Voltage Feedback versus Current Feedback Operational Amplifiers

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Abstract

This application note compares the basic performance features of Voltage Feedback (VFB) and Current Feedback (CFB) operational amplifiers (op amps), and is intended for engineers unfamiliar with CFB amplifiers. Readers familiar with the subject can go straight to Table 1 on page 9, which summarizes the key features discussed in this application note.

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1. Introduction

Current Feedback (CFB) operational amplifiers have been around for more than 30 years. They were designed for extreme high-speed performance, which Voltage Feedback (VFB) amplifiers could not accomplish at that time. The VFB amplifiers have caught up and sometimes with strikingly better performance than the CFB counterparts. However, CFB amplifiers have one major advantage over VFBs, they maintain their bandwidth over a wide range of signal gain. VFB amplifiers are gain-bandwidth dependent, meaning their bandwidth decreases with increasing signal gain. CFB amplifiers are commonly used in high-speed applications while VFB amplifiers are preferably used in precision applications.

2. Voltage Feedback versus Current Feedback Amplifier

From a superficial look at an amplifier circuit, the user cannot tell whether the circuit uses a VFB or CFB op-amp. Both types have inverting and non-inverting signal inputs, a signal output, two supply pins for positive and negative voltage supplies, and use feedback and gain resistors (R_F and R_G) to stabilize circuit operation and to set the overall circuit gain. The difference between a VFB and a CFB amplifier is in the internal design structure.

A VFB amplifier has two symmetrical, high-impedance inputs. The fact that the negative input is high-impedance makes the feedback network, driven by the output voltage V_O, operate in Voltage-Source mode. Here the series source impedance of this voltage source is the parallel circuit of R_F and R_G. The output of this voltage source is connected to the inverting input, providing the voltage potential, v_n, at this pin. The voltage potential at the non-inverting input, v_p, is identical to the signal input voltage V_I. Thus, the difference between the two input potentials is an ***error voltage***, v_e, that is amplified to generate V_O (Figure 1).

Unlike the VFB amplifier, the CFB amplifier has asymmetric inputs. Internally the non-inverting input connects using a unity-gain buffer to the inverting input. Thus, the non-inverting input exhibits the high impedance of the buffer input, while the inverting input presents the low impedance of the buffer output to the feedback network. This low input impedance makes the feedback network operate in Current-Source mode. The parallel source impedance of this current source again is the parallel circuit of R_F and R_G. During normal operation, the input voltage V_I drives a current, i_p, into the non-inverting input, and the output of the feedback current source drives a current, i_n, into the inverting input. The difference between the two input currents is the ***error current***, i_e. This error current is driven into an internal high-impedance stage, which results in the output voltage, V_O (Figure 2).

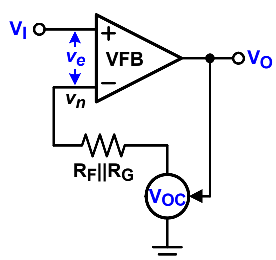


Figure 1. VFB Amplifier with Feedback Network in Voltage-Source Mode

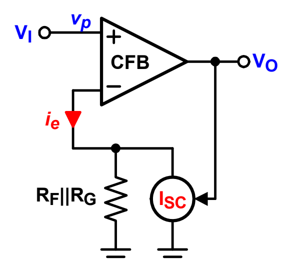


Figure 2. CFB Amplifier with Feedback Network in Current-Source Mode

To summarize, the major difference between a VFB and a CFB amplifier is the type of input error signal generating the output voltage. A VFB op-amp uses an error voltage while a CFB op-amp uses an error current.

3. Internal Design Structures

To fully understand the differences between the two amplifier types with regards to performance and application, a brief evaluation of their internal design structures is necessary. From these structures, simplified op-amp models that allow the user to analyze an amplifier circuit with regards to its transfer function and operation stability are defined.

3.1 Voltage Feedback Amplifier

Figure 3 shows the simplified schematic of a voltage feedback amplifier, consisting of a differential input amplifier, a high-impedance stage, and an output buffer.

