So Many Amplifiers to Choose From; Matching Amplifiers to Applications

High-Speed Applications and Tradeoffs

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High-Speed Amplifier

Typical Amplifier Categories

All of these have different speed ranges

- Dominant types of amplifiers
  - OPA’s → Op Amps
  - INA’s → Instrumentation Amplifiers
  - FDA’s → Fully Differential Amplifiers
- In Op Amps, two dominant types –
  - Voltage Feedback
  - Current Feedback
- In INA’s, typically of the 3 amplifier type
- In FDA’s, all present implementations are voltage feedback
- Specialty amplifiers
  - Unity gain buffers
  - Fixed Gain amplifiers – video buffers
  - Transconductance amplifiers

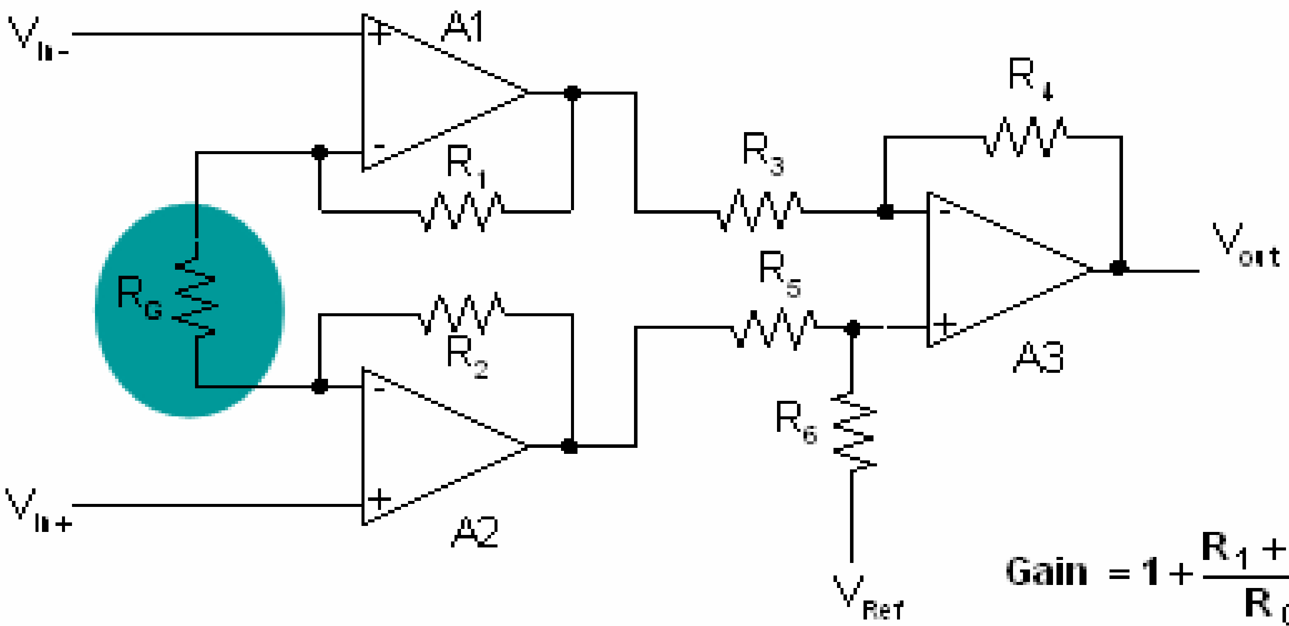
Presentation Outline

- Brief discussion of
  - INA’s and Differencing amplifiers
  - Transconductance based INA
  - Wideband Buffers and Fixed Gain Devices
- Overview of wideband closed loop devices
  - Stability issues
  - Topology review and typical selection criteria
  - Gain of 1 Bandwidth – just what is it – really?
- Loop gain discussion
- The benefits of going differential
- Noise models
- Getting the lowest noise and distortion

INA’s and Difference Amplifiers

- Most of these are lower frequency oriented with DC precision and CMRR the primary areas of concern
- A difference amplifier is a single amplifier structure with 4 equal resistors around it.
- Instrumentation topology is most common.
  - These are essentially, 3 very good amplifiers with a precision trimmed resistor network
- Two amplifier INA also used occasionally.
- Very few high speed INA type devices.
  - Typical signal bandwidths range from 5kHz to 2Mhz
  - CMRR is very high at DC, but typically starts to roll off for F > 10kHz even for 2MHz INA bandwidth devices.
- One newer approach to getting improved high frequency CMRR uses two open loop transconductance devices.

