High Speed Analog Design and Application Seminar

from

Texas Instruments

INTRODUCTION

Texas Instruments is pleased to present the High Speed Analog Design and Applications Seminar to our High Speed customers. This material represents some innovative investigations into problems plaguing analog designers, as well as some straight forward explanations of fundamental analog principles and design techniques.

We have customized this presentation to best suit designers as a reference book to be used for years to come. Much of this material will be expanded upon in application notes and published articles in the near future. However, it was assembled in this manual for the immediate benefit of the audience.

Sections 1 and 2 set a technical basis for high speed analysis for amplifiers and data converters, and include an explanation of the mathematical investigations of analog circuits. Section 3 builds on the previous two chapters by combining the amplifier and data converters and investigates the optimization of the interface between the two components. Section 4 discusses the effects of PCB layout on high speed performance, and offers layout techniques and suggestions to optimize circuit performance. Finally, Section 5 combines all of these elements in the discussion of high speed applications.

This material was prepared by our High Speed Amplifier and Data Converter Systems Engineers and Applications Engineers. It was originally presented and printed in 2004. Significant effort was contributed by numerous individuals to create an outstanding technical seminar and reference book. Most notably, we wish to thank the key contributors that ensured this material was technically sound, beneficial to the audience, and relatively straight forward as a standalone reference book:

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Understanding Voltage Feedback and Current Feedback Amplifiers

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Introduction

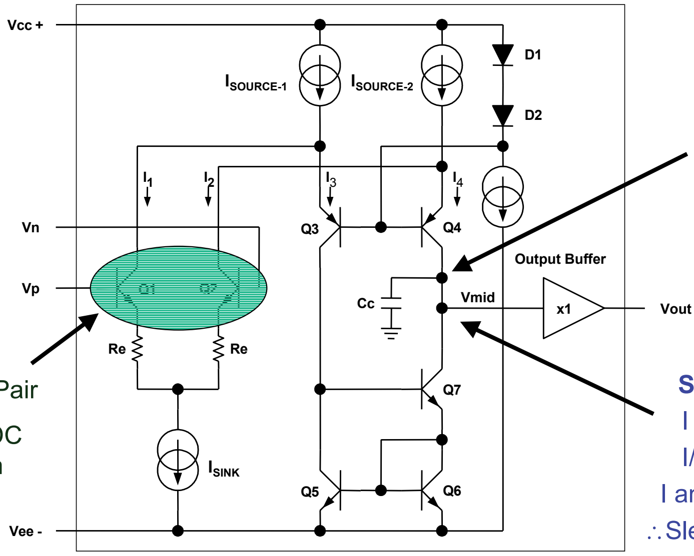
- **VOLTAGE FEEDBACK AMPLIFIER**
  (commonly abbreviated VFA or VFB) and
- **CURRENT FEEDBACK AMPLIFIER**
  (commonly abbreviated CFA or CFB) are the two most prevalent architectures used to design high-speed op amps today.

- The following discussion details the two architectures, modeling, how they are different, how they are the same, stability issues for each, and shows examples of when one is preferred over the other.

Definition of VFB and CFB Amplifiers

- VOLTAGE FEEDBACK AMPLIFIER
  - An op amp in which the error signal is modeled as a voltage. Both inputs are high impedance and feedback is modeled as a voltage
- CURRENT FEEDBACK AMPLIFIER
  - An op amp in which the error signal is modeled as a current. The positive input is high impedance, the negative input is low impedance, and feedback is modeled as a current

Simplified VFB Op Amp Schematic



High Impedance Node

Matched Differential Pair

Good for DC Precision

Slew Rate:

$I = C\,dV/dt$

$I/C = dV/dt$

I and C = fixed

∴Slew Rate fixed

Differential Pair

Q1 and Q2 comprise a classic differential pair (sometimes referred to as a long tail pair). Three equal current sources, I, are used to balance and bias the circuit.

When Vn = Vp, I1 = I2 and the collector currents of Q1, Q2, Q3, and Q4 are equal.

When Vp < Vn, Q2 turns on harder and I2 increases. Since I1 + I2 = I-Sink, I1 decreases. Due to I-Source1 and I-Source2 currents being constant, a decrease in I2 results in an increase in I4. At the same time, since I1 decreased, I3 increased.

When Vp > Vn, Q1 turns on harder and I1 increases. Since I1 + I2 = I-Sink, I2 decreases. Due to I-Source1 and I-Source2 currents being constant, a decrease in I1 results in an increase in I3. At the same time, since I2 decreased, I4 increased.

Thus the differential voltage at the input Vn and Vp causes differential currents to be generated in Q3 and Q4 “folding” them into the high impedance node.

The differential input stage is modeled by a transconductance amplifier, gm.

Since both inputs drive the base of differential pair transistors, the input is fairly high impedance and well matched. This results in generally very good DC precision (Vio is very low along with low drift) and good low frequency distortion.

High Impedance Node

The push-pull currents of I3 and I4 develops a voltage at the high impedance node, Vmid, formed by Q4 and the Wilson current mirror Q5 – Q7. The high impedance stage is modeled by a parallel impedance, Rz||Cc. Rz models the equivalent dc impedance comprised of the output impedance of the current mirror and Q4. Cc is purposely added by design for compensation.

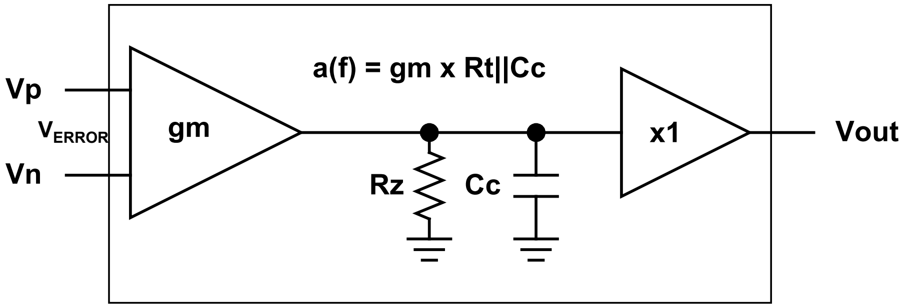
The maximum slew rate of the amplifier is set by the available current, I-Source2 and the mirrored current of I-Source1 (through the Wilson Mirror) of which I-Source1 and I-Source2 are made equal to each other, and the value of Cc.

The open loop gain of the amplifier, a(f) = gm x Rz||Cc.

X1 Output Buffer

Various architectures are used for the output buffer, but it is typically a 2 or 3 stage class AB amplifier. The purpose of the output buffer is simply to give the op amp output drive capability.

VFB Simplified Model

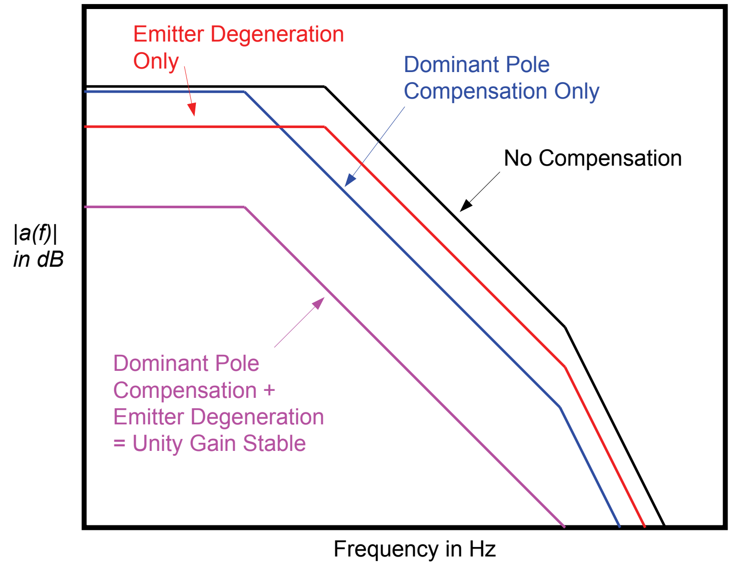


$$V_{ERROR} = (Vp - Vn)$$

$$V_{OUT} = (Vp - Vn) \times a(f)$$

A useful block diagram can be constructed for a voltage feedback amplifier as shown above, where the open loop gain, a(f), is equal to gm x Rt||Cc. In this model Vout = Ve x a(f), where the "error" voltage Ve = Vp – Vn.

VFB Open Loop Bode Plot and Compensation



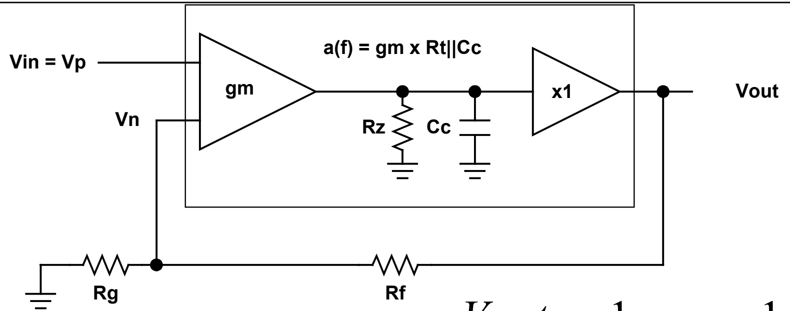
Compensation Components

Changing the value of the emitter degeneration resistors, Re, will vary the gm of the input stage. Larger values reduce the gm of the input stage, the open loop gain of the amplifier, and the bandwidth. The thermal noise of the Re resistors also has a direct impact on the input noise of the op amp, where larger values mean more noise.

Adding Cc is called dominant pole compensation. Larger values reduce the pole frequency and the bandwidth of the amplifier. Slew rate (SR) is set by the current I and the capacitor Cc, where SR = I / Cc. So increasing Cc reduces the slew rate

A balance between emitter degeneration and dominant pole compensation is used to compensate the amplifier for the desired performance. The trade offs are noise and slew rate. Unity gain or minimum gain amplifiers can be designed.

