

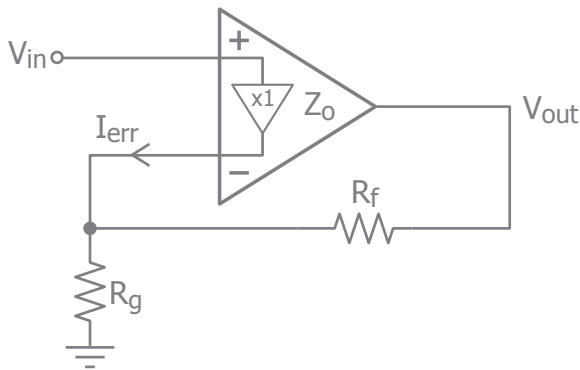
AN-3

The Ins and Outs of Current Feedback Amplifiers



Introduction

The traditional definition of an op amp states that it has two high impedance inputs and a low impedance output. This immediately brings questions to people's minds when confronted with an internal model of a current feedback (cfb) amplifier:



The non-inverting input is high impedance, but the inverting input is low impedance open loop (ideally, zero Ohms). How can this configuration act like an op amp?

The key to an intuitive understanding of this is to look first at how voltage feedback (vfb) and cfb op amps behave with feedback applied. Consider the vfb op amp. The non-inverting input is high impedance. The inverting input tracks the non-inverting input when the loop is closed (ignoring offset voltage and assuming the output is not clipping). If you apply a current to the inverting input, the output adjusts so that the inverting input voltage does not change. Closed loop, the inverting input of a vfb op amp is low impedance, just like a cfb op amp.

On a basic level, both cfb and vfb op amps behave the same when operated closed loop. Since the terminal voltages have the same relation (closed loop) in both, they both follow the same closed loop gain equation:

$$\frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_g}$$

The piece left out (so far) is how the open loop gain causes the output to follow the closed loop gain equations. Understanding this, and what the consequences are, requires delving into the details.

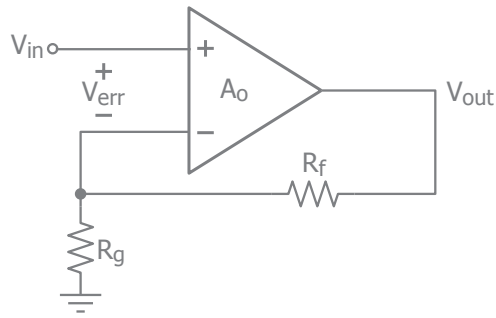
Open Loop and Closed Loop Gain

A vfb op amp has a very high open loop voltage gain. A small voltage difference (V_{err}) between the inputs causes a large change in output voltage. Feedback causes the input voltage difference to become much smaller, until it is just large enough to support the output voltage.

A cfb op amp multiplies any small current flowing in or out of the inverting input (I_{err}) into a large change in output voltage (transimpedance gain). Feedback causes the output to move to a voltage where the inverting input current is made much smaller, until it is just large enough to support the output voltage (ignoring the dc inverting input bias current).



Voltage Feedback



Open Loop Gain = A_o (voltage input = voltage output)

$$V_{out} = A_o * V_{err}$$

Computing V_{err} from V_{out} and V_{in} :

$$V_{err} = V_{in} - V_{out} * \left(\frac{R_g}{R_f + R_g} \right)$$

Solving for V_{out}/V_{in} in terms of V_{err} .

$$\frac{V_{out}}{V_{in}} = \left(1 + \frac{R_f}{R_g} \right) * \left(\frac{1}{1 + \frac{R_f}{R_g} + \frac{1}{A_o}} \right)$$