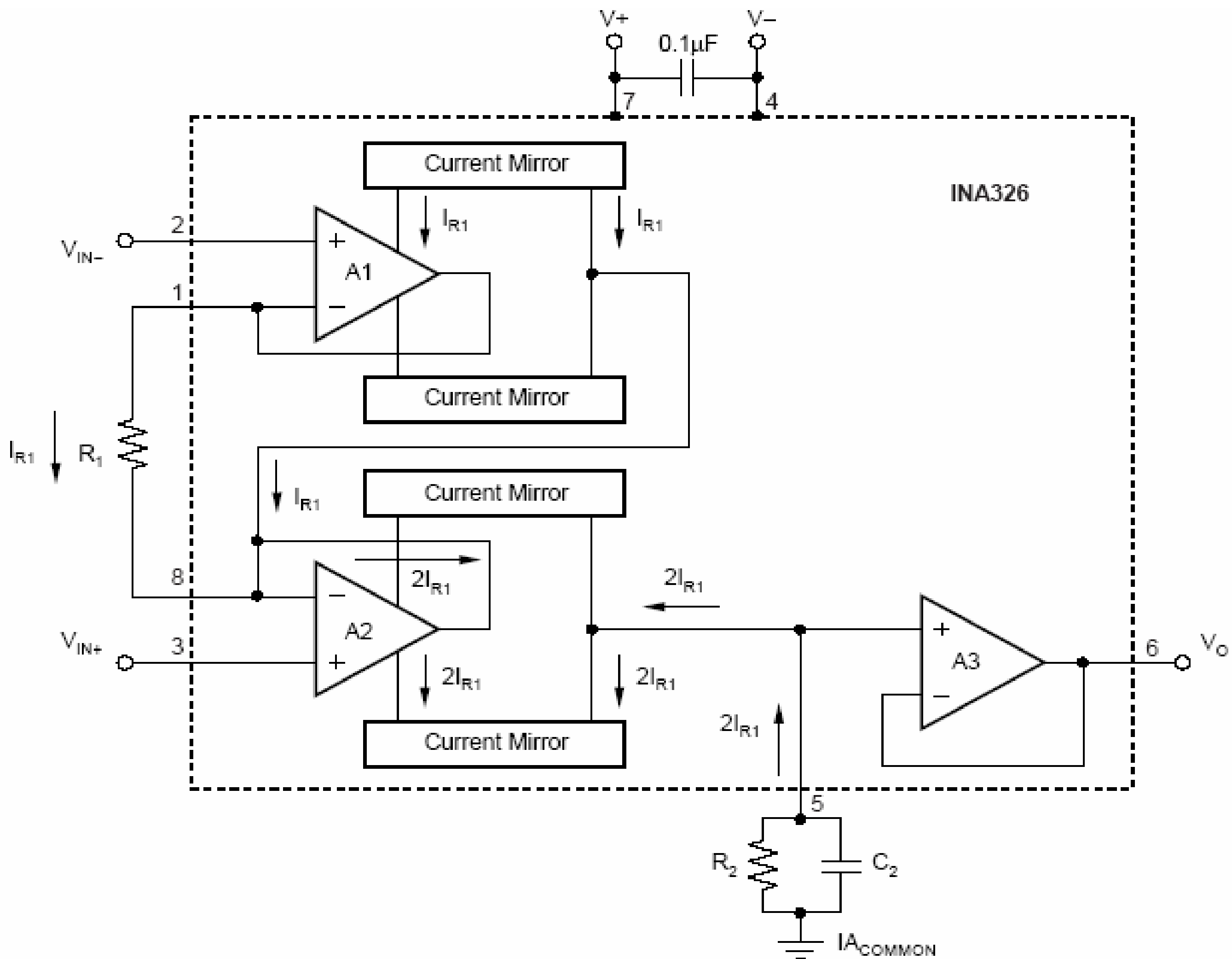
Instrumentation Amplifier (INA)
Three Op Amp Structure



$$\text{Gain} = 1 + \frac{R_1 + R_2}{R_G}$$

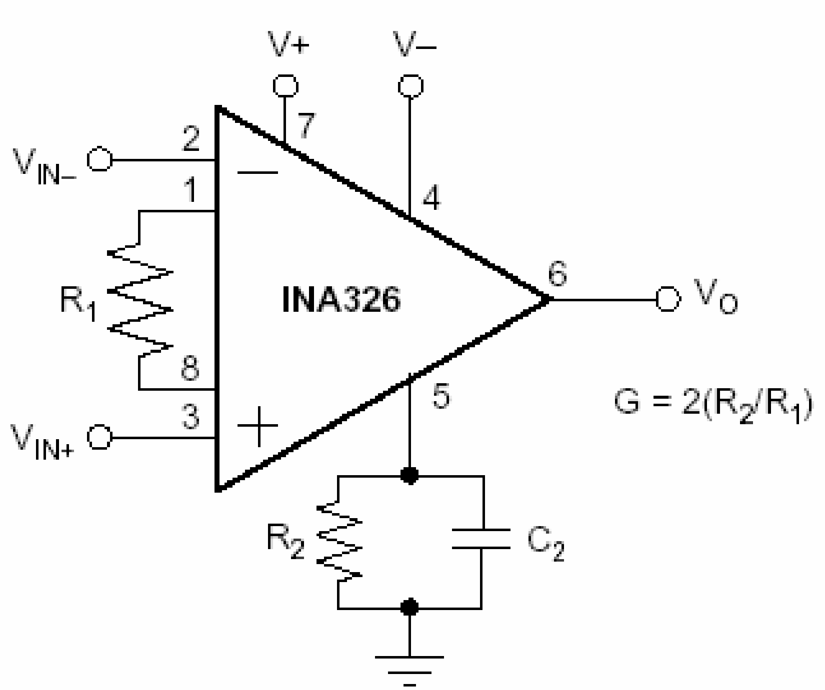
$$\text{Where}: \frac{R_4}{R_3} = \frac{R_6}{R_5}$$

