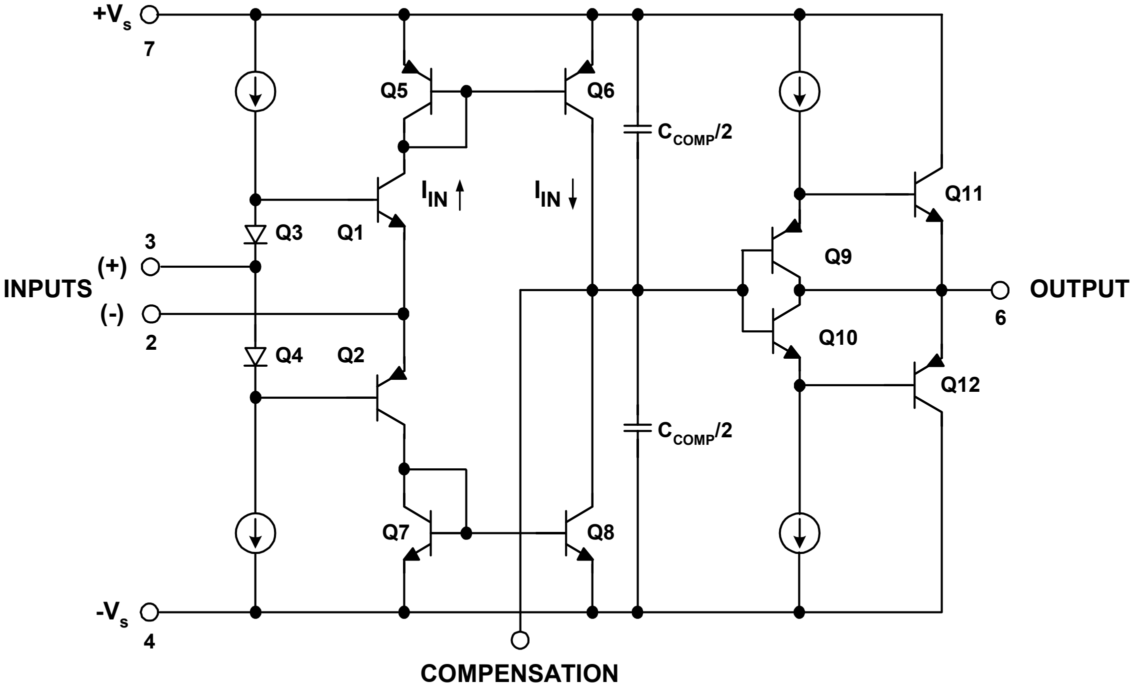


***Figure 1-15:** AD846 current feedback op amp (1988)*

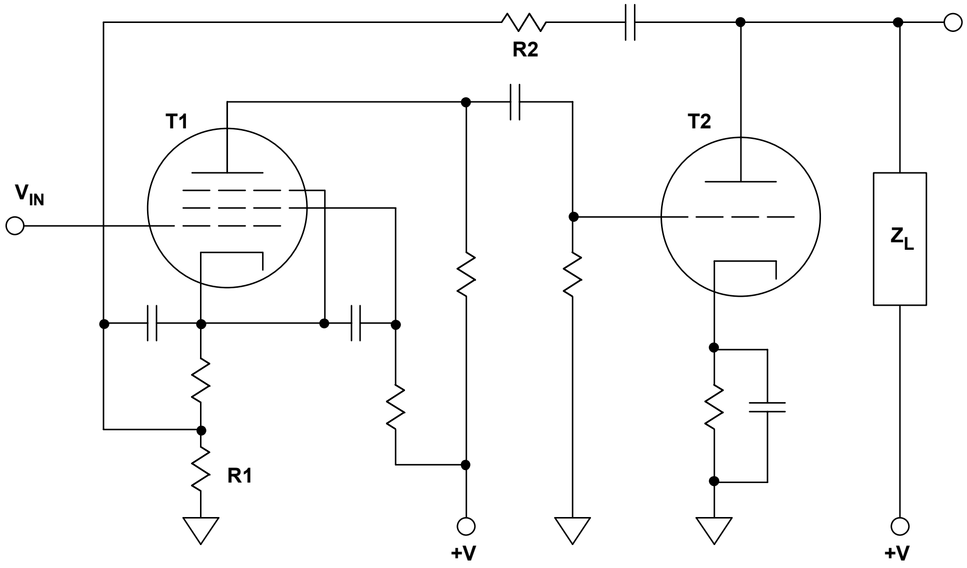
Transistors Q1-Q2 buffer the non-inverting input (pin 3) and drive the inverting input (pin 2). Q5-Q6 and Q7-Q8 act as current mirrors that drive the high impedance node. The C_{COMP} capacitor provides the dominant pole compensation; and Q9, Q10, Q11, and Q12 comprise the output buffer. In order to take full advantage of the CFB architecture, a high speed complementary bipolar (CB) IC process is required. With modern IC processes, this is readily achievable, allowing direct coupling in the signal path of the amplifier.