VFB with Feedback



$$Vout = (Vp - Vn) \times a(f)$$

$$Vp = Vin$$

$$Vn = Vout \times \frac{Rg}{Rg + Rf}$$

=>

$$\frac{Vout}{Vin} = \frac{1}{\beta} \times \frac{1}{1 + \frac{1}{a(f)\beta}}$$

where $\beta = \frac{Rg}{Rg + Rf}$

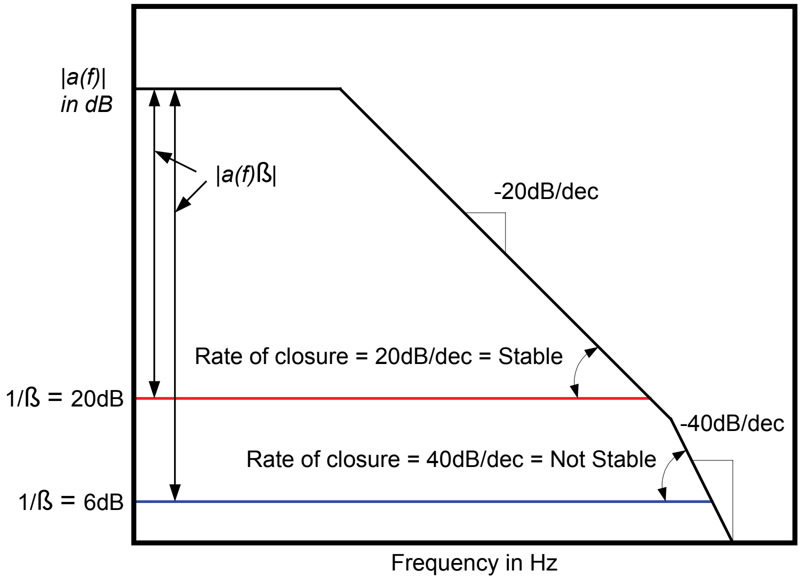
Negative feedback provides a means to set the amplifier gain with stable passive components, and the non-inverting gain can be calculated as shown above. As long as a(f)ß >> 1, the non inverting gain is 1 + Rf/Rg.

In similar fashion, it can be shown the inverting gain is equal to
(1 – 1/ ß) x 1 / (1 + 1 / a(f) ß), which can be idealized to
(1 – 1/ ß) = -Rf/Rg if a(f)ß >> 1.

Rg / (Rg + Rf) = ß is called the feedback factor as it determines the amount of the output voltage that is fed back to the negative input to null the error voltage, Vp – Vn.

a(f)ß is called the “loop gain” as it is the gain around the loop from the negative input to output and back again. It is one of the most critical factors in op amp performance and has special meaning in the context of stability as shown in the following slide.

VFB Stability and Constant GBW Product



The diagram shows an op amp that is stable in a gain of 20dB (10V/V), but is not stable in a gain of 6dB (2V/V). This is usually referred to as a minimum gain stable op amp or a “de-compensated” op amp (in reference to a unity gain op amp, which is “compensated” for all non-reactive feedback conditions).

Plotting the inverse of the feedback factor, 1/ß, on the plot of a(f) is a good way to visually show the interaction of gain and stability. 1/ß is the non-inverting gain of the op amp also referred to as the “noise gain”.

Remember from that analog class you took in college:

- When the slope of the magnitude in dB is -20dB/dec, the phase is -90°
- When the slope of the magnitude in dB is -40dB/dec, the phase is -180°
- On a log scale (which a dB scale is), subtracting is the same as dividing the linear numbers
- The signal is phase shifted -180° going from inverting input to the output

So on this graph, the difference between the 1/ß and a(f) is |a(f)| - |1/ß| = |a(f)ß|. When the difference is 0dB (the point where the two lines intersect) the magnitude of the loop gain, a(f)ß = 1.

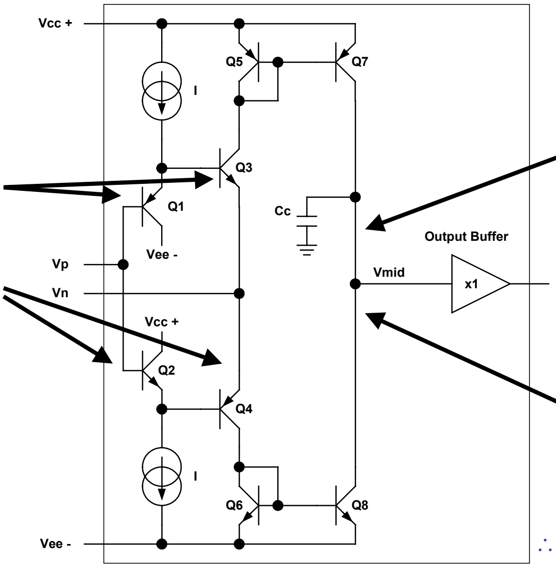
The rate of closure between 1/ß and a(f) indicates the phase of the loop gain. At 20dB, the phase is -90° and at 40dB it is -180°.

Add the -180° phase shift of the op amp when the closure rate is 40dB, the criteria for oscillation is met i.e. |a(f)ß| = 1 and < a(f)ß = ±360°. Under this condition the amplifier will spontaneously oscillate. So the amplifier is stable at a noise gain of 10V/V, but not at 2V/V.

Another point to be drawn from the graph is the constant gain bandwidth product (GBW), which is a standard feature of a VFB op amp. The point where 1/ß and a(f) intersect sets the -3dB bandwidth of the amplifier. The -20dB/dec slope is actually a slope of -1. So over most of the useable bandwidth of the op amp the bandwidth is inversely proportional to the gain of the amplifier. Thus it has a constant GBW i.e. if the bandwidth is 100MHz at a gain of 10, it will be 10MHz at a gain of 100 – the GBW is 1000MHz.

For high gain applications, use de-compensated op amps. De-compensated op amps sacrifice stability at lower gain for higher GBW, higher slew rate, and lower noise. They are easily spotted in data books and selection guides by their minimum gain requirements.

Simplified CFB Op Amp Schematic



Un-Matched
Input Pairs

Not very good
for DC Precision

Rail-to-Rail input
stage cannot be
created

High
Impedance
Node

Slew Rate:
I = C dV/dt
I/C = dV/dt
C = fixed
I = Dynamic
∴Slew Rate Dynamic

Class AB Input

Q1 through Q4 comprise a class AB amplifier with input Vp and output Vn. The current sources supply current to the stage to bias it into class AB operation.

When Vn = Vp, no current flows from Vp to Vn, the stage sees only the bias current of the current sources, and Q7's current matches Q8's current.

When Vp > Vn, Q3 turns on harder and Q4 starts to turn off causing an offset current in the current mirrors, Q5/Q7 and Q6/Q8.

When Vp < Vn, Q4 turns on harder and Q3 starts to turn off offsetting the mirrors in the opposite direction.

The voltage gain from Vp to Vn is unity. The positive input, Vp, is high impedance, and the negative input, Vn, is low impedance where the input signal (Vp – Vn) produces a current. This is modeled by a unity gain buffer with offset or "error" current out of the inverting input.

Since the positive input, Vp, drives the base of a transistor(s) it is high impedance, whereas the negative input, Vn, drives the emitter of a transistor(s) and is low impedance. Thus the inputs are not well matched and do NOT have good DC precision (higher Vio and drift) and only reasonable low frequency distortion performance.

High Impedance Node

The currents from the mirrors, Q5/Q7 and Q6/Q8, flow into the high impedance node, and develops the output voltage at Vmid.

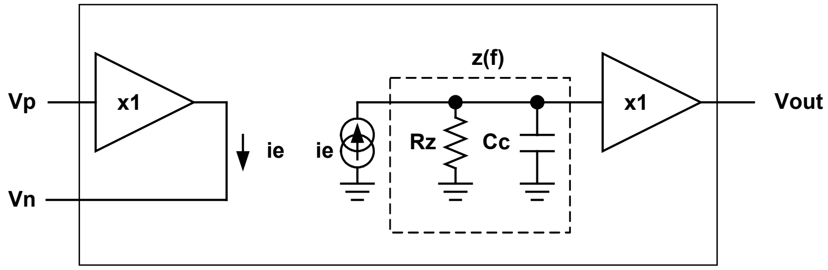
The high impedance stage is modeled by a parallel impedance, Rz||Cc fed by the offset current from the input stage. Rz models the equivalent dc impedance comprised of the output impedance of the current mirrors. Cc is purposely added by design for compensation. Rz||Cc = Zc or the transimpedance gain.

The maximum slew rate of the amplifier is set by the current, I, the beta of the transistors, the transistor size ratios used in the mirrors, and the value of Cc. So the maximum slew rate can be much higher for a CFB op amp than a VFB op amp for the same quiescent bias current.

X1 Output Buffer

Various architectures are used for the output buffer, but it is typically a 2 or 3 stage class AB amplifier. The purpose of the output buffer is simply to give the op amp output drive capability.

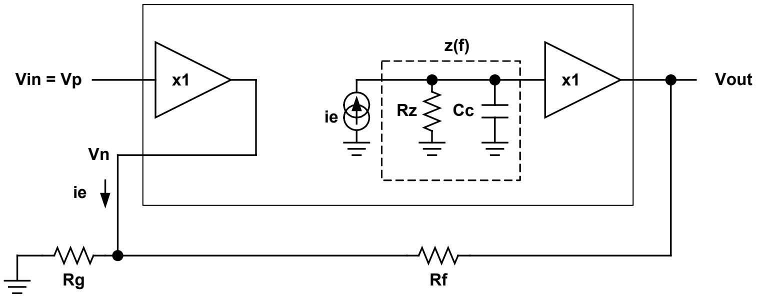
CFB Model



$$V_{OUT} = i_{ERROR} \times z(f)$$

A useful block diagram can be constructed for a current feedback amplifier as shown above, where the transimpedance gain, z(f), is equal to Rt||Cc. In this model Vout = ie x z(f), where the “error” is ie.

