Current-Feedback Myths Debunked

Introduction

Mystery needlessly surrounds the operation and use of current feedback operational amplifiers. Many engineers refuse to design with these op amps due to misunderstandings which are easily rectified.

Much has been written to date on the internal circuitry of current feedback op amps. These open-loop "tutorials" obfuscate how current feedback works in a closed-loop circuit. Practical op amp circuits are closed-loop feedback systems which yield to classical control theory analysis. Analog circuit designers are comfortable with voltage feedback op amps in a closed-loop circuit and with the familiar ideal op amp approximations feedback affords. It will be shown that current feedback op amps can be analyzed in an analogous fashion. Once this closed-loop similarity is appreciated, it is easy to see that most circuits commonly built with voltage feedback op amps can be realized with a current feedback op amp, and with better results at high frequencies.

Refer to *Figure 1* to review the open-loop terminal characteristics of a voltage feedback amplifier. Ideally the non-inverting input impedance is infinite, as is the inverting input impedance. The output is a voltage source, the output impedance of which is zero. This voltage source is controlled by the potential difference between the two op amp input terminals. This is the error voltage, hence the term voltage feedback. Feedback will drive the error voltage to zero. The open-loop dynamics are contained in A(s). This A(s) is a dimensionless gain, often represented in units of volts per volt or decibels.

Assumptions

$$Z_i^+ \longrightarrow \infty$$
$$Z_i^- \longrightarrow \infty$$
$$Z_o = 0$$
$$V_o = A(s)[V_1 - V_2]$$
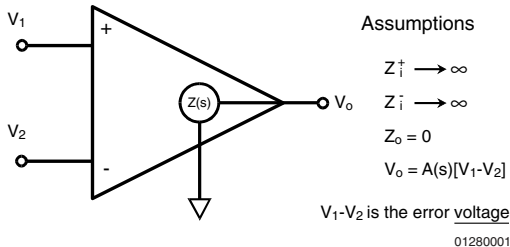
$V_1 - V_2$ is the error voltage

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FIGURE 1. Voltage Feedback Op Amp

A typical voltage feedback circuit is shown in *Figure 2*, the inverting amplifier. The transfer function is developed from the following equations:

$$V_1 = 0, \quad V_o = -A(s)V_2, \quad (V_i - V_2)/R_1 = (V_2 - V_o)/R_2.$$

As A(s) approaches infinity, the closed-loop gain is $-(R_2/R_1)$. The frequency response of the closed-loop circuit is determined by the denominator of the transfer function. Both the noise gain $(1 + R_2/R_1)$ of the circuit and the frequency-dependent source (A(s)) appear in the denominator, linking the closed-loop gain and bandwidth.

$$\frac{V_o}{V_i} = \frac{-\dfrac{R_2}{R_1}}{1 + \dfrac{1 + \dfrac{R_2}{R_1}}{A(s)}}$$
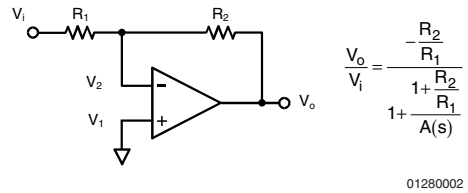
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FIGURE 2. Voltage Feedback Op Amp Inverting Gain

The familiar Bode plot of this circuit is shown in *Figure 3*. The amplifier is typically compensated with a dominant low-frequency pole to ensure stability down to a specified minimum gain, often unity. In the region where the one-pole approximation of the open-loop response is valid, the phase is around −90˚. This is the gain-bandwidth product region. The intersection of the zero-slope noise gain line and the open-loop gain curve determines the closed-loop system −3 dB bandwidth. A high gain circuit will have less bandwidth than a lower gain circuit. As the circuit moves to lower gains, bandwidth increases, phase margin is lost and stability suffers.
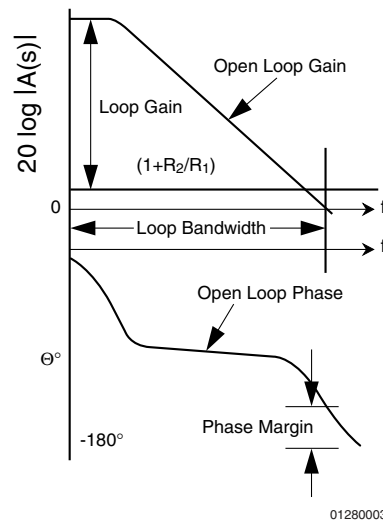