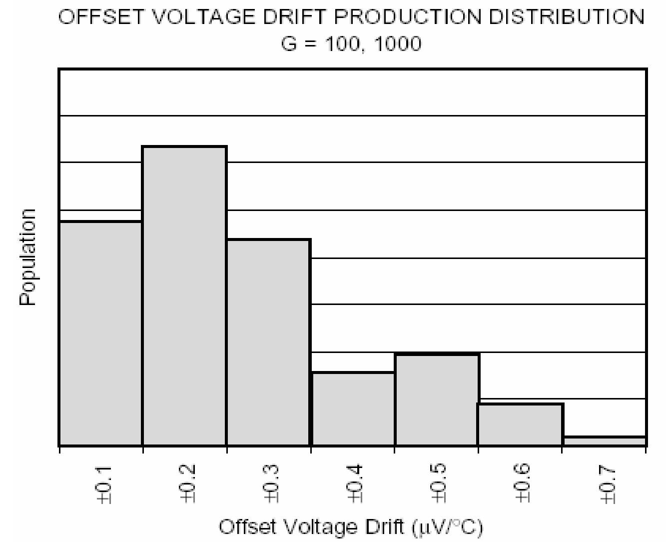
Newer Current Mode INA326



INA326

High-Precision CMOS IA

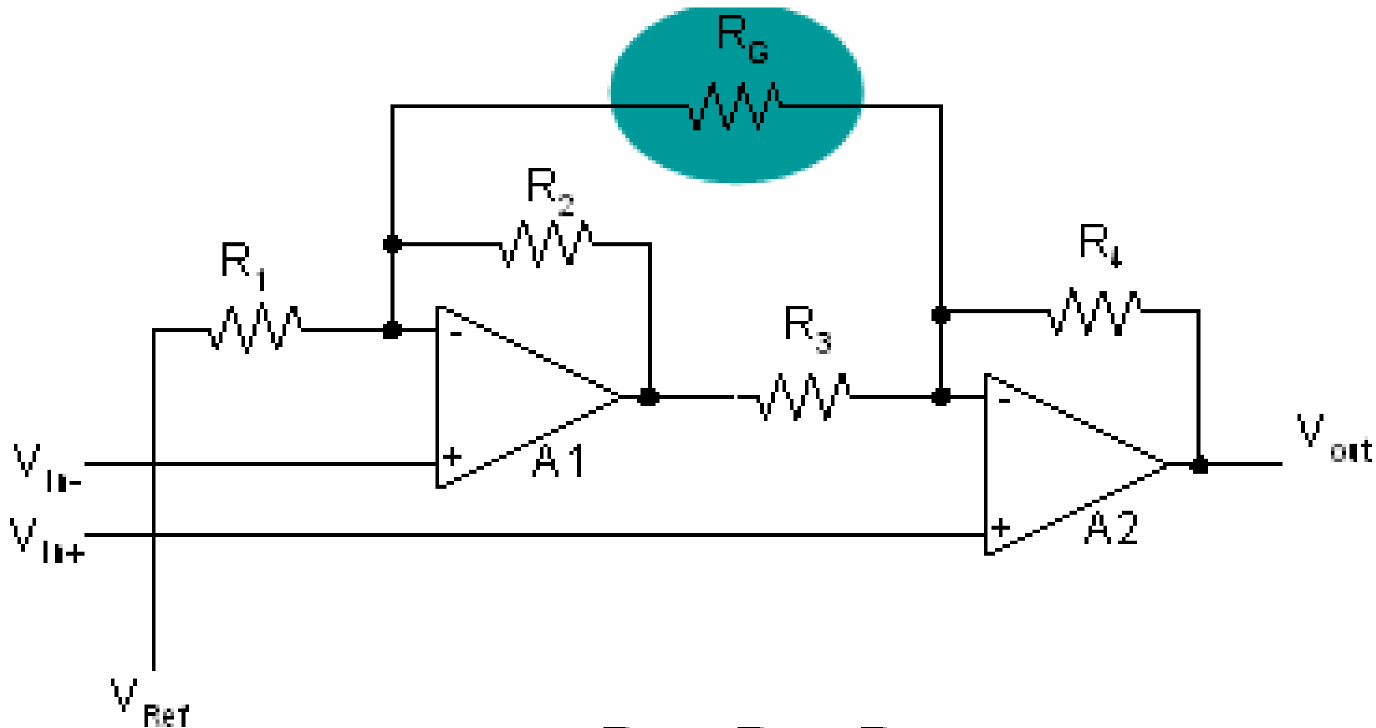




Extremely low offset and offset drift!!

- **INA321 – RRO, 0.5µV offset, low Iq, shutdown**
- **INA331 – RRO, 1mV offset, low Iq, shutdown**
- **INA327 – shutdown version of INA326**

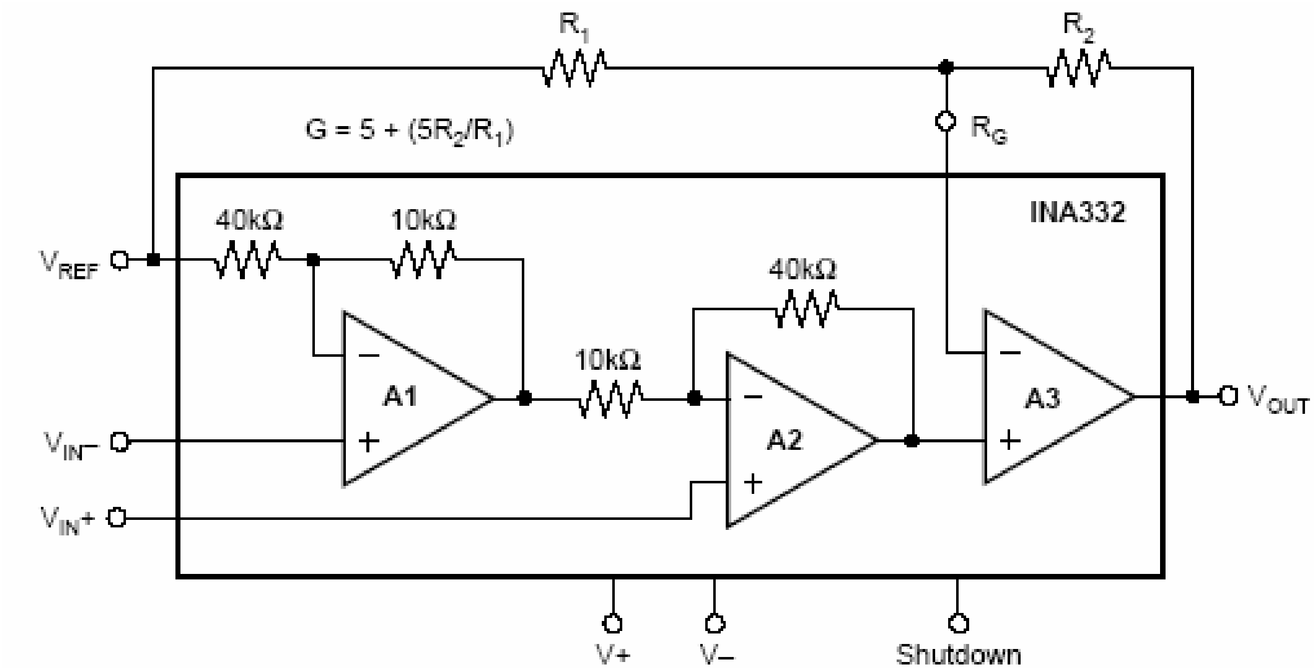
Instrumentation Amplifier (INA)
Two Op Amp Structure