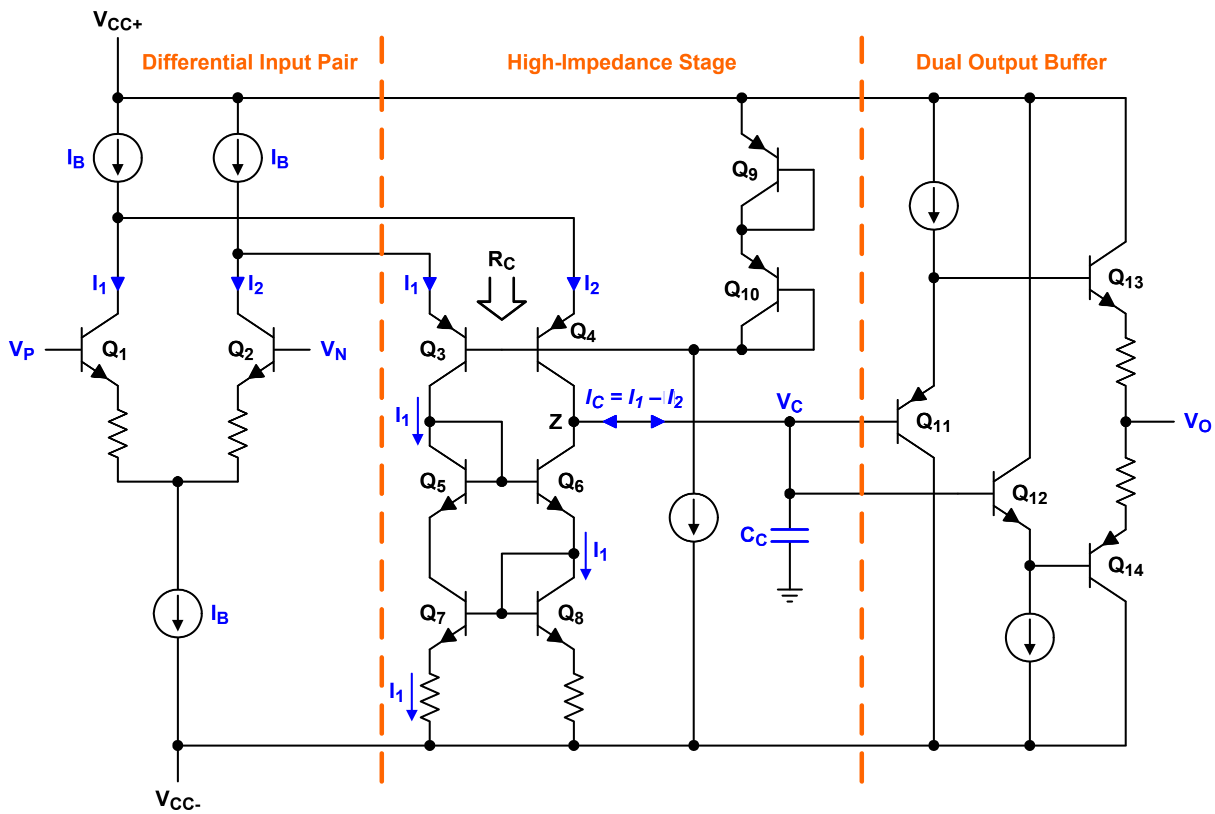


Figure 3. Simplified Schematic of a Voltage Feedback (VFB) Amplifier

3.1.1 VFB Amplifier Stages

3.1.1.1 Differential Input Pair

Transistors Q_1 and Q_2 form a differential input amplifier that uses three equal current sources (I_B) to bias the input circuit for normal operation, so that $I_B = I_1 + I_2$.

- When $V_P = V_N$, $I_1 = I_2$, and the collector currents of Q_1, Q_2, Q_3, and Q_4 are equal.
- When $V_P > V_N$, Q_1 turns on harder and I_1 increases. I_2 decreases because the bottom current source ensures that $I_B = I_1 + I_2$.
- When $V_P < V_N$, Q_2 turns on harder and I_2 increases. Again, the bottom current source, ensuring that $I_B = I_1 + I_2$, forces I_1 to decrease.

Thus, the differential voltage between the V_P and V_N inputs causes differential currents to flow through Q_3 and Q_4. This voltage–to-current conversion of the differential input stage is modeled by a transconductance amplifier, g_m, in Figure 4.