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FIGURE 3. Bode Plot

The open-loop terminal characteristics of a current feedback amplifier are depicted in *Figure 4*. There is a unity-gain buffer between the two op amp inputs. This buffer ideally has infinite input impedance and zero output impedance. Thus the non-inverting input impedance of the current feedback op amp is infinite, and the inverting input impedance is zero. The output is a voltage source, so the output impedance is

zero. This voltage source is controlled by the current out of the inverting input. This is the error current, hence current feedback. Feedback forces the error current to zero. The open-loop dynamics are determined by Z(s). This Z(s) is a current controlled voltage source which has units of transimpedance, ohms.

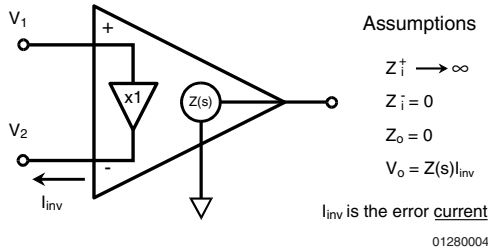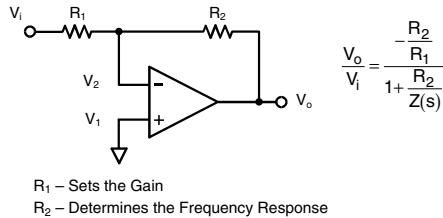Assumptions

$Z_i^+ \longrightarrow \infty$

$Z_i^- = 0$

$Z_o = 0$

$V_o = Z(s)I_{inv}$

I_{inv} is the error <u>current</u>

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FIGURE 4. Current Feedback Op Amp

The inverting amplifier employing a current feedback op amp is shown in *Figure 5*. The transfer function is derived from the following equations:

$$V_1 = 0, \quad V_o = Z(s)I_{inv}, \quad (V_i/R_1) + I_{inv} = -(V_o/R_2)$$

$$\frac{V_o}{V_i} = \frac{-\dfrac{R_2}{R_1}}{1 + \dfrac{R_2}{Z(s)}}$$

R_1 – Sets the Gain
R_2 – Determines the Frequency Response

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FIGURE 5. Current Feedback Op Amp Inverting Gain

As Z(s) approaches infinity, the closed-loop gain is $-(R_2/R_1)$. Notice that only the feedback resistor appears in the characteristic equation, in the term with Z(s). The closed-loop gain has been decoupled from the frequency response determining term of the transfer function. Only the feedback resistor affects the closed-loop frequency response.

A Bode plot for the circuit is shown in *Figure 6*. A current feedback amplifier is also compensated with a dominant low-frequency pole. This pole is usually at a higher frequency than that of a voltage feedback op amp. A current feedback op amp is commonly compensated for maximally flat response at a specified closed-loop gain and with a specified feedback resistor. The phase is approximately –90° where this one-pole approximation is valid. The ideal current feedback op amp does not have a gain-bandwidth product. The closed-loop bandwidth is determined by the feedback resistor, not the closed-loop gain. One could entertain the idea of a "feedback-resistor-bandwidth" product. The intersection of the zero-slope feedback resistor line and the open-loop transimpedance curve yields the closed-loop –3dB bandwidth. A circuit with a higher feedback resistor will have reduced bandwidth. This is a good way to over-compensate the current feedback op amp. A feedback resistor of twice the manufacturer's recommended value will cut the circuit bandwidth in half. As the feedback resistance, or impedance, is reduced to a lower value, there is a loss of