$$\text{Gain} = 1 + \frac{R_4}{R_3} + \frac{R_4 + R_1}{R_G}$$

Newer Two-Amplifier INA

INA332



INA331/332

Low Cost, 5V/µs, CMOS Instrumentation Amps

Key Features:

- Rail-to-Rail Output: 0.25mV from rails, G=10
- FET (CMOS) input for very low : 0.5pA typ Ib
- Excellent Speed/Power Ratio: 2MHz, 5V/µs
- Low Quiescent Current: 415µA/channel
- Extended Temperature Range: -55°C to +125°C

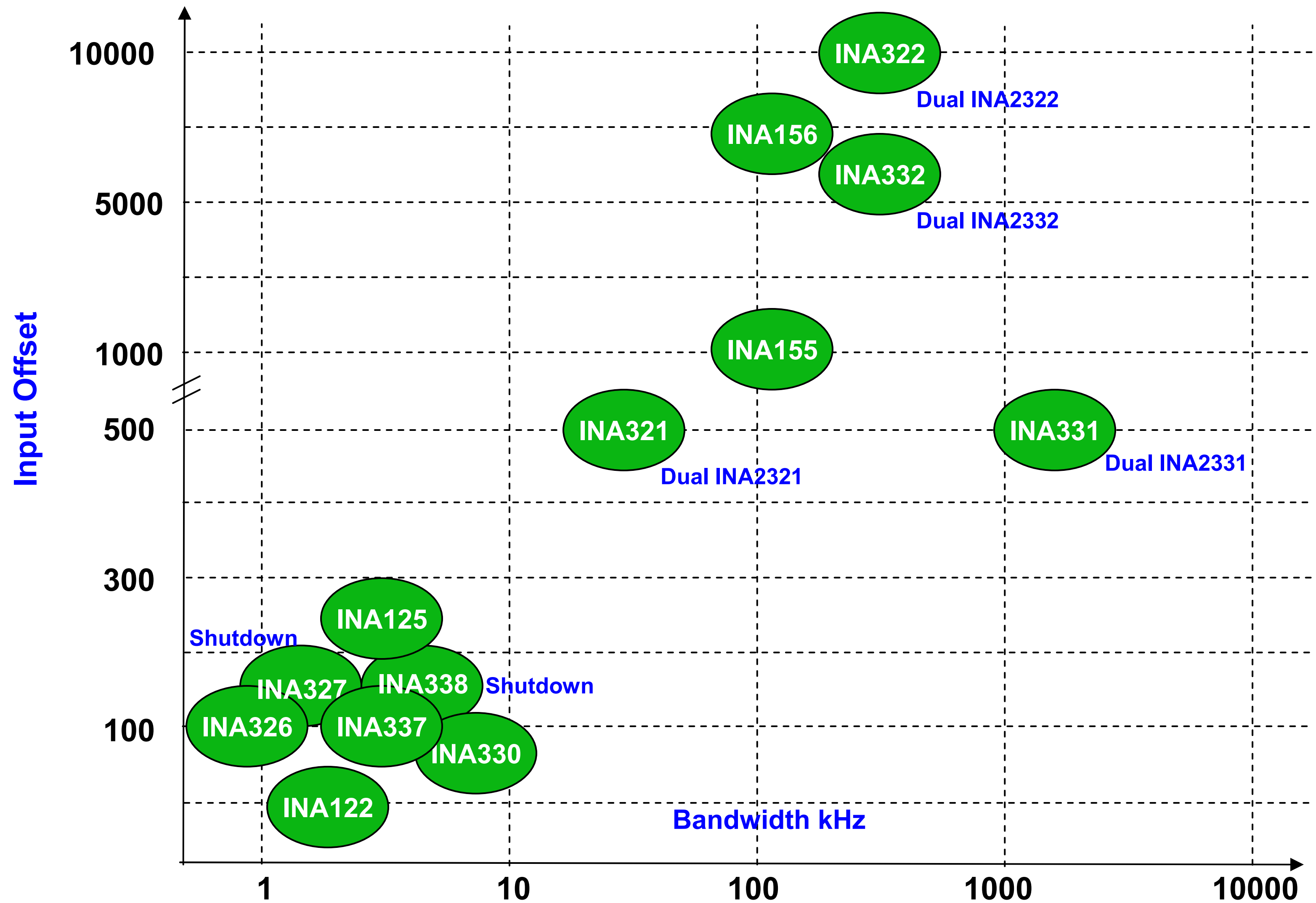
Key Differentiators:

- Ultra-Low Shutdown Current: 0.15µA typ
- Tiny Package: MSOP-8 (single) TSSOP-14 (dual)
- Low Price: Well-Under $1/Channel

- Low-Cost, High-Volume Consumer Applications
- Sensor Amplifier
- PCMCIA and general Data Acquisition Cards
- Medical Instrumentation, e.g. Heart Rate Monitors
- Differential Input Amplifier for A/D Converters
- Automotive Applications
- High-Temperature Industrial

Suggested Resale	Package Options	Temperature Ranges	Options
$0.90 (1k pcs)	MSOP-8 (single) TSSOP-14 (dual)	-55C to +125C	

Instrumentation Amplifiers Single-Supply Product Portfolio



OPA861

Wide Bandwidth Operational Transconductance Amplifier

Features

- Wide Bandwidth OTA (>80Mhz)
- 900V/usec Slew Rate
- 2.4nV/√Hz Input Noise Voltage
- Very Flexible Circuit Building Block
- Ideal Complementary Transistor Function
- Tuneable Transconductance
- Externally settable supply current

Benefits

- Simple to use Ideal Transistor
- Very high speed flexible circuit element
- Externally adjustable transconductance
- High I/O voltage range (+/-4.2V on +/-5V supply)
- Low Cost Filter Design Element

Applications

- DC Restore Circuits
- NIC Filters
- High CMRR ADC Driver
- Capacitive Load Driver

EVM

1ku / $0.95

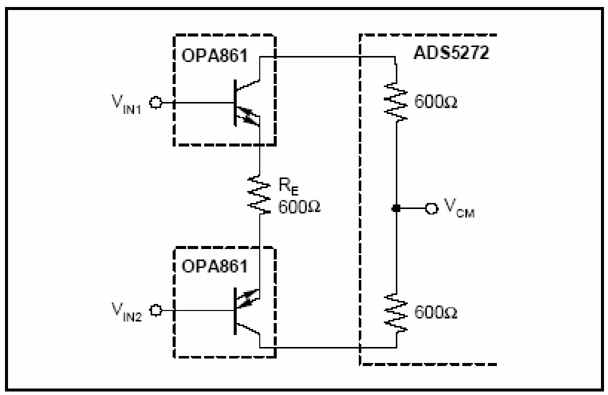


Figure 45. High CMRR, Moderate Precision, Differential I/O ADC Driver

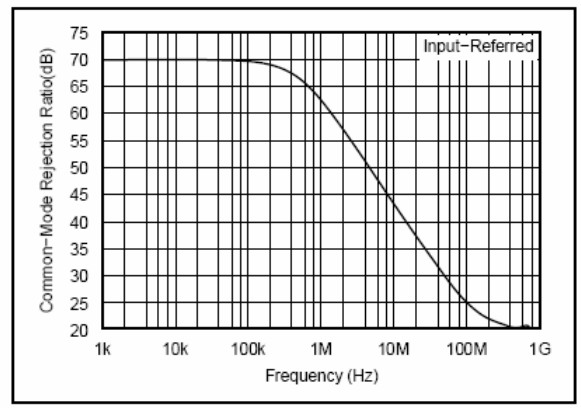


Figure 47. CMRR of the ADC Driver

This 70dB CMRR at 100kHz compares to 25dB for the INA331

Texas Instruments

Unity Gain and Fixed Gain Amplifiers

- Gain set by internal elements
- Buffers used for impedance transformation – High input impedance to low output impedance. Usually can drive a demanding load.
- Fixed gain amplifiers can often get to higher frequencies at lower power due to reduced parasitics for the internal feedback path
- Wideband parts –
  - BUF602 1.2GHz fixed gain of 1, closed loop buffer
  - OPA693 gain of 2 video buffer, >1GHz bandwidth
  - THS4302 fixed gain of 5V/V, > 2.5Ghz bandwidth
- RGB line drivers
  - OPA3692, Triple fixed gain of 2 > 200Mhz bandwidth

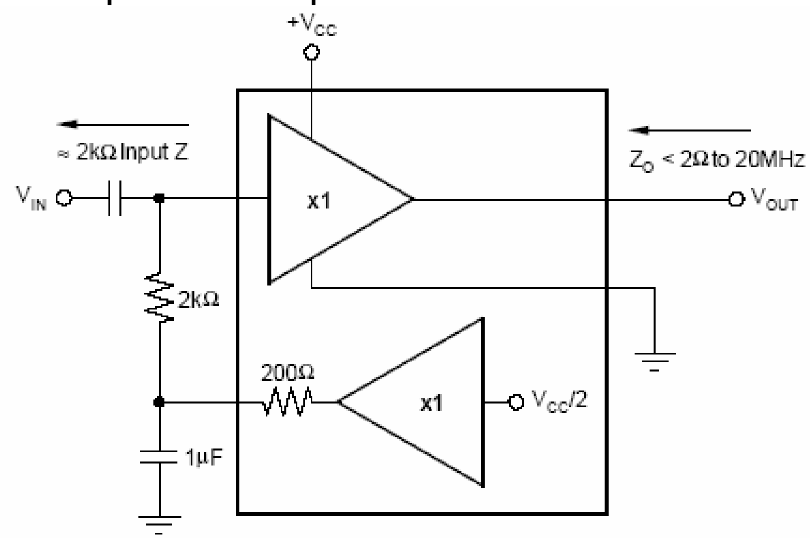
BUF602
High-Speed, Closed-Loop Buffer

Features

- Wide Bandwidth: 1000Mhz
- Very High Slew Rate: 8000V/μsec
- Low Supply Current: 5.8mA
- Closed Loop Design
  Low Output Impedance (1.4Ω typ)
- Flexible Supply Range:
  ±1.4V to ±6.3V Dual Supply
  +2.8V to +12.6V Single Supply
- Optional Midsupply DC reference on Chip