CFB with Feedback



$$Vout = ie \times z(f)$$

$$Vn \cong Vp \cong Vin$$

$$(-ie) + \left(\frac{Vn}{Rg}\right) + \left(\frac{Vn - Vo}{Rf}\right) = 0$$

=>

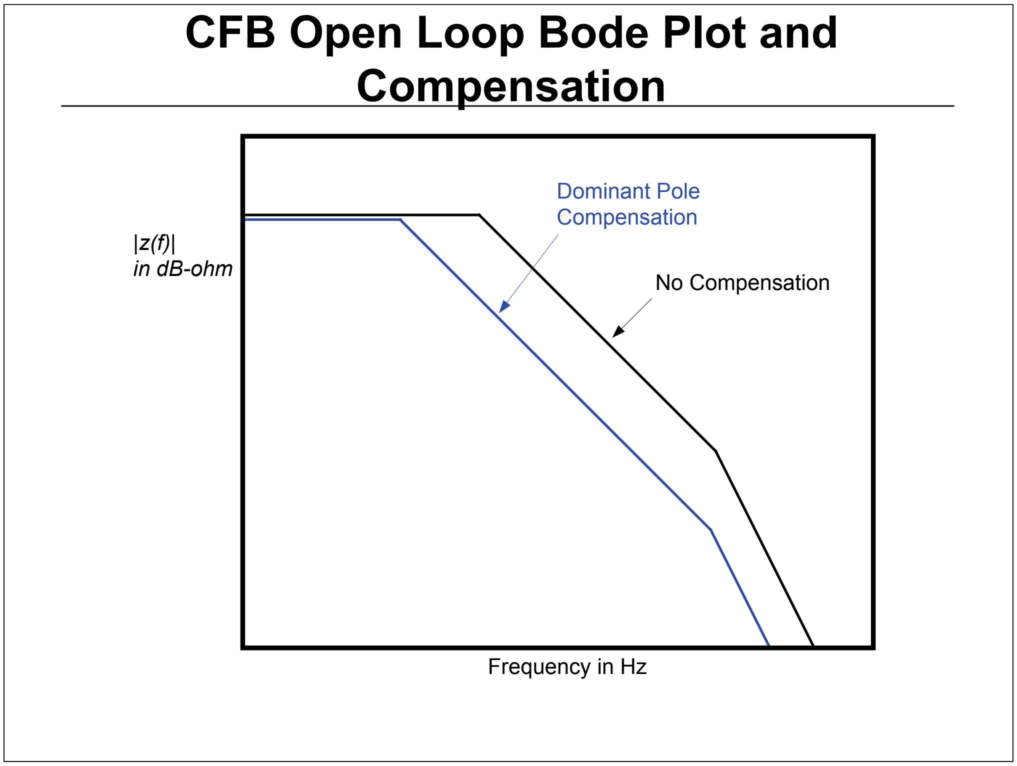
$$\frac{Vout}{Vin} = \left(\frac{Rg + Rf}{Rg}\right)\left(\frac{1}{1 + \left(\frac{Rf}{Z(f)}\right)}\right)$$

As with a VFB op amp, negative feedback provides a means to set the amplifier gain with stable passive components, and the non-inverting gain can be calculated as shown above. As long as Rf/z(f) << 1, the non inverting gain is set by the resistor ratio 1 + Rf/Rg.

In similar fashion, it can be shown the inverting gain is equal to
= -Rf/Rg if Rf/z(f) << 1.

In a CFB op amp 1/Rf is the feedback factor as it transfer function that determines the amount of the output voltage that is fed back as a current to the negative input to null the error current, ie.

Look back at the formula we derived for gain in a VFB op amp and you will see that Rf/z(f) is equivalent to the term a(f)ß. In a CFB, z(f)/Rf is the “loop gain” of the op amp as it is the gain around the loop from the negative input to output and back again. As with VFB op amps, it is one of the most critical factors in op amp performance and has special meaning in the context of stability as shown in the following slide.



CFB Open Loop Bode Plot and Compensation

Compensation Components

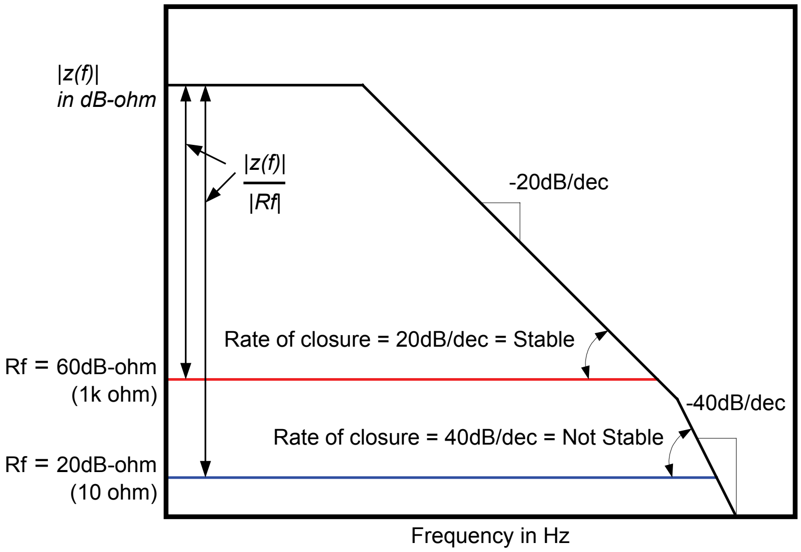
In a CFB op amp there is no emitter degeneration and compensation is controlled with the Cc capacitor only.

Adding Cc will add a dominant pole that reduces the frequency response and helps compensate the op amp. Larger values reduce the pole frequency and the bandwidth of the amplifier.

Increasing Cc will reduce the slew rate, but also will require a lower value of feedback resistor for stable operation (this is covered on the next slide). A lower value of feedback resistor is desired to reduce the noise developed due to the current noise at the inverting input and the impedance seen at the node.

A balance between feedback resistor value and dominant pole compensation is used to compensate the amplifier for the desired performance. The trade offs are noise and slew rate.

CFB Stability and GBW Product Not Constant



The diagram shows an op amp that is stable with a feedback resistor, Rf = 1k? (60dB-ohm), but is not stable with Rf = 10Ω (20dB-ohm).

Plotting Rf or the inverse of the feedback factor on the plot of z(f) is a good way to visually show the interaction of feedback impedance and stability.

As before:

- When the slope of the magnitude in dB is -20dB/dec, the phase is -90°
- When the slope of the magnitude in dB is -40dB/dec, the phase is -180°
- On a log scale (which a dB scale is), subtracting is the same as dividing the linear numbers
- The signal is phase shifted -180° going from inverting input to the output

So on this graph, the difference between the Rf and z(f) is |z(f)| - |Rf| = |z(f)/Rf|. When the difference is 0dB (the point where the two lines intersect) the magnitude of the loop gain, z(f)/Rf = 1.

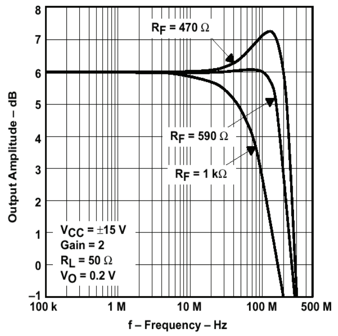
The rate of closure between Rf and z(f) indicates the phase of the loop gain. At 20dB, the phase is -90° and at 40dB it is -180°.

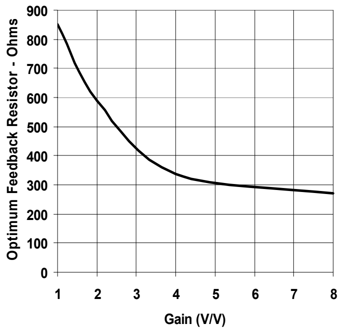
Add the -180° phase shift of the op amp when the closure rate is 40dB, the criteria for oscillation is met i.e. |z(f)/Rf| = 1 and < z(f)/Rf = ±360°. Under this condition the amplifier will spontaneously oscillate. So the amplifier is stable with Rf = 1kΩ, but not with Rf = 10Ω.

Another point to be drawn from the graph is the bandwidth is set by the value of feedback resistor and is independent of gain. The point where Rf and z(f) intersect sets the -3dB bandwidth of the amplifier. You can lower the value of Rg, keeping Rf the same, and get higher gain with the same bandwidth or you can raise the values of both Rg and Rf, keeping the ratio the same, and lower the bandwidth of the amplifier. In essence the gain of a CFB of amp is separated from the open loop transimpedance and stability criteria, and so the bandwidth is separated from the gain.

If you want to think about it too much, you could come up with the fact that a CFB has a constant feedback resistor bandwidth product in the same way a VFB has a constant GBW