phase margin. As can be seen from the transfer function in *Figure 5*, if the negative of the loop transmission, $(R_2/(Z)s)$, equals –1 the loop is unstable.
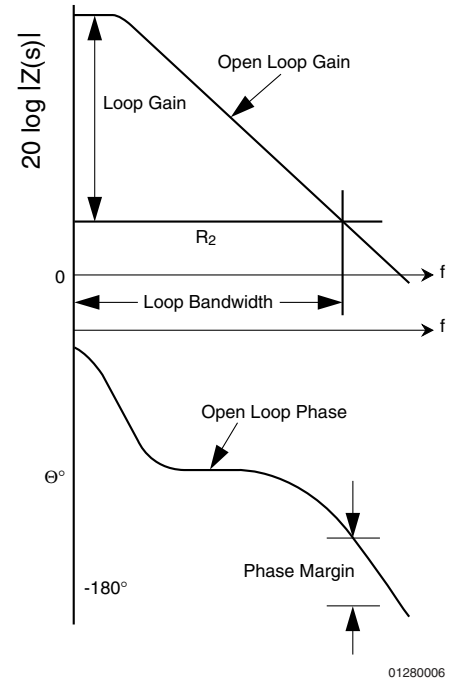

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FIGURE 6. Bode Plot

The design trade-offs between current feedback and voltage feedback differ. Voltage feedback allows freedom of choice of the feedback resistor (or impedance) at the expense of sacrificing bandwidth for gain. Current feedback maintains high bandwidth over a wide range of gains at the cost of limiting the feedback impedance.

For example, a common error in using a current feedback op amp is to short the inverting input to the output in an attempt to build a voltage follower. This circuit will oscillate. The circuit is perfectly stable if the recommended feedback resistor is used in place of the short. Similarly, an integrator is commonly accomplished by placing a capacitor between the inverting input and output. At high frequencies a capacitor has a low impedance and can easily have an impedance less than that required for stability. The proper feedback resistor in series with the feedback capacitor will stabilize the amplifier, and introduce a high frequency zero into the integrator transfer function.

Another aspect of current feedback op amps which causes much consternation is the low open-loop inverting input impedance. This feature, which causes the decoupling of closed-loop gain and bandwidth, is often viewed as making current feedback op amps unsuitable for use as differential amplifiers. In fact, the low inverting input impedance can result in a better high-frequency differential amplifier than a similar circuit built with a voltage feedback op amp.

First consider the closed-loop driving-point impedance of an op amp, regardless of the nature of the error signal. The circuit and equations to find this closed-loop impedance are shown in *Figure 7*. The resistor, R, is the open-loop inverting input impedance. Note that R is simply a resistance. A

voltage feedback amplifier will have an R approaching infinity; in a current feedback op amp R approaches zero. A test current, I_T, is applied to the inverting input and the inverting node currents are summed. To find the closed-loop inverting input impedance of either amplifier simply substitute the proper form of the output voltage, V_o.

R is the open loop inverting input impedance

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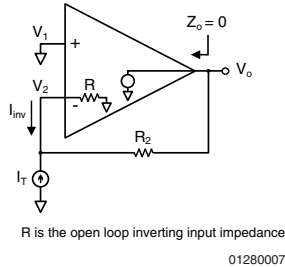
FIGURE 7. Closed-Loop Inverting Input Impedance

In the case of the voltage feedback op amp, $V_o = -V_2 A(s)$ for this circuit. The result, $Z_{inv}(s)$, is in *Figure 8*. The familiar result is that when A(s) approaches infinity, the incremental inverting impedance approaches zero. This is the incremental or virtual ground on which much first-order op amp analysis is based.

$$\text{Traditional Op Amp } V_o = -V_2 A(s)$$

$$Z_{inv}(s) = R \| \left(\frac{R_2}{1 + A(s)} \right) \xrightarrow{A(s) \to \infty} 0$$

$$\text{Current Feedback Op Amp } V_o = -V \left(\frac{Z(s)}{R} \right)$$

$$Z_{inv}(s) = R \| \left(\frac{R_2}{1 + \frac{Z(s)}{R}} \right) \xrightarrow{R \to 0} 0$$

$$\text{or} \xrightarrow{Z(s) \to \infty} 0$$

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FIGURE 8. Inverting Input Impedance Comparison

The output voltage is derived differently in the current feedback op amp. When $V_o = -V_2(Z(s)/R)$ is substituted, the result is in *Figure 8* also. It can be seen that two mechanisms force the inverting input impedance to a low value, ideally zero. When Z(s) is very large, $Z_{inv}(s)$ goes to zero. In addition, as R goes to zero so does the closed-loop inverting input impedance. The topology of the input buffer keeps R

small to very high frequencies. Thus a current feedback op amp can have a better virtual ground at the inverting input than a voltage feedback amp, especially at high frequencies.