Benefits

- Low Cost Wideband Buffer
- Simple single supply operation with internal mid-scale DC reference
- Standard pinout for SO-8 and SOT23-5
- Improved drop in to the LMH6559



Self-Referenced, AC-Coupled, Single-Supply Buffer

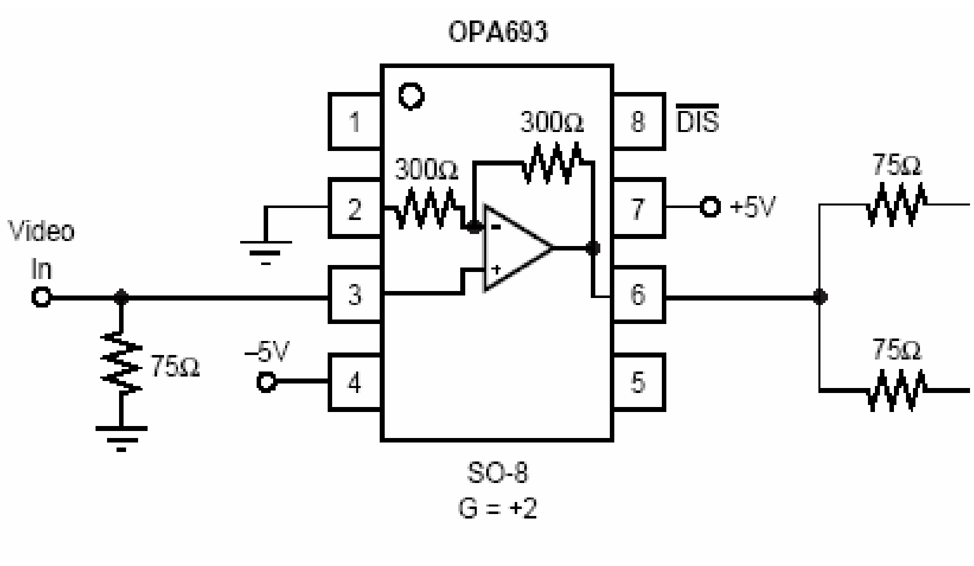
Applications

- Low Impedance Reference Buffer
- Unity Gain Active Filters
- Clock or LO distribution
- Single Supply Mid-Scale Reference
- Wideband Video Mux Buffer
- Voltage Clamp for high speed lines

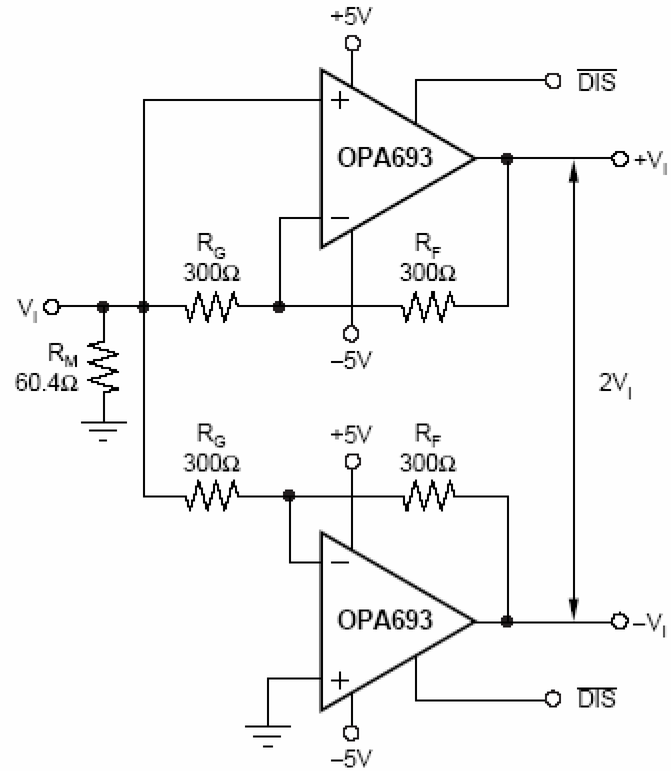
EVM

1ku / $0.85

OPA693 wideband, gain of two video line driver – typical applications



700MHz, 2-Output Component Video DA



DC coupled to 700Mhz, single to differential conversion. Output is ground referenced

Most Amplifiers use Negative Feedback

- Commercially available amplifiers are built on state of the art semiconductor processes –
  - These have great density, and good transistor parameters, but poorly controlled absolute specifications
- Open loop amplifiers are available, but they typically have poor power efficiency and more performance variation than closed loop devices.
  - The uA733 is an example of an open loop amplifier.
- Once you close the loop you get improved DC and AC accuracy - But, particularly for high speed devices, you also have the possibility of high frequency oscillation.
- Normally, we look at stability issues from a loop gain and phase standpoint .

Signs of Instability

- Time Domain, or Pulse Response
  - Overshoot and/or sustained ringing.
- Frequency Domain
  - Higher apparent noise than you would expect
  - Sharp spike in the frequency response
- DC
  - Elevated case temperature
  - Higher Output Offset Voltage
  - Higher supply current than expected.