Selecting Feedback Resistor Value for CFB Amplifiers

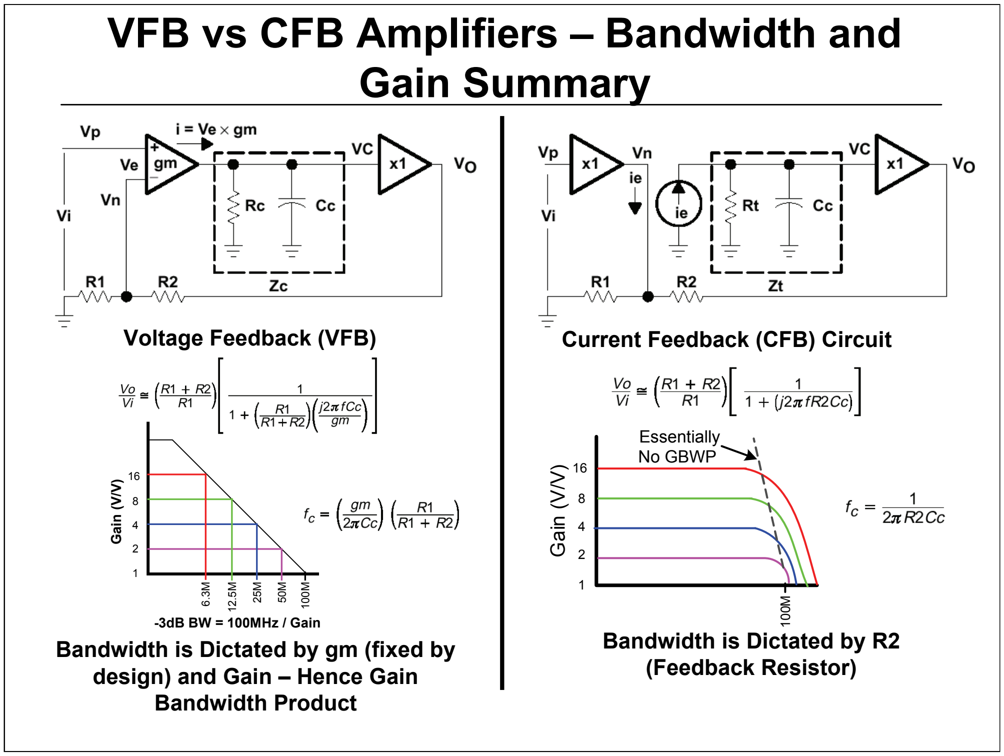




- Current Feedback (CFB) Amplifiers stability is dependant on feedback resistor (RF)
- As RF decreases, Bandwidth increases, but Phase-Margin (stability) decreases
- Increasing the Bandwidth can reduce distortion (increases excess open-loop gain)
- Reducing RF (and RG) reduces overall output noise
- Optimum RF value is different for every amplifier
- Feedback Resistor value can be reduced as gain increases to maximize performance

Reducing the feedback resistor can substantially improve overall performance!

CFB op amps allow you to optimize the loop gain, by selection of the feedback resistor value, based on the closed loop gain of the amplifier. At higher gains, lower feedback resistors can be used without sacrificing stability.



VFB vs CFB Amplifiers – Bandwidth and Gain Summary

Voltage Feedback (VFB)

$$\frac{Vo}{Vi} \cong \left(\frac{R1+R2}{R1}\right)\left[\frac{1}{1+\left(\frac{R1}{R1+R2}\right)\left(\frac{j2\pi fCc}{gm}\right)}\right]$$

$$f_C = \left(\frac{gm}{2\pi Cc}\right)\left(\frac{R1}{R1+R2}\right)$$

-3dB BW = 100MHz / Gain

Bandwidth is Dictated by gm (fixed by design) and Gain – Hence Gain Bandwidth Product

Current Feedback (CFB) Circuit

$$\frac{Vo}{Vi} \cong \left(\frac{R1+R2}{R1}\right)\left[\frac{1}{1+(j2\pi fR2Cc)}\right]$$

$$f_C = \frac{1}{2\pi R2Cc}$$

Bandwidth is Dictated by R2 (Feedback Resistor)

VFB and CFB Amplifiers Have the Same Ideal Gain

Ideal Gain VFB Amplifier = Ideal Gain CFB Amplifier

Non-Inverting Amplifier

$$Gain = 1 + \frac{R_F}{R_G}$$

Inverting Amplifier

$$Gain = \frac{-R_F}{R_G}$$

Distortion

Intrinsic Linearity

+

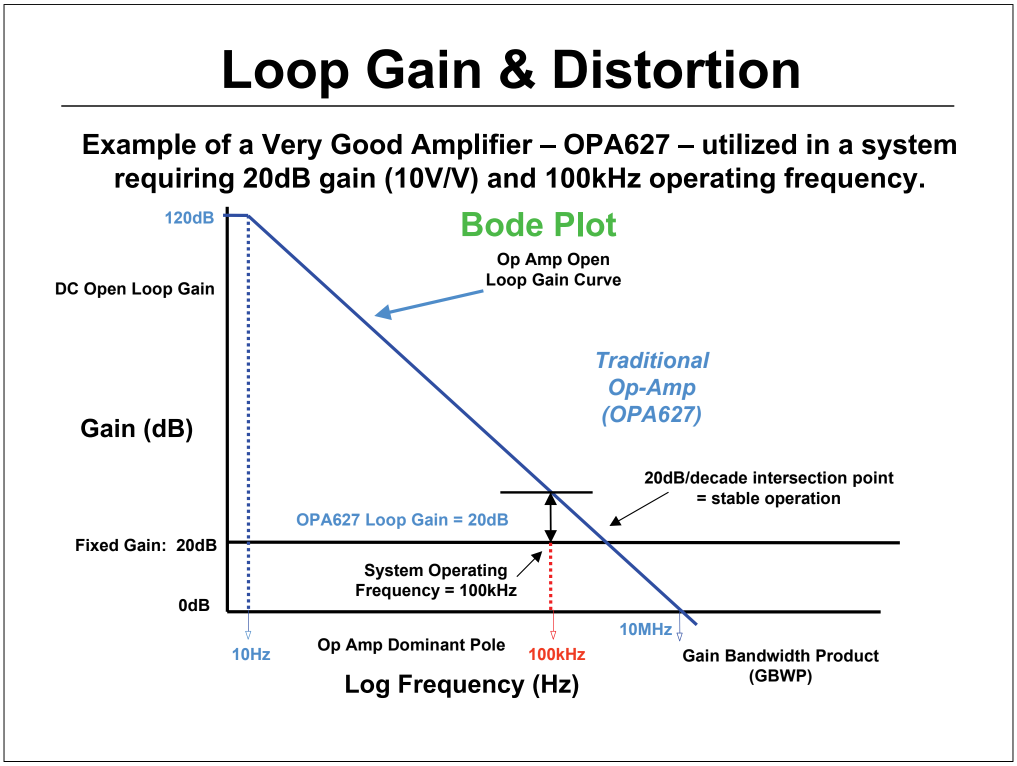
Reduction in distortion due to loop gain in negative feedback configuration

---

= Total distortion

Intrinsic Linearity is internally set by architecture.

Why is this important?
The only control over distortion is with Loop Gain



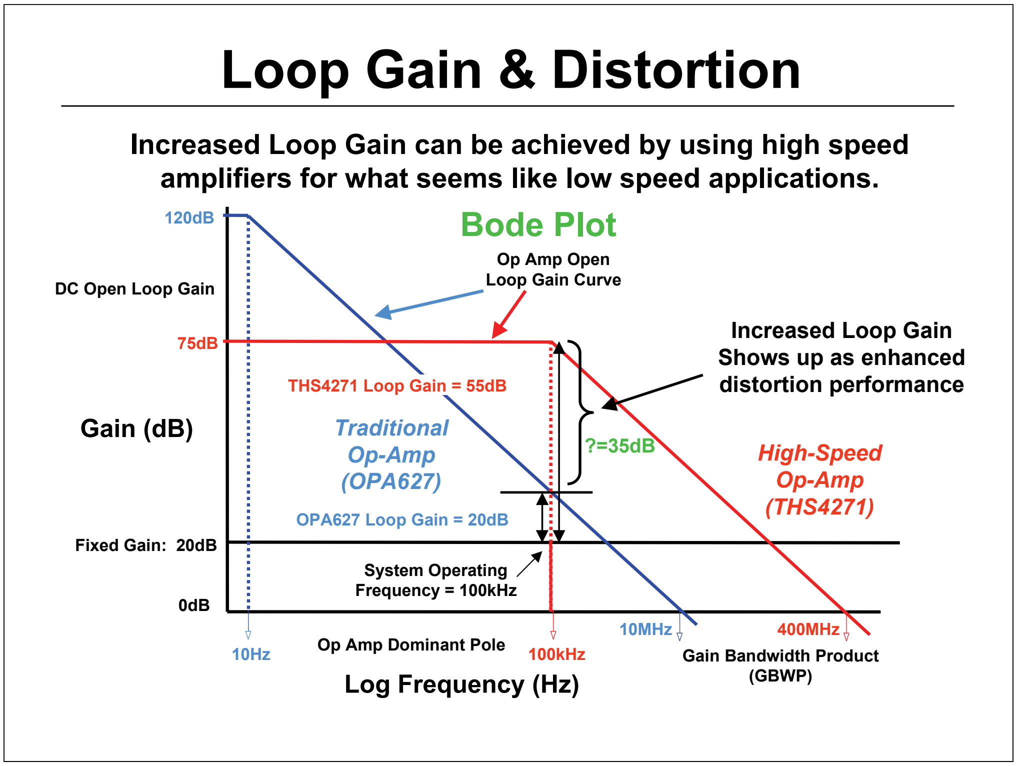
Loop Gain & Distortion

Example of a Very Good Amplifier – OPA627 – utilized in a system requiring 20dB gain (10V/V) and 100kHz operating frequency.

Example of a system that requires 20dB gain at 100kHz AND better than 90 dB distortion. The choice of a very good amplifier – the OPA627 – with it's gain bandwidth product of 10MHz is first selected.

This is a common mistake !!!

As the Bode plot shows, there is only 20dB of loop gain at 100kHz. The net distortion will be about -72dB which may not be good enough for the application.