3.1.1.2 High-Impedance Stage

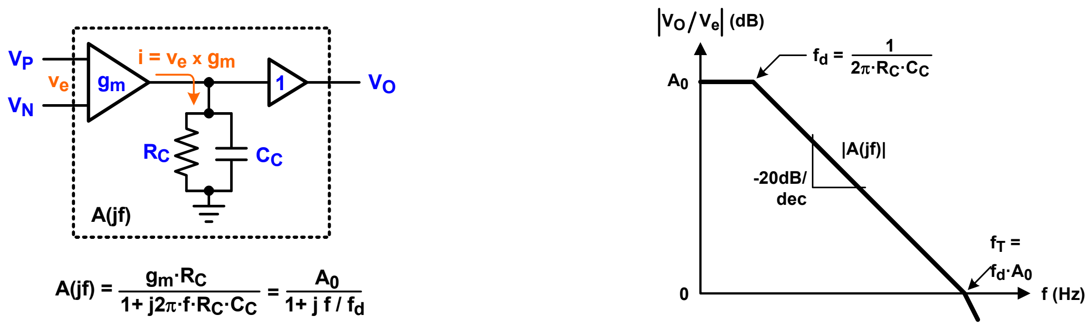
The current, I_2, develops voltage, V_C, at the high impedance node formed by the current mirror structure, Q_3–Q_4 and Q_5–Q_6, and capacitor C_C. The high-impedance stage is modeled by the parallel impedance, $Z_C = R_C \parallel C_C$, with R_C being the equivalent DC resistance to ground, and C_C the parallel combination of two compensation capacitors; one connected to the positive, the other one to the negative supply.

3.1.1.3 Output Buffer

Q_{11} through Q_{14} form a double buffer operating in class AB mode at unity gain. Thus, the capacitor voltage, V_C, is buffered to the output voltage, V_O. This buffer is modeled by a unity-gain stage.

3.1.2 VFB Frequency Dependent Model

Figure 4 shows the frequency-dependent model of the VFB op-amp and its gain-frequency characteristic. Here the product of $g_m \cdot R_C$ is the DC open-loop gain, A_0, commonly specified in datasheets, and f_d is the dominant pole frequency. This is the frequency where the reactance of C_C equals the value of R_C, and the open-loop gain, A(f), starts rolling off at 20dB/decade.



$$A(jf) = \frac{g_m \cdot R_C}{1 + j2\pi \cdot f \cdot R_C \cdot C_C} = \frac{A_0}{1 + j\,f / f_d}$$

Figure 4. Frequency Dependent Model and Open-Loop Gain Characteristic of a VFB Amplifier

3.2 Current Feedback Amplifier

Figure 5 shows the simplified schematic of a current feedback amplifier, consisting of a Class AB input amplifier, a current mirror, a high-impedance stage, and an output buffer.