However, the basic concept of current feedback can be traced all the way back to early vacuum tube feedback circuitry, which used negative feedback to the input tube cathode. This use of the cathode for feedback would be analogous to the CFB op amp's low impedance (-) input, in Fig. 1-15.

Current Feedback Using Vacuum Tubes

Figure 1-16 below is an adaptation from a 1937 article on feedback amplifiers by Frederick E. Terman (see Reference 2). Notice that the AC-coupled R2 feedback resistor for this two-stage amplifier is connected to the low impedance cathode of T1, the pentode vacuum tube input stage. Similar examples of early tube circuits using cathode feedback can be found in Reference 3.

DC-coupled op amp design using vacuum tubes was difficult for numerous reasons. One reason was a lack of suitable level shifters. Multi-stage op amps either required extremely high supply voltages or suffered gain loss because of resistive level shifters. In a 1941 article, Stewart E. Miller describes how to use gas discharge tubes as level shifters in several vacuum tube amplifier circuits (see Reference 4). A circuit of particular interest is shown in Figure 1-17 (opposite).



Adapted from: Frederick E. Terman, "Feedback Amplifier Design," *Electronics*, January 1937, pp. 12-15, 50.

Figure 1-16: *A 1937 vacuum tube feedback circuit designed by Frederick E. Terman, using current feedback to the low impedance input cathode (adapted from Reference 2)*

In the Fig. 1-17 reproduction of Miller's circuit, the R2 feedback resistor and the R1 gain setting resistor are labeled for clarity, and it can be seen that feedback is to the low impedance cathode of the input tube. The author suggests that the closed-loop gain of the amplifier can be adjusted from 72dB-102dB, by varying the R1 gain-setting resistor from 37.4Ω to 1.04Ω.

What is really interesting about the Miller circuit is its frequency response, which is reproduced in Figure 1-18 (opposite). Notice that the closed-loop bandwidth is nearly independent of the gain setting, and the circuit certainly does not exhibit a constant gain-bandwidth product as would be expected for a traditional VFB op amp.