Loop Gain & Distortion

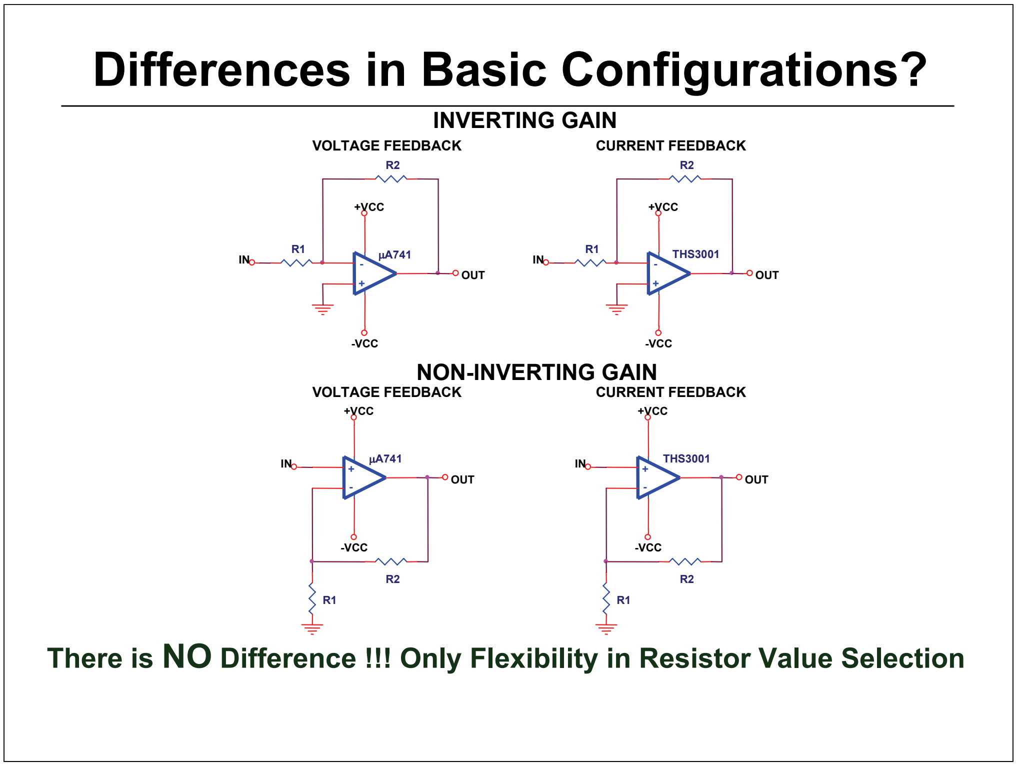
Increased Loop Gain can be achieved by using high speed amplifiers for what seems like low speed applications.

Plotting a very high speed VFB amplifier – THS4271 – open-loop response shows that while the DC open-loop gain is much less than the OPA627, the first pole is not until 100kHz. This results in an amplifier with a 400MHz gain-bandwidth product.

The net result of this is an increase of excess loop gain of 35dB more than the OPA627. This translates to a distortion of better than -100dB at 100kHz.

Keep in mind that high-speed amplifiers may make an excellent choice for “Low-Speed” Applications simply due to the loop gain !!! For VFB op amps, gain bandwidth products (GBW) in the GHz range may be required to have enough loop gain to significantly reduce distortion in the 10 MHz to 100 MHz range.

Current feedback (CFB) op amps have much higher slew rates than VFB op amps. If the output cannot track the input due to slew rate limitations, the effectiveness of negative feedback is null and void. For this reason, CFB op amps can provide lower distortion in high frequency applications.



Differences in Basic Configurations?

INVERTING GAIN

VOLTAGE FEEDBACK

CURRENT FEEDBACK

NON-INVERTING GAIN

VOLTAGE FEEDBACK

CURRENT FEEDBACK

There is NO Difference !!! Only Flexibility in Resistor Value Selection

This slide is presented to drive home a single point – in almost every case where a gain is needed, you can use a current feedback opamp the same way you would use a voltage feedback amplifier – NO DIFFERENCE!!! Well – almost none.

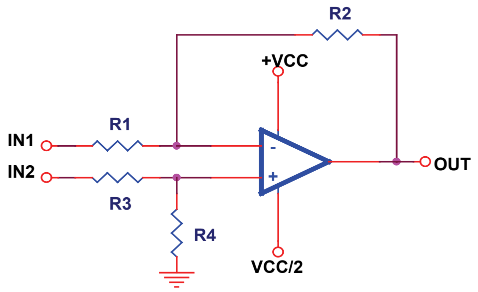
The gain of an inverting stage is –Rf/Rg, and a non-inverting stage is 1+Rf/Rg, but not for just any Rf. It has to be the right one for the amplifier. The correct value for Rf is specified on the data sheet for the part. Voltage Feedback amplifiers allow a lot of flexibility for the choice of the feedback resistor. But, the current feedback amplifiers will have a limited selection as shown in the previous slides. In general, the data sheets will recommend the proper feedback resistor values. Use of these listed values are a great starting point and can be tweaked in accordance with stability / bandwidth trade-offs.

Also keep in mind that the non-inverting input impedance of both VFB and CFB amplifiers is extremely high (>1MOhm) resulting in NO difference in the use of either circuit.

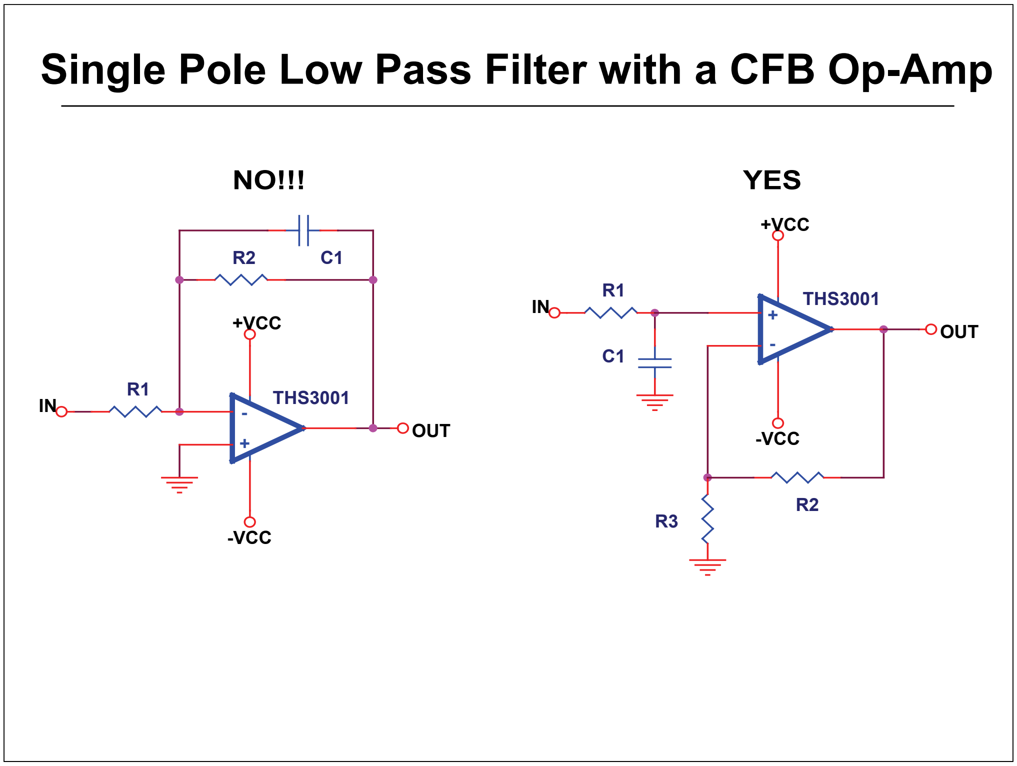
The inverting node input impedance is very low (typically between 10 and 50 ohms) for a CFB amplifier while a VFB amplifier maintains a very high input impedance. BUT, in the closed loop-configuration, there is no difference between these amplifiers when looking at the input impedance from a system standpoint.

Differences in Basic Configurations?

Differential Amplifier Configuration



Again There is NO Difference !!!
Only Flexibility in Resistor Value Selection is limited with CFB amps



Single Pole Low Pass Filter with a CFB Op-Amp

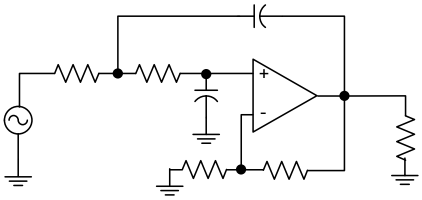
For a majority of cases, you should never use a capacitor in the feedback path. The impedance of this capacitor goes to essentially zero resulting in NO compensation of the amplifier and the result will be an oscillator.

For the advanced designer, there are special tricks that can be done to get around this limitation which allows capacitors to be used in the feedback path to create filters. Basically it is a matter of placing a resistor, inductor, or ferrite chip between the – input node of the amplifier and the “summing” node of the original design. Of course there are trade-offs when this is done such as noise and offsets. But, for some applications this may be acceptable.

See TI Analog Applications Journal 3Q 2003 and 3Q 2004 for more information on this technique.

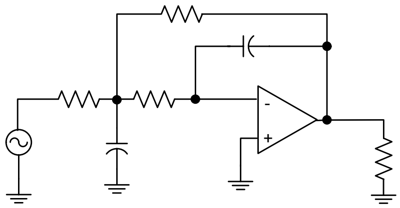
Active Low Pass Filters

Sallen-Key
Low-Pass Filter



NO Problem with both VFB and CFB amplifiers

Multiple Feedback (MFB)
Low-Pass Filter



Only for use with Unity-Gain Stable VFB amplifiers – slight mods allow use with CFB

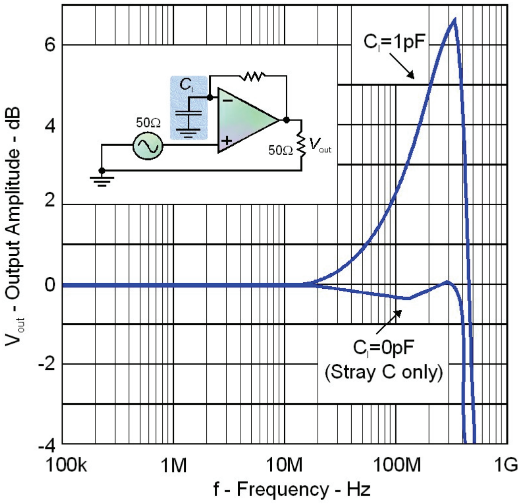
Sallen-Key filters can be used with both CFB and VFB amplifiers with no problems as the negative feedback path has resistors in the path. The feedback resistor value can be chosen independently of the filter component values.

The Mulitple Feedback (MFB) filter has a capacitor between the amplifier output and the inverting summing node. This does NOT allow the use of CFB amplifiers or de-compensated VFB amplifiers. Only unity gain stable VFB amplifiers can be used with this filter. Although a CFB amplifier can be used if the same simple modification to the MFB circuit done in the previous slide is applied to this circuit.