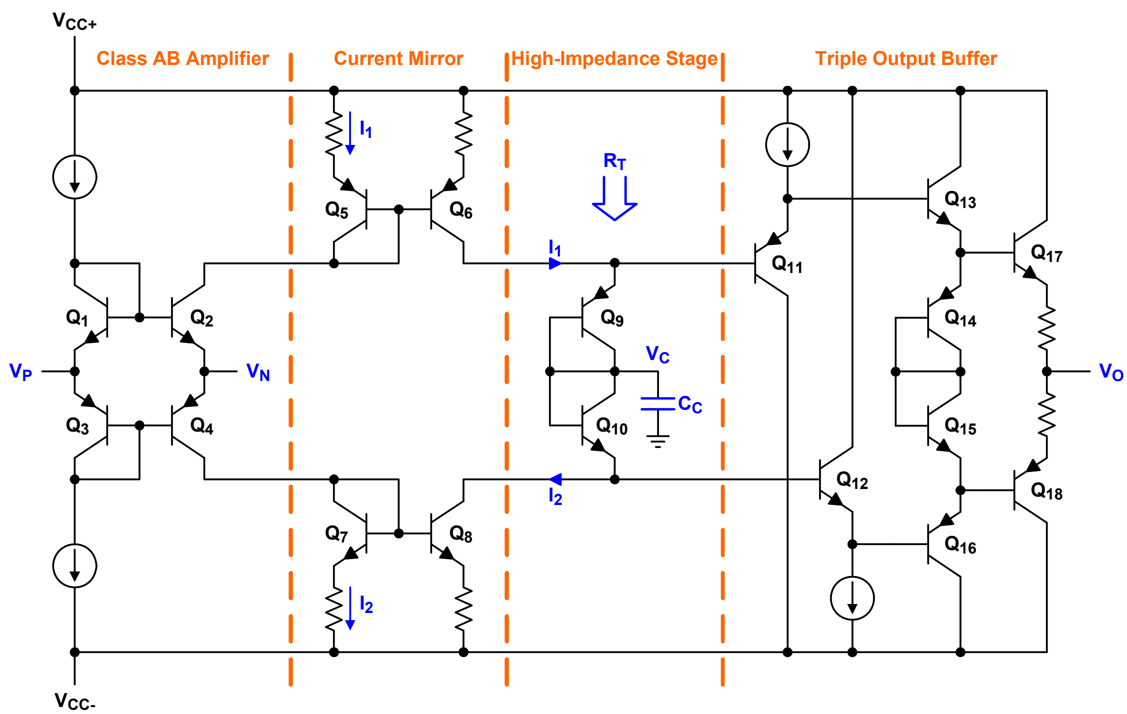


Figure 5. Simplified Schematic of a Current Feedback (CFB) Amplifier

3.2.1 CFB Amplifier Stages

3.2.1.1 Class AB Amplifier Input

The diode-connected pairs Q1-Q2 and Q3-Q4 comprise a unity-gain class AB amplifier that buffers the input signal v_p and makes it available at input v_n. This stage is modeled by a unity-gain buffer in Figure 6.

3.2.1.2 Current Mirror

The collector current of Q2 is drawn through diode-connected Q5. Q5 and Q6 form a current mirror so that the collector current of Q6 equals the collector current of Q2. The same is true for the bottom side so that Q4's current is mirrored by Q8. This is modeled as a current source equal to the input error current, i_e, driving the high impedance stage.

3.2.1.3 High-Impedance Stage

Either current, I_1 or I_2, develops the voltage, V_C, at the high impedance node formed by the diode-connected Q_9–Q_{10} and C_C. The high-impedance stage is modeled by the parallel impedance, $Z_T = R_T \parallel C_C$, with R_T being the equivalent DC resistance to ground, and C_C the parallel combination of two compensation capacitors; one connected to the positive, the other one to the negative supply.

3.2.1.4 Output Buffer

Q_{11} through Q_{18} form a triple buffer operating in class AB mode at unity gain. The voltage, V_C, is buffered to the output voltage, V_O. This output buffer is modeled by a unity-gain buffer.

3.2.2 CFB Frequency Dependent Model

Figure 6 shows the resulting frequency-dependent model of a current feedback amplifier and its corresponding open-loop transimpedance characteristic. Here R_T is the DC transimpedance, and f_d is the dominant pole frequency. This is the frequency where the reactance of C_C equals the value of R_T, and $Z_T(f)$ starts rolling off at 20dB/decade.

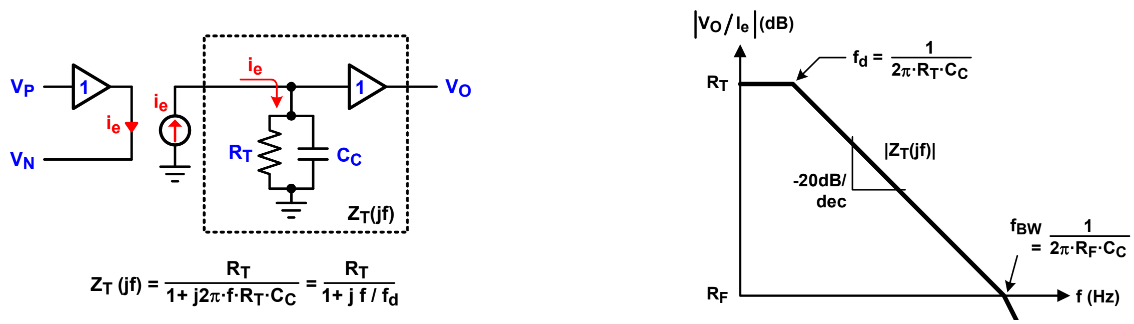


Figure 6. Frequency Dependent Model and Open-Loop Gain Characteristic of a CFB Amplifier