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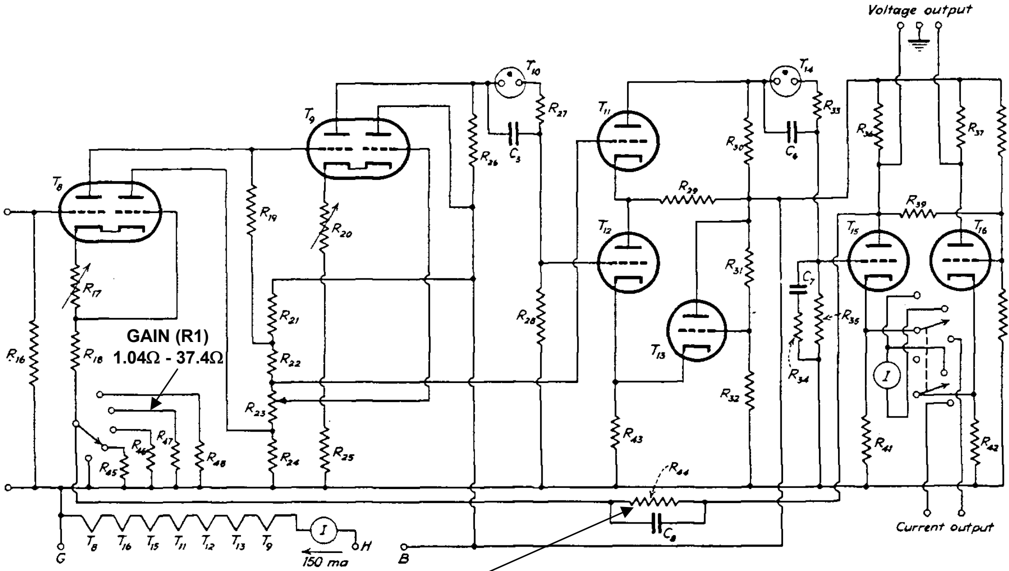
For a gain of 72dB, the bandwidth is about 30kHz, and for a gain of 102dB (30dB increase), the bandwidth only drops to ~15kHz. With a 72dB gain at 30kHz VFB op amp, bandwidth would be expected to drop 5 octaves to ~0.9kHz for 102dB of gain.

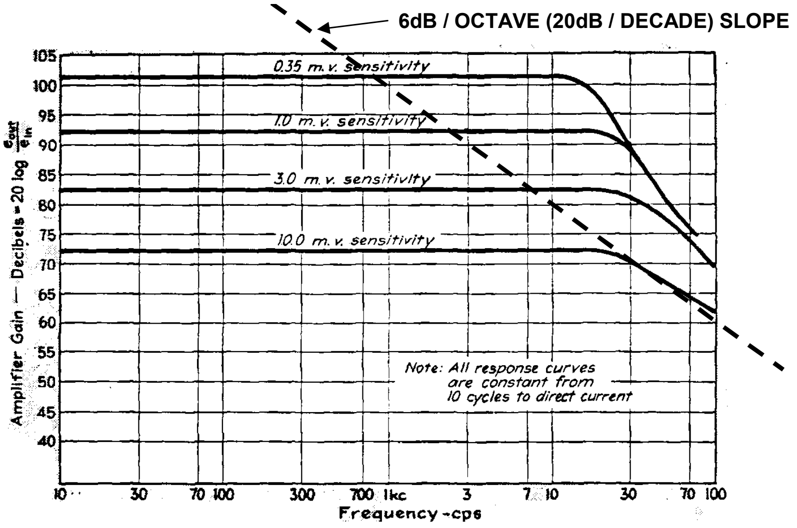


FEEDBACK RESISTOR (R2)
(151kΩ)

Adapted from: Stewart E. Miller, "Sensitive DC Amplifier with AC Operation," *Electronics*, November 1941, pp. 27-31, 105-109

Figure 1-17: *A 1941 vacuum tube feedback circuit using current feedback*

To clarify this point on bandwidth, a standard VFB op amp 6dB/octave (20dB/decade) slope has been added to Fig. 1-18 for reference.



Adapted from: Stewart E. Miller, "Sensitive DC Amplifier with AC Operation," *Electronics*, November 1941, pp. 27-31, 105-109

Figure 1-18: *A 1941 feedback circuit shows characteristic CFB gain-bandwidth relationship*

Although there is no mention of the significance of this within the text of the actual article, it nevertheless illustrates a popular application of CFB behavior, in the design of high speed programmable gain amplifiers with relatively constant bandwidth.