High pass circuits also follow these exact same rules – the Sallen-Key circuit can be used for both amplifiers while the MFB circuit can only be used with unity-gain stable VFB amplifiers and CFB amplifiers with slight modifications.

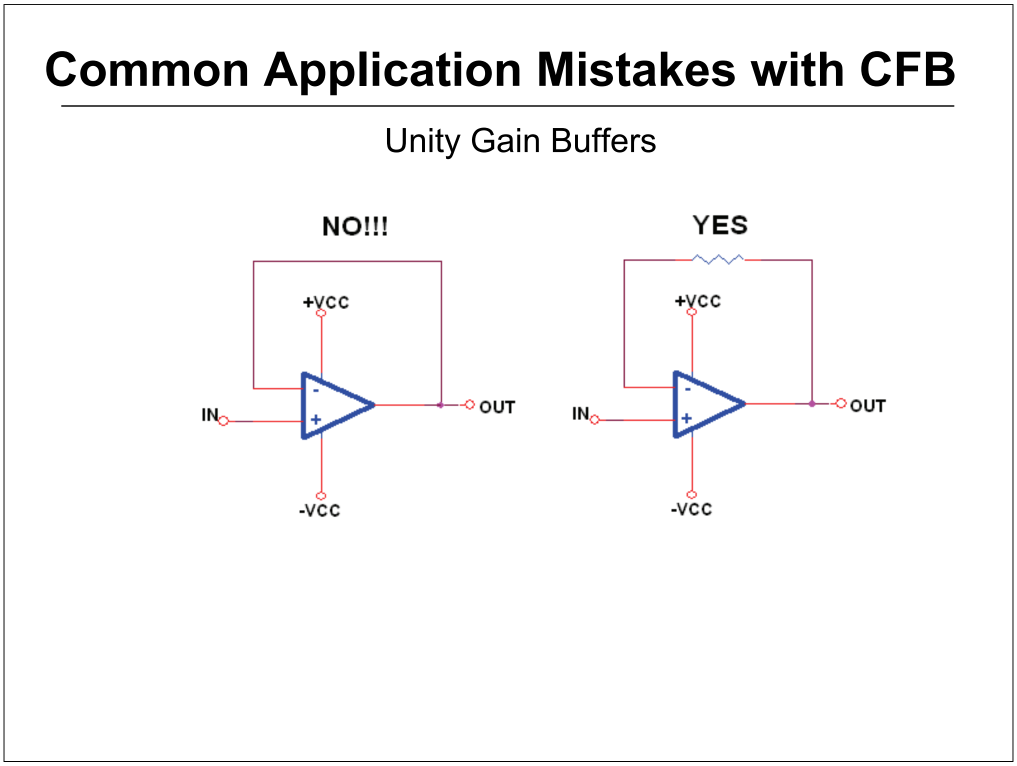
Common Application Mistakes

Capacitance on the inverting input



The high bandwidth of the current feedback amplifiers coupled with their low input impedance makes them extremely sensitive to parasitic capacitance on the inverting input. There should be substantially less than 180 degrees phase shift around the loop at the unity gain crossover frequency. The most important way to do this is to minimize stray capacitance at the inverting node. This can easily be accomplished by notching ground and power planes away from the inverting input and minimize PCB trace lengths of the summing node.

Note that although CFB amplifiers are more sensitive to this, VFB amplifiers can also be susceptible to this same effect.



Common Application Mistakes with CFB

Unity Gain Buffers

Do *not* use a current-feedback op amp as a traditionally configured unity gain buffer (output connected directly to inverting input)! Correct and incorrect unity gain buffers are shown on the slide. A feedback resistor – value recommended on the data sheet – should always be used as a starting point.

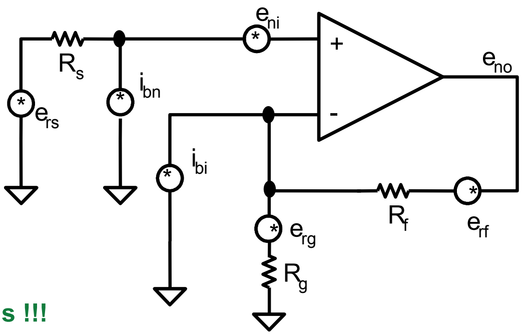
Noise Analysis Differences

$$e_{no}^2 = (e_{rs}NG)^2 + (i_{bn}R_sNG)^2 + (e_{ni}NG)^2 + (i_{bi}R_f)^2 + (e_{rf}^2) + (e_{rg}^2(\frac{R_F}{R_G})^2)$$

$$e_{no}^2 = \left[e_{ni}^2 + (i_{bn}R_s)^2 + 4kTR_s\right]NG^2 + (i_{bi}R_f)^2 + (4kTR_fNG)$$

$$NG = 1 + \frac{R_f}{R_g}$$

4kT=16.4E-21 J @ T = 298° K



VFB Amplifier:

- **i_{bn} = i_{bi} : Typically 1 to 2pA/√Hz**
- **Dominated by e_{ni} : generic amp is 10 to 15 nV/√Hz**

CFB Amplifier:

- **Dominated by I_{bn} , i_{bi} : Typically 12 to 18 pA/√Hz – INDEPENDENT terms !!!**
- **e_{ni} : typically 2 to 3 nV/√Hz**

See Application Note SBOA066 “Noise Analysis for High Speed Op Amps”

This is the general analysis circuit for op amp output noise including all noise sources. It is important to remember that the specs in a data sheet do not include the total noise due to the external components. Therefore vendors can mislead one to believe their part is lower noise when in fact they are required to use large resistors possibly giving higher overall noise even if the input voltage noise for the op amp itself is quite low.

Noise can be a very confusing issue. Some points to keep in mind.

The only noise that can be measured is at the output of the amplifier.

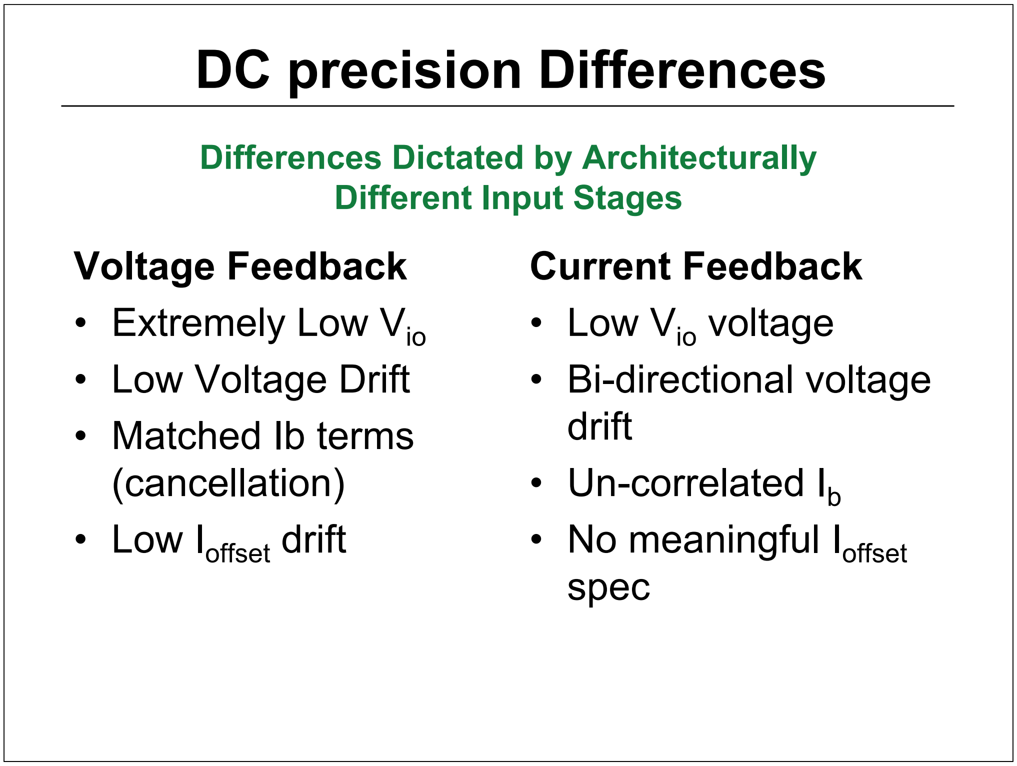
Input referred noise is simply the output noise divided by the gain back to the input that you care about - could be the non-inverting input, inverting input, or the input of a prior stage.

Output noise power is made up of the sum of numerous noise contributors. Often, one or two of these are clearly dominant and swamp out all others. This leads to simplified noise equations that drop out terms - leading to much confusion. General equations should include a fairly complete model even if some terms are often (but not necessarily always) negligible.

VFB amplifiers are dominated by Voltage noise (Eni)

CFB amplifiers are dominated by current noises, especially the inverting current (ibi) noise when utilized in low gains (<5V/V)

CFB amplifiers can have lower noise than a VFB amplifier when used in high gains – although decompensated VFB amplifiers may result in even better noise performance than a CFB amplifier.