A comparison between the frequency dependent models shows both amplifiers use error currents to drive high-impedance stages that generate the output voltage. In the VFB op-amp this current is derived through a transconductance stage whose biasing current sources limit the charge and discharge current into the high-impedance node. This, of course, limits the switching speed, thus reducing amplifier bandwidth and slew rate. The CFB op-amp does not possess such limits and draws its charge/discharge currents directly from the supply rails. This current-at-demand provision shortens switching times significantly, thus allowing for high slew rates and wide bandwidth – the main intent of CFB op-amps.

4. Ideal Op-Amp Models

Ideal op-amp models help determine a circuit's transfer function and stability during circuit analysis. The most commonly applied models for VFB and CFB op-amps are shown in Figures 7 and 8.

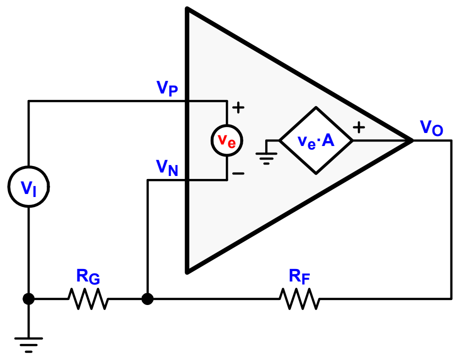


Figure 7. Ideal VFB Amplifier Model

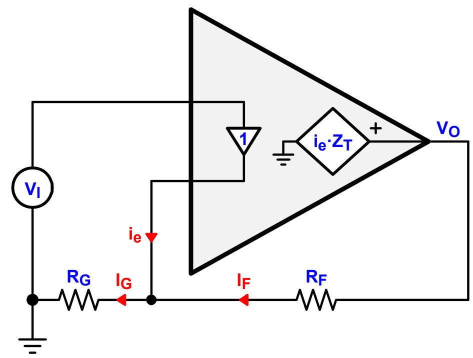


Figure 8. Ideal CFB Amplifier Model

4.1 Transfer Function of the VFB Model

To establish the transfer function, V_O/V_I, for the VFB amplifier, we write the output voltage, as given by the model, with: $V_O = A \cdot v_e = A \cdot (v_p - v_n)$ and substitute the generic terms v_p and v_n with $v_p = V_I$ and $v_n = V_O \cdot R_G/(R_G + R_F)$ so that $V_O = A \cdot V_I - A \cdot V_O \cdot R_G/(R_G + R_F)$. After collecting terms and solving for V_O/V_I, the transfer function is:

(EQ. 1)
$$\frac{V_O}{V_I} = \left(1 + \frac{R_F}{R_G}\right) \cdot \frac{1}{1 + \frac{1}{A} \cdot \left(1 + \frac{R_F}{R_G}\right)}$$

Here $1+R_F/R_G$ is the ideal closed-loop gain, A_{CLi}, of the non-inverting amplifier and the product $1/A \cdot (1 + R_F/R_G)$ is the reciprocal of the loop-gain, T. To be able to compare the transfer functions between the two amplifier types, Equation 1 is converted into the generic form:

(EQ. 2)
$$\frac{V_O}{V_I} = A_{CLi} \cdot \frac{1}{1 + 1/T} \quad \text{with} \quad A_{CLi} = \left(1 + \frac{R_F}{R_G}\right) \quad \text{and} \quad T = \frac{A}{A_{CLi}}$$

4.2 Transfer Function of the CFB Model

The CFB model shows the output voltage as the product of the transimpedance and the input error current $V_O = Z_T \cdot i_e$.