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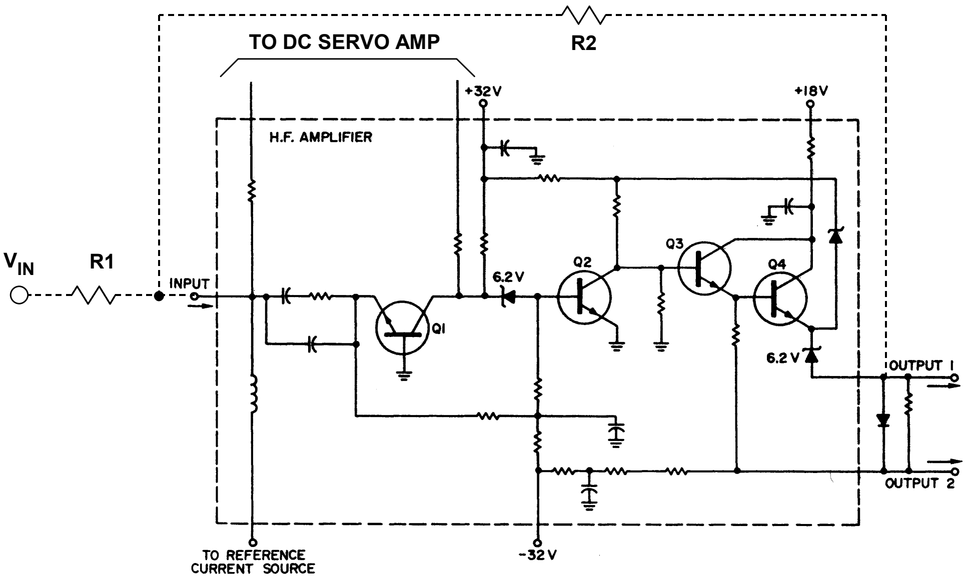
When transistor circuits ultimately replaced vacuum tube circuits between the late 1950s and the mid-1960s, the current feedback architecture became popular for certain high speed op amps. Figure 1-19 below shows a fast-settling op amp designed at Bell Labs in 1965, for use as a building block in high speed A/D converters (see Reference 5).

The circuit shown is a composite amplifier containing a high speed AC amplifier (shown inside the dotted outline) and a separate DC servo amplifier loop (not shown). The feedback resistor R2 is AC coupled to the low-impedance emitter of transistor Q1. The circuit design was somewhat awkward because of the lack of good high frequency PNP transistors, and it also required zener diode level shifters, and non-standard supplies.



Adapted from: J. O. Edson and H. H. Henning, "Broadband Codecs for an Experimental 224Mb/s PCM Terminal," *BSTJ*, Vol. 44, No. 9, November 1965, pp. 1887-1950

Figure 1-19: *A 1965 solid state current feedback op amp design from Bell Labs*

Hybrid circuit manufacturing technology, which was well established by the 1980s, allowed the use of fast, relatively well-matched NPN and PNP transistors, to realize CFB op amps. The Analog Devices' AD9610 and AD9611 hybrids were good examples of these devices introduced in the mid-1980s.

With the development of high speed complementary bipolar IC processes in the 1980s (see Reference 6) it became possible to realize completely DC-coupled current feedback op amps using PNP and NPN transistors such as the Analog Devices' AD846, introduced in 1988 (Fig. 1-15, again). Device matching and clever circuit design techniques give these modern IC CFB op amps excellent AC and DC performance without a requirement for separate level shifters, awkward supply voltages, or separate DC servo loops.

Various patents have been issued for these types of designs (see References 7 and 8, for example), but it should be remembered that the fundamental concepts were established decades earlier.

REFERENCES: OP AMP TOPOLOGIES

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5. J. O. Edson and H. H. Henning, "Broadband Codecs for an Experimental 224Mb/s PCM Terminal," **Bell System Technical Journal**, Vol. 44, No. 9, November 1965, pp. 1887-1950.

6. "Op Amps Combine Superb DC Precision and Fast Settling," **Analog Dialogue**, Vol. 22, No. 2, pp. 12-15.

7. David A. Nelson, "Settling Time Reduction in Wide-Band Direct-Coupled Transistor Amplifiers," **US Patent 4,502,020**, Filed October 26, 1983, Issued February 26, 1985.

8. Royal A. Gosser, "DC-Coupled Transimpedance Amplifier," **US Patent 4,970,470**, Filed October 10, 1989, Issued November 13, 1990.

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