DC precision Differences

Differences Dictated by Architecturally Different Input Stages

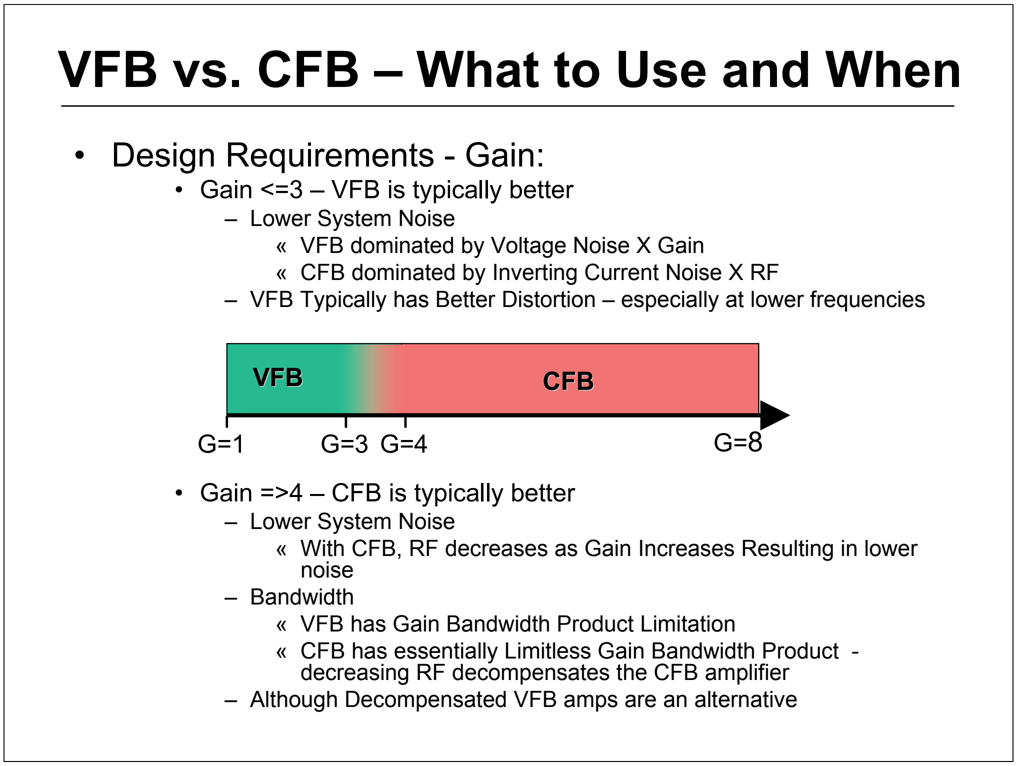
Voltage Feedback

- Extremely Low V_{io}
- Low Voltage Drift
- Matched Ib terms (cancellation)
- Low I_{offset} drift

Current Feedback

- Low V_{io} voltage
- Bi-directional voltage drift
- Un-correlated I_b
- No meaningful I_{offset} spec

As the beginning of this presentation showed, the input stages of each type of amplifier will dictate the DC precision – aka accuracy – of each amplifier. The VFB amplifier’s matched input differential pair consisting of same size transistors and same bias points will allow for better DC accuracy. The CFB amplifier has unmatched transistors operating at different bias points – typically due to NPN and PNP’s having different characteristics – resulting in poor DC accuracy.



VFB vs. CFB – What to Use and When

- Design Requirements - Gain:
  - Gain <=3 – VFB is typically better
    - Lower System Noise
      - « VFB dominated by Voltage Noise X Gain
      - « CFB dominated by Inverting Current Noise X RF
    - VFB Typically has Better Distortion – especially at lower frequencies

  - Gain =>4 – CFB is typically better
    - Lower System Noise
      - « With CFB, RF decreases as Gain Increases Resulting in lower noise
    - Bandwidth
      - « VFB has Gain Bandwidth Product Limitation
      - « CFB has essentially Limitless Gain Bandwidth Product - decreasing RF decompensates the CFB amplifier
    - Although Decompensated VFB amps are an alternative

Although there are several attributes that separate a VFB amplifier from a CFB amplifier, there are typically only a few specifications that can be looked at when deciding on what topology is best for a given application. The first specification to look at is gain requirements of the amplifier. There are typically other specifications that go along with gain requirements. All of the key requirements dictate the best amplifier for the socket – not just one. Remember that there are always exceptions to these rules of thumb, but this does give a good starting point.

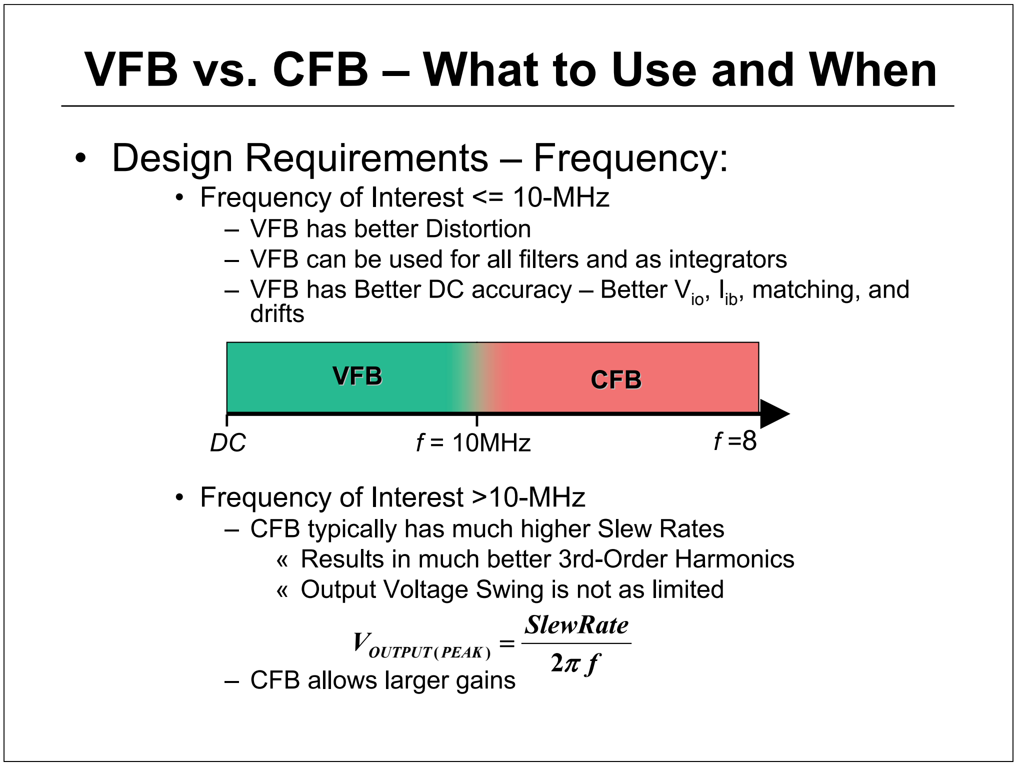
For gains equal to or less than 3, a VFB amplifier generally makes for a very good choice. One of the biggest reasons for this is the output noise of the amplifier. As other slides have shown, a VFB amplifier output noise is dominated by the voltage noise of the amplifier. Thus, the dominant VFB output noise is equal to voltage noise times the gain. Thus, as long as the gain is low, the overall noise will also be low.

A CFB amplifier output noise is generally dictated by the inverting current noise times the feedback resistance. Although this noise is not multiplied by the amplifier gain at the output, this contribution with low gain is generally the dominate noise component in the amplifier.

One other aspect of VFB amplifier working at low gains is their loop gain is very large. This will help keep distortion very low.

For amplifier gains greater than or equal to 4, the CFB amplifier is generally a better amplifier. The main reason for this is the feedback resistor is typically reduced as gain increases. This does two things. The first thing it does is to reduce the main noise contributor as the inverting current noise multiplied by the feedback resistor term is decreased. The other thing reducing the feedback resistor accomplishes is it decompensates the CFB amplifier. This results in a the lack of a gain bandwidth product the VFB amplifier has. Thus, high bandwidths are maintained at high gains with a CFB amplifier. Additionally, this decompensation helps maintain the distortion performance even at higher gains.

An alternative to using a CFB amplifier with high gains is to choose a decompensated VFB amplifier. The only limitation is these decompensated VFB amplifiers must maintain a minimum closed loop gain as dictated by their specifications. Failure to do so can easily result in oscillations. But, if the gain requirement is say 15V/V, and a VFB amplifier is desired, then choosing a decompensated VFB amplifier with a minimum gain of 10V/V or 12V/V – such as the THS4021 or OPA846 - would perform very well in the application.



VFB vs. CFB – What to Use and When

- Design Requirements – Frequency:
  - Frequency of Interest <= 10-MHz
    - VFB has better Distortion
    - VFB can be used for all filters and as integrators
    - VFB has Better DC accuracy – Better V_{io}, I_{ib}, matching, and drifts
  - Frequency of Interest >10-MHz
    - CFB typically has much higher Slew Rates
      - « Results in much better 3rd-Order Harmonics
      - « Output Voltage Swing is not as limited

$$V_{OUTPUT(PEAK)} = \frac{SlewRate}{2\pi f}$$

    - CFB allows larger gains

The next specification to look at is the frequency of interest. This is not necessarily the bandwidth of the amplifier, but rather the frequency range of the signals that are of most importance. If the frequency of interest is 10-MHz or less, a VFB amplifier is typically a very good choice. Again there are exceptions to this rule of thumb, but it is a good starting point. VFB amplifiers work very well with these frequencies due mainly to the architecture of the amplifier. Additionally any type of filter can be constructed with a VFB amplifier including integrators. Couple this with good input offset voltage, matched input bias currents, and low drift, the VFB amplifier makes for an excellent choice for low frequency operation.

As the frequency of interest increases to over 10-MHz, the CFB amplifier generally makes an excellent choice. The ability to work at high gains and high frequencies is an obvious reason for this. But the other key attribute for the CFB amplifier is the exceptionally large slewrates. Third order harmonics are dominated by slewrate limitations. Thus, the higher the slewrate, the better the third order harmonics tend to be.

Coupled with slewrate is the output swing. Using the formula Vout(peak) = SlewRate / (2 Pi f) one can easily see that at high frequencies, to achieve reasonably large output swings requires significantly large slewrates. Thus, even if a VFB amplifier has a very large bandwidth, if it does not have a large slewrate, the output swing will be severely limited.