To find the transfer function, we define the currents in the negative input node with $i_e = I_G - I_F$ and substitute each current through its voltage/resistor ratio $V_O/Z_T = V_I/R_G - (V_O - V_I)/RF$. After collecting terms and solving for V_O/V_I, the transfer function is:

(EQ. 3)
$$\frac{V_O}{V_I} = \left(1 + \frac{R_F}{R_G}\right) \cdot \frac{1}{1 + \frac{R_F}{Z_T}}$$

or

(EQ. 4)
$$\frac{V_O}{V_I} = A_{CLi} \cdot \frac{1}{1 + 1/T} \quad \text{with} \quad A_{CLi} = \left(1 + \frac{R_F}{R_G}\right) \quad \text{and} \quad T = \frac{Z_T}{R_F}$$

Comparing Equation 4 with Equation 2 shows the ideal closed-loop gain to be the same for both amplifier types. Their loop-gains however, differ.

5. The Importance of Loop-Gain

The loop-gain is the most important parameter to observe during amplifier design, because it determines the amplifier's bandwidth and also its stability, or tendency towards self-sustaining oscillation. By definition the loop-gain, T, is the product of the op-amp's open-loop gain times the circuit's feedback factor.

(EQ. 5) $$T = A_{OL} \cdot \beta$$

5.1 VFB Loop-Gain

For the VFB amplifier $\beta = 1/A_{CLi}$ making the loop-gain $T_{VFB} = A/A_{CLi}$. On the logarithmic scale of a Bode plot, this ratio appears as the difference between the magnitude functions of A and A_{CLi} due to $T_{VFB} = 20(\log A - \log A_{CLi})$ (see Figure 9). At the intercept of A_{CLi} and A, $|A| = |A_{CLi}|$ and $|T| = 1$. The frequency at this point is the signal bandwidth, f_{BW}, of the amplifier circuit. At frequencies above f_{BW}, the loop-gain drops below 1 due to the |A| roll off, and the op-amp cannot support further amplification. Thus, the closed-loop gain, A_{CL}, deviates from is ideal value (A_{CLi}) and follows A_{OL}.

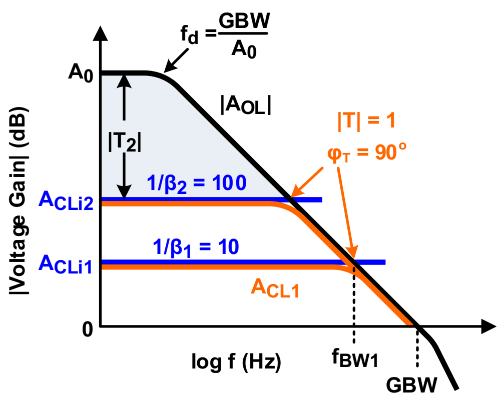


Figure 9. Gain – Bandwidth Dependence of VFB Amplifier

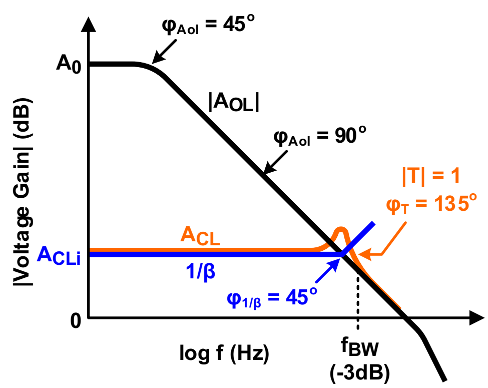


Figure 10. Gain Peak due to Parasitic Input Capacitance

The linear roll-off of A_{OL} presents a constant limit of the "Gain-Bandwidth Product". Higher gains require smaller bandwidths and lower gains allow wider bandwidths. Hence, VFB amplifiers are known to be gain-bandwidth limited. The maximum bandwidth is at unity-gain (0dB), and called the unity-gain bandwidth, or simply the gain-bandwidth, GBW. This parameter allows to quickly determine the bandwidth for any gain factor by calculating $f_{BW} = GBW/A_{CLi}$.

The other important aspect of loop-gain is its phase shift, Φ_T, at $|T| = 1$. Normal amplifier operation produces loop phases only in the range of 45° to 135°, which is due to A_{OL}, because a resistive feedback does not phase lag. However, parasitic capacitance at the op-amp input as well as load capacitance at the op-amp output can add phase shifts to the 1/β and A_{OL} curves respectively, causing the loop phase to approach 180°. Gain-peaking starts at about 125°, with the typical 3dB peak occurring at 135°, and worsening from then on with increasing phase shift. At 180° and $|T| = 1$, both magnitude and phase conditions for self-sustaining oscillations are satisfied. At this point, the amplifier oscillates at the frequency of the $1/\beta$-A_{OL} intercept, ignoring any signals applied to the non-inverting input.