For large A_o , this simplifies: $V_{out}/V_{in} = 1 + R_f/R_g$

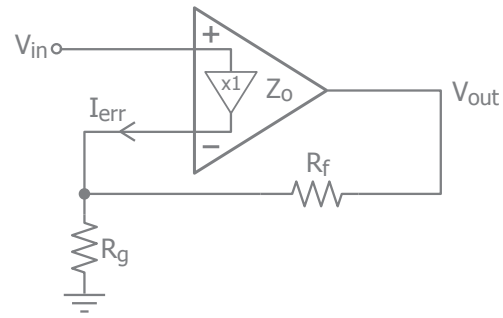
The approximate closed loop gain equation is the same for both vfb and cfb op amps ($1+R_f/R_g$), but tradeoffs specific to the type of feedback are quite different. Understanding the details of the feedback is important if you want to be able to predict amplifier performance in configurations different from those in the datasheet.

Tradeoffs

Each type of feedback has both tradeoffs and advantages. The key to understanding these is to look at the error term in the detailed gain equations. First, let's look at voltage feedback:

VFB error term:
$$\frac{1}{1 + \frac{R_f}{R_g} + \frac{1}{A_o}}$$

Current Feedback



Open Loop Gain = Z_o (current input = voltage output)

$$V_{out} = Z_o * I_{err}$$

A current sum at inverting input gives I_{err} :

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

Solving for V_{out}/V_{in} in terms of I_{err} .

$$\frac{V_{out}}{V_{in}} = \left(1 + \frac{R_f}{R_g} \right) * \left(\frac{1}{1 + \frac{R_f}{Z_o}} \right)$$

For large Z_o , this simplifies: $V_{out}/V_{in} = 1 + R_f/R_g$

For the vfb error term to drop out of the gain equation (approach unity), the closed loop gain ($1+R_f/R_g$) must be much less than the open loop gain, A_o . The amount of error in the feedback loop depends on the ratio of open loop gain to the closed loop gain. It does not depend on the value of either R_f or R_g alone, but on the ratio of the two resistors.

A_o is a frequency dependent term, very large at low frequency, decreasing at high frequency. When the magnitude of A_o equals $(1+R_f/R_g)$, the vfb op amp closed loop bandwidth reaches its -3dB point (ignoring parasitic effects and excess phase in the amplifier). As the desired closed loop gain is changed, the closed loop bandwidth changes inversely. This is known as the Gain-Bandwidth Product, which for vfb op amps is a constant at higher gains. This is the chief tradeoff for vfb op amps. The related advantage is that you can use any value of R_f , picking R_g corresponding to the gain desired.



Current feedback behaves in a significantly different fashion. Here is its error term:

$$\text{CFB error term: } \frac{1}{1 + \frac{R_f}{Z_o}}$$

For the cfb error term to drop out of the gain equation (approach unity), the value of the feedback resistor must be much less than the open loop gain, Z_o . The amount of error in the feedback loop depends on the ratio of open loop transimpedance gain to the value of the feedback resistor. It does not depend on the value of R_g (in this idealized discussion).

Z_o is a frequency dependent term, having very high impedance at low frequency, and decreasing at high frequency. When the magnitude of Z_o equals R_f , the cfb op amp closed loop bandwidth reaches its -3dB point. As the feedback resistor value is changed, the closed loop bandwidth changes inversely. This can be thought of as an R_f – bandwidth product that is constant. This is the chief tradeoff for cfb op amps.

The theoretical advantage of a cfb op amp is that if you change the value of R_g , keeping R_f fixed, the gain changes but the bandwidth stays the same. The penalty you pay is that you aren't free to choose the value of R_f (without changing bandwidth). Worse, using a capacitor in the feedback will actually destabilize the cfb op amp. If you are making an inverting integrator, you will have a much easier time with a voltage feedback op amp.