VFB vs. CFB – Example 1 : xDSL Line Driver

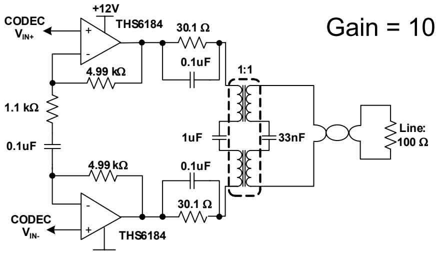
- ADSL2+ Line Driver Requirements (CO Side):
  - High Gain of +10V/V (+20dB)
    - Implies CFB
  - Frequency of Interest – 163-kHz to 2.2-MHz
    - Implies VFB but CFB can work
  - Low Noise of <60nV/rt(Hz) Differentially
    - High gain with Low Noise = CFB
  - Low Distortion – MTPR > 65dB (similar to IMD3)
    - Not Too Difficult – VFB or CFB can work
  - Low Power
    - Both VFB and CFB can be low power
  - Drive High Peak Currents > 400mA
    - Both VFB and CFB can do this
  - Low Cost !!!
    - Both VFB and CFB can be Low Cost

Let's look at a few examples of when and where to use a VFB or a CFB amplifier. The first example is a ADSL2+ central office line driver. There are several requirements of the amplifier that must be met in order for the system to function properly. The large gain requirement implies that a CFB amplifier should be highly considered. The frequency of interest is <10MHz though, which implies a VFB may work here. The noise requirement coupled with a large gain also implies CFB. The distortion requirement allows for both CFB or VFB amplifiers to work here. But, when looking at the low power AND the high peak current drive, the CFB architecture has an advantage due to the dynamic currents inside the amplifier.

As this example points out, several specifications may need to be looked at simultaneously in order to find the best amplifier for the job. Although some specifications may imply a VFB amplifier would work well here – especially a decompensated VFB amplifier – other specifications point directly to the use of CFB amplifiers. This is the reason that while there are a few VFB line driver amplifiers in the market, a vast majority of line drivers are indeed CFB amplifiers. One good example of a de-compensated VFB Line driver is the OPA2614.

VFB vs. CFB – Example 1 : xDSL Line Driver

- Best Solution:
  - Due to High Gain and Low Noise Requirement, CFB makes best solution.



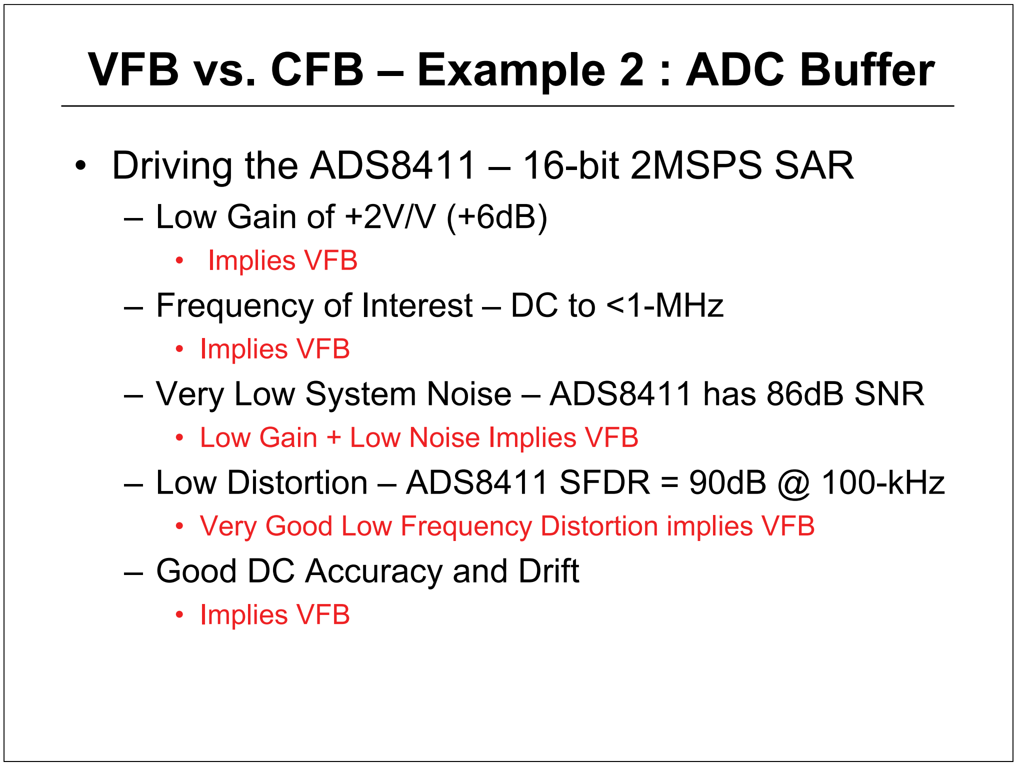
Gain = 10 V/V (+20dB)

$$e_{no}^2 = 2\times\left[(e_{rs}NG)^2 + (i_{bn}R_sNG)^2 + (e_{ni}NG)^2 + (i_{bi}R_f)^2 + (e_{rf}^2) + ((\frac{e_{rg}^2}{2})(\frac{R_F}{R_G})^2)\right]$$

  - Due to Dynamic Internal Currents, driving 400mA is best done with CFB for Lowest Power
  - Other specs are acceptable for a CFB amplifier

The CFB amplifier is highly versatile. The fact that the compensation is derived by the feedback resistance is a powerful tool for the System Designer. A system with a gain requirement of +5V/V can use a CFB amplifier just as well as a system that requires a gain of +10V/V. This is one area where a decompensated VFB amplifier is more limited.

The above shows an example of the ADSL2+ line driver that is commonly found in the market today. It meets the large gain, low noise, low distortion, low power, and low cost requirements of the design.



VFB vs. CFB – Example 2 : ADC Buffer

- Driving the ADS8411 – 16-bit 2MSPS SAR
  - Low Gain of +2V/V (+6dB)
    - Implies VFB
  - Frequency of Interest – DC to <1-MHz
    - Implies VFB
  - Very Low System Noise – ADS8411 has 86dB SNR
    - Low Gain + Low Noise Implies VFB
  - Low Distortion – ADS8411 SFDR = 90dB @ 100-kHz
    - Very Good Low Frequency Distortion implies VFB
  - Good DC Accuracy and Drift
    - Implies VFB

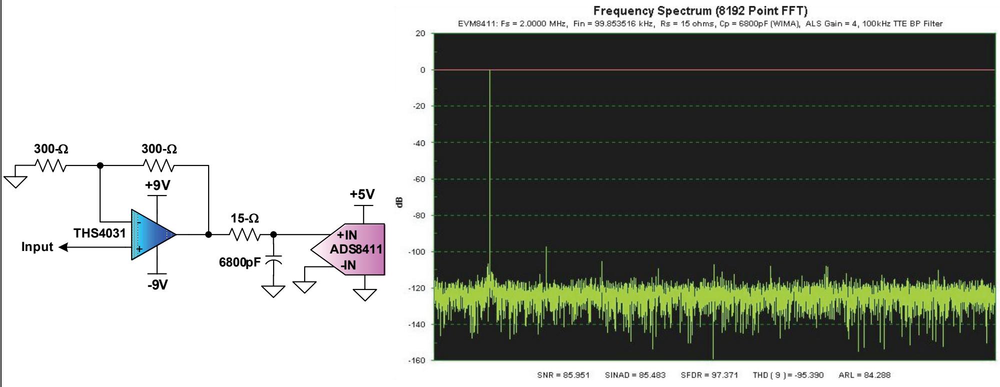
Another example is an amplifier to drive an Analog-to-Digital Converter (ADC). In this example a 16-bit, 2MSPS SAR Analog-to-Digital Converter (ADC) is chosen for the system. To isolate the signal source or sensor form the ADC, especially the charge injection of the ADC front-end, an amplifier is used as an interface between the two sections. The question is will a VFB or a CFB amplifier be best?

Looking at the retirements of the system gives us a better idea of what topology is best to use. The gain is typically very low. This helps minimize the noise of the amplifier and keeps the excess loop gain as high as possible resulting in low distortion. Since the frequency of interest is in the first nyquist zone, using a VFB amplifier also makes sense. Lastly, since DC accuracy is also required, the VFB amplifier makes for an obvious choice.

Keep in mind that the goal is to pick an amplifier that is transparent in the system. So if the ADC has 86dB spurious free dynamic range (SFDR), then the amplifier goal is to be better than 106dB SFDR. This is also true for the signal-to-noise ratio (SNR). The amplifier system should have at least 10X lower noise than the rest of the system to be transparent. This is why a 10-MHz amplifier would not be a good choice for this system even thought the frequency of interest is <1MHz.

VFB vs. CFB – Example 2 : ADC Buffer

- Best Solution:
  - VFB Amplifier Excels at Low Gain and Low Frequency Operation
  - Low Noise Requires a Very Low Noise VFB Amplifier
  - Low Input Offset Voltage and Drift Requires VFB



The best solution for this system is a VFB amplifier. But to make sure the amplifier is transparent, a very low noise and low distortion amplifier was chosen. The spectral plot of the ADS8411 is shown with a 100-kHz tone resulting in a SFDR of 97.3dB, a SNR of 85.9dB, and SINAD of 85.4dB. Based on the pure specifications of the ADS8411, the THS4031 amplifier becomes essentially transparent in the system meeting the requirements of the system. An alternative, lower supply choice, would be the OPA820.

Again, keep in mind every system is unique and what works in one system may not be the best choice for a similar system. A CFB amplifier can make a good choice for interfacing to ADC's, especially extremely fast ADC's such as the ADS5500 (14-bit and 125MSPS). If the system does not require going down to DC, then the VFB amplifier and the CFB amplifier both can work very well in the system.

VFB vs CFB Amplifier - Summary

Voltage Feedback Amplifiers (VFB)

- Better DC specs
  - Generally important in pulse apps
  - Bias current cancellation
  - Tighter dc drift specs
- Decomp'd VFB = Lowest overall noise & high SNR
- Better distortion at low frequencies
- Bandwidth 'dependent' on gain as first order approximation
- Applications
  - High & Low gain amplifiers with high SNR

Current Feedback Amplifiers (CFB)

- Gain Bandwidth Independence
  - More flexible than VFB
  - Has lower inverting input impedance
- Highest achievable Slew Rates
  - Allowing for larger full power signal bandwidths than VFB
- Better distortion at high frequencies
- Different noise terms to deal with.
- Poor DC precision
- RRIO cannot be built
- Some restrictions on topology
  - Cannot do traditional integrators easy