To maintain stable amplifier operation, it is important to prevent the loop-gain from exceeding 135° phase shift at the $1/\beta$-A_{OL} intercept. Note that a 135° phase shift is often called a 45° phase margin, Φ_M, with regards to the 180° oscillatory condition ($\Phi_M = 180° - \Phi_T$).

One benefit of VFB amplifiers is that they allow for a number of compensation techniques to prevent instability. Another, often underrated advantage of VFBs is that they do not pose limits on the choice of resistor values. As the reader shall see, CFB op-amps do not provide this freedom of choice.

5.2 CFB Loop-Gain

For a CFB amplifier the open-loop gain is Z_T and its feedback factor is $1/R_F$, making the loop-gain $T_{CFB} = Z_T/R_F$. On the logarithmic scale of the Bode plot in Figure 13, the loop-gain is the difference (dB_Ω) between Z_T and R_F. The signal bandwidth is where the R_F line crosses the Z_T roll-off and the loop-gain magnitude becomes one $|T_{CFB}| = 1$, which means:

(a) the signal bandwidth is determined by R_F and not by the circuit gain

(b) the circuit gain is independently set with R_G

(c) the signal bandwidth remains stable for all gain settings

(d) even for unity-gain operation, an R_F resistor is required

Points a) to c) only hold true for the ideal CFB op-amp model, where the output impedance of the input buffer is assumed with 0Ω. In this case, R_B shunts gain resistor, R_G, thus eliminating the influence of signal gain.

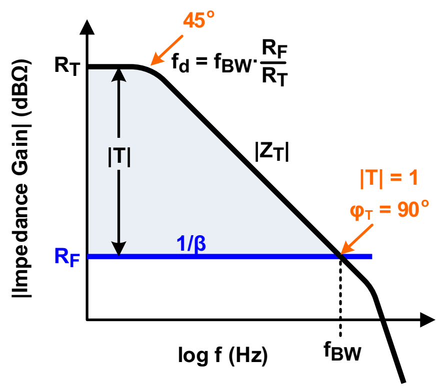


Figure 11. Transimpedance – Bandwidth Dependence of CFB Amplifier

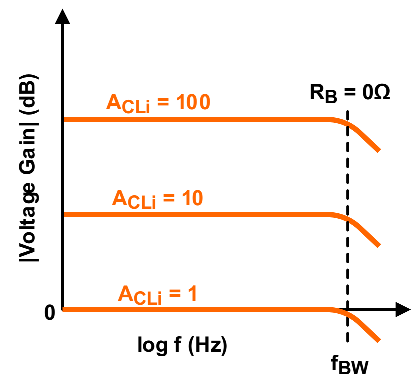
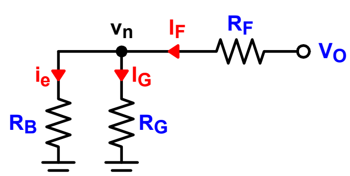


Figure 12. Gain – Bandwidth Dependence of Ideal CFB Amplifier

However, when measuring the bandwidth of CFB op-amps for various signal gains, a slight shift in bandwidth can be detected. This is because R_B is not zero but somewhere in the range of 20Ω to 100Ω (Figure 13). The parallel combination of R_B and R_G then changes the feedback factor to $\beta = 1/(R_F + R_B \cdot A_{CLi})$, where the A_{CLi} term causes the reduction in bandwidth with rising gain levels (Figure 14).