A summary of the above discussion is tabulated in *Figure 9*. The voltage difference between the input terminals is zero. Voltage feedback drives this difference to zero. The current feedback amplifier input buffer forces the two input terminals to equal voltages. Both amplifier types have a high non-inverting input impedance, so the non-inverting current is small. A voltage feedback op amp has a high open-loop inverting input impedance, thus the inverting current approaches zero. Current feedback forces the inverting current to zero. Both op amps display similar input voltage and current characteristics. Only the mechanism forcing these to zero differs.

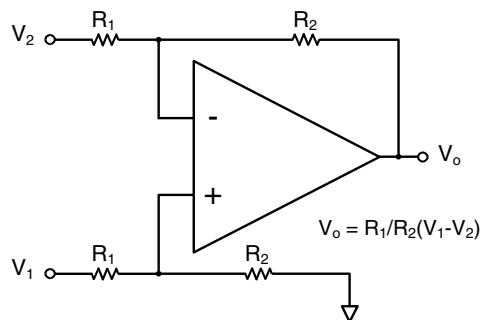|	Voltage Feedback	Current Feedback
V_1-V_2	→ = 0	= 0
I^+	= 0	= 0
I^+	= 0	→ = 0
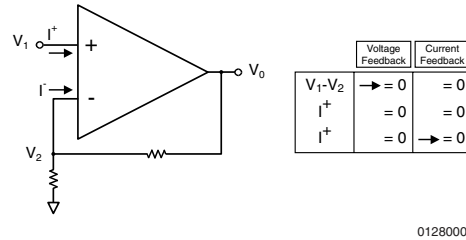
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**FIGURE 9. Op Amp Comparison Closed-Loop Operation**

It can now be seen that from a closed-loop standpoint both current and voltage feedback op amps allow the same ideal op amp assumptions to be made. Voltage feedback has a gain-bandwidth product which limits the lowest stable gain. Current feedback displays a "feedback-resistor-bandwidth" product which limits the lowest stable feedback impedance.

The inverting input impedance of an ideal voltage feedback op amp in a closed-loop circuit is zero. Feedback accomplishes this by dividing a high open-loop impedance by a high loop gain. The open-loop inverting input impedance of an ideal current feedback op amp is zero. A practical current feedback op amp has a finite inverting input impedance, less than 100Ω. Feedback reduces this further by dividing the initially low open-loop inverting input impedance by the loop transmission. The result is a better incremental ground at the inverting input to very high frequencies.

As both amplifier types are used in closed-loop topologies, the same methods of analysis are equally applicable. Now that this is seen, current feedback op amps can easily be designed into amplifiers of any arbitrary gain (inverting and non-inverting), integrators, differential amplifiers (*Figure 10*), and current-to-voltage converters, commonly known as transimpedance amplifiers (*Figure 11*).

$$V_o = R_1/R_2(V_1-V_2)$$

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FIGURE 10. Difference

$$V_o = -I_{in} * R_f$$
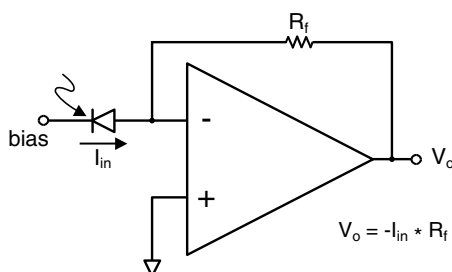
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FIGURE 11. Transimpedance Amplifier with a Current Feedback Op Amp

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