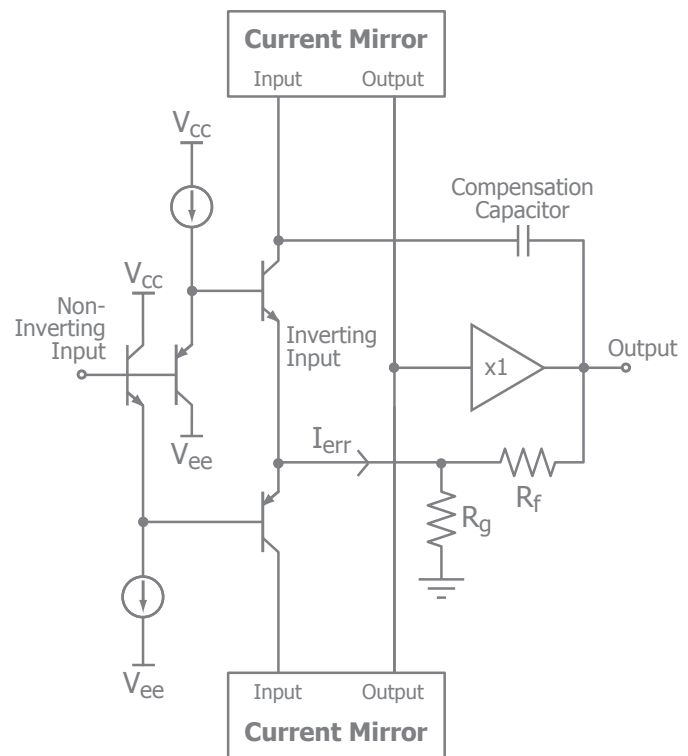
Practice finds that the theoretical advantage of a cfb op amp is smaller than it appears on paper. Two other things affect bandwidth as you change gain via R_g ; parasitic capacitance on the inverting input and a non-ideal input stage buffer. At low gains, the value of R_g increases (keeping R_f constant). Any parasitic capacitance to ground will cause the amplifier to peak, pushing the -3dB corner higher in frequency. At high gains, the value of R_g becomes small. Since the input stage buffer of the op amp has non-zero output impedance, current starts to split between the buffer and R_g , reducing loop transmission and decreasing bandwidth. Overall, cfb op amps still have a significant advantage in bandwidth achievable at a given gain, but not quite as much as in theory.

So Why Do People Really Use Current Feedback Op Amps?

The single largest advantage of cfb op amps over almost all vfb op amps is slew rate. High slew rate contributes directly to dramatically better large signal pulse response, full power bandwidth and distortion. This advantage is only secondarily due to the use of cfb—there are a few vfb op amps that use techniques similar to cfb to achieve high slew rates.

The simple way to build a vfb op amp input stage is the tried and true differential pair. Usually, the maximum charging current available to the compensation capacitor (which limits slew rate) is the tail current biasing the differential pair input stage. Degenerating the differential pair can improve slew rate, but at the expense of noise and open loop gain.

The simple way to build a cfb op amp is to implement its input stage (the buffer) with a four transistor, complementary emitter-follower buffer. The diagram below, is a typical (simplified) cfb topology.





Slew rate in this circuit is set by the maximum charging current that can be delivered to the compensation capacitor (only one is shown, usually there would be a second capacitor for the lower half circuit). This is the maximum value of I_{err} that can be supported. The main limitation on I_{err} is input stage transistor beta; the slew rate achievable is approximately beta times greater than a simple voltage feedback topology at the same bias level and compensation. There are a few vfb op amps available that have slew rates similar to cfb op amps; this is done by using more complex input stages. The sheer simplicity of a cfb op amp as shown above gives it an edge over similar slew rate vfb op amps in both bandwidth and power requirements.

Current feedback op amps have the same closed loop transfer function as a voltage feedback op amp, but different tradeoffs. Vfb op amps are limited by their gain-bandwidth product but allow using a wide range of feedback resistor values or even a feedback capacitor; cfb op amps are limited by their R_f – bandwidth product (and cannot be easily used with a feedback capacitor), but allow a wide range of gains while still maintaining a high bandwidth.

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