$$\beta = \frac{i_e}{V_O} = \frac{1}{R_F + R_B \cdot A_{CLi}}$$

Figure 13. Alteration of β due to $R_B \neq 0\Omega$

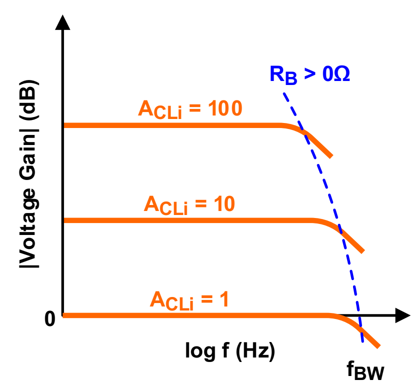


Figure 14. Gain-Bandwidth Dependence of Real CFB Amplifier

As previously mentioned, CFB op-amps do not allow users to freely choose the values of feedback resistors. Manufacturers of CFB op-amps typically specify one or two R_F values at different gain settings, for which the op-amp provides the largest bandwidth under the most stable phase conditions. Note that even for unity-gain operation, the CFB amplifier always requires feedback resistors.

The designer might choose to deviate from these values, but must be aware of the possible changes in performance this might cause.

Figure 15 depicts this scenario for three different R_F values. $R_{F(O)}$ represents the optimized value, specified for maximum bandwidth and minimum gain-peak. Increasing R_F to the higher value, $R_{F(H)}$, overcompensates the loop-gain, causing a drastic reduction in bandwidth. On the other hand, lowering the R_F value ever so slightly to $R_{F(L)}$, moves the device closer towards 180° phase shift and thus, instability.

The best practice when designing with CFB op-amps is to use the R_F values given in the datasheet and to adjust the desired gain level through R_G.

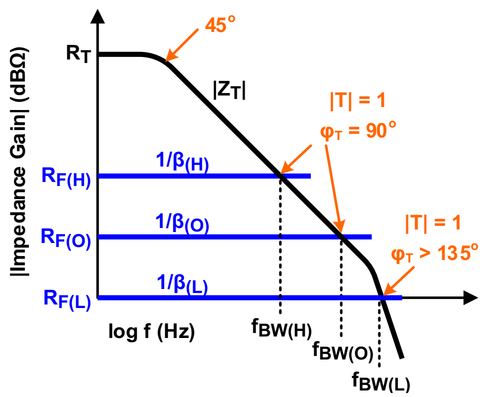


Figure 15. Changing RF Impacts Bandwidth and Stability

6. Summary

For a quick comparison, Table 1 summarizes the key parameters discussed in this application note.

Table 1. Key Parameters

Parameter	VFB Amplifier	CFB Amplifier
Input Error Signal	Input error voltage, v_e	Input error current, i_e
Open-Loop Gain	Frequency dependent Voltage Gain: V_O/v_e $A_{OL}(f) = \frac{A_0}{1 + jf/f_d}$	Frequency dependent Transimpedance: V_O/i_e $Z_T(f) = \frac{R_T}{1 + jf/f_d}$
Feedback Factor	$\beta = \frac{R_G}{R_F + R_G}$	$\beta = \frac{1}{R_F + R_B \cdot A_{CLi}}$
Loop-Gain	$T(f) = \frac{A_{OL}(f)}{A_{CLi}}$	$T(f) = \frac{Z_T(f)}{R_F + R_B \cdot A_{CLi}}$
Closed-Loop Gain	$A_{CL}(f) = A_{CLi} \cdot \frac{1}{1 + \frac{A_{CLi}}{A_{OL}(f)}}$	$A_{CL}(f) = A_{CLi} \cdot \frac{1}{1 + \frac{R_F + R_B \cdot A_{CLi}}{Z_T(f)}}$
Ideal Closed-Loop Gain	$A_{CLi} = 1 + \frac{R_F}{R_G}$	$A_{CLi} = 1 + \frac{R_F}{R_G}$
Maximum Bandwidth	GBW specified at Unity-Gain	f_{MAX} specified at $R_{F(O)}$
Bandwidth at A_{CLi}	$f_{BW} = \frac{GBW}{A_{CLi}}$	$f_{BW} = \frac{f_{MAX} \cdot R_{F(O)}}{R_F}$
Stability	Determined by Loop-Gain, Typically unity-gain stable	Determined by Loop-Gain, Typically $R_{F(O)}$ stable
Resistor Values	Wide range of choice	Limited to values close to specified $R_{F(O)}$

7. Revision History

Rev.	Date	Description
0.00	May 31, 2018	Initial release

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