Comparing Voltage and Current Feedback Op Amps

- Classical Advantages of Voltage Feedback Op Amps
  - Typically can deliver better DC accuracy
    - This is most applicable to pulse oriented signal requirements - typically, DC precision is less important in AC coupled (communications) channels
  - Can be the lowest overall equivalent input noise
    - Best noise (< 1.2nV/√Hz) comes at the price of high quiescent current and non-unity gain stability

Comparing Voltage and Current Feedback Op Amps

- Classical Advantages of Current Feedback Op Amps
  - Essentially unlimited slew rate - gives very high full power bandwidth
    - Most data sheet slew rate numbers are either limited by the input stage buffer or are actually reporting bandwidth limited rise time by mistake
  - Nearly gain bandwidth independent
    - Most useful aspect of this is intrinsic low gain stability with very high closed loop BW

Loop Gain Review

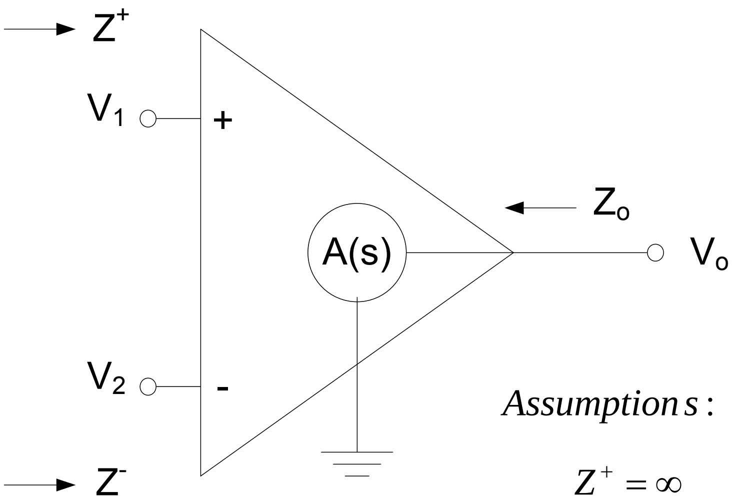
- **For Voltage Feedback op amps, the loop gain varies directly with the signal gain for simple external circuits. Changing the gain, changes the frequency response directly**
- **For Current Feedback op amps, the loop gain is set by the feedback impedance allowing an independent setting for the signal gain. The feedback resistor becomes the frequency response compensation.**

Loop Gain is Everything in Op Amps

- Op Amp suppliers are essentially selling a device that does impedance transformation (high input Z to low output Z) and a whole lot of open loop gain.
- The customer then closes the loop to get a more controlled voltage gain, but also gets a huge improvement in precision (both DC and AC) due to the high open loop gain.
- For high frequency parts, the DC open loop gain is a secondary issue and it is really the one pole rolloff curve that is of interest and where the magnitude of the open loop gain equals the inverse of the feedback ratio. (Loop Gain x-over).
- While the closed loop response is what is normally observed and reported, hiding inside this is a loop gain over frequency that is critical for distortion and stability analysis.

Simplified VFB Analysis

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



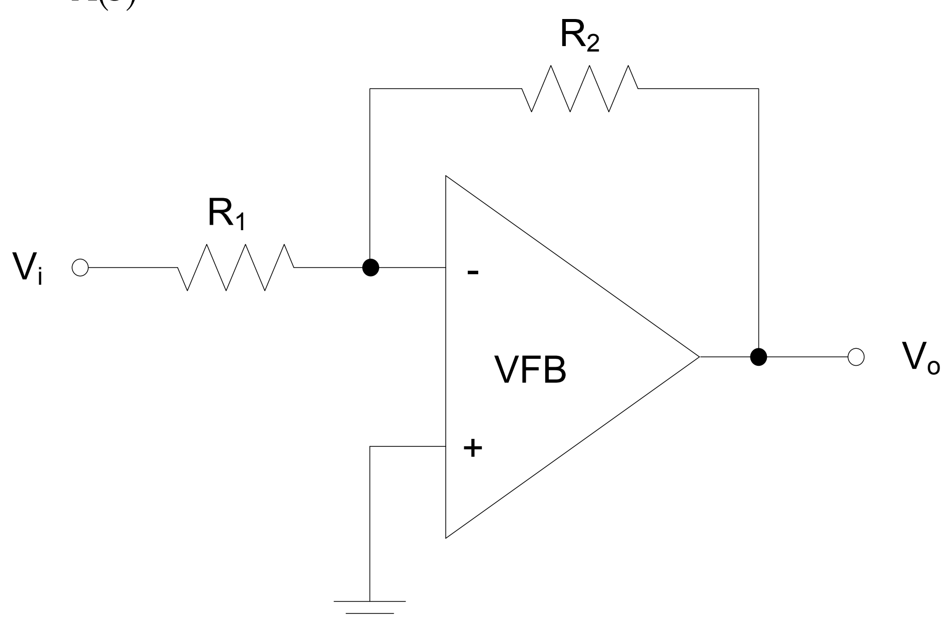
Assumptions:

$$Z^+ = \infty$$

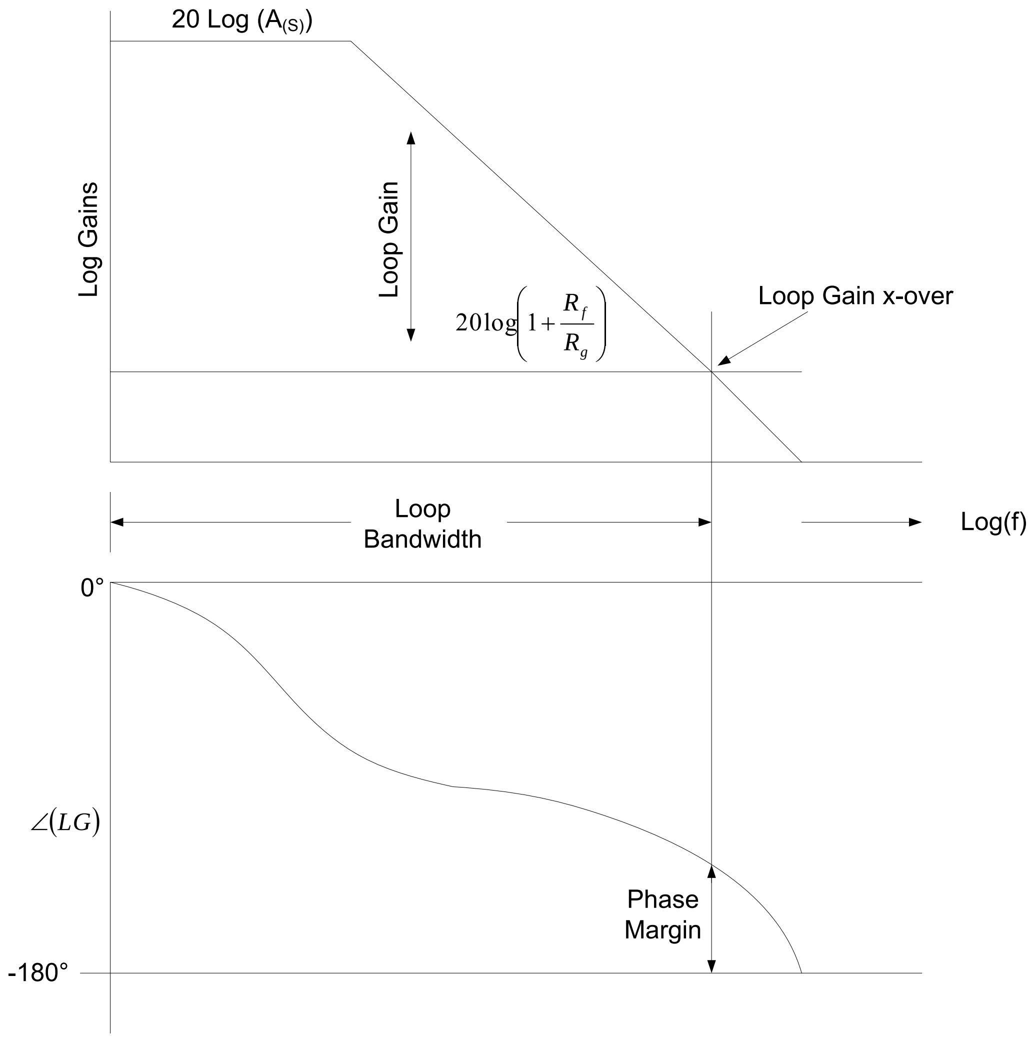
$$Z^- = \infty$$

$$Z_o = 0$$

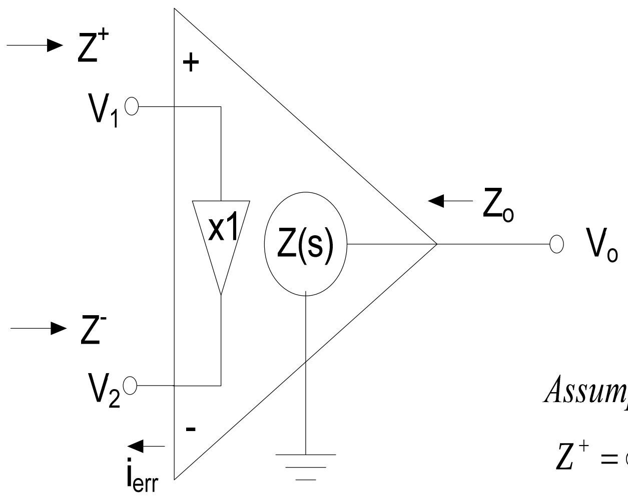
$$V_o = A(s)[V_1 - V_2]$$



Simplified VFB Loop Gain Analysis



Simplified CFB Analysis



Assumptions:

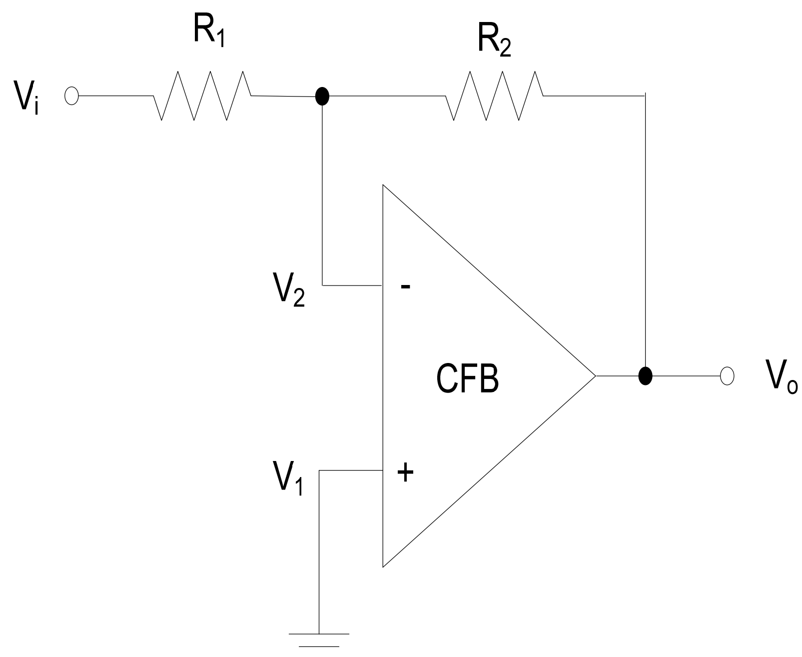
$Z^{+} = \infty$

$Z^{-} = 0$

$Z_o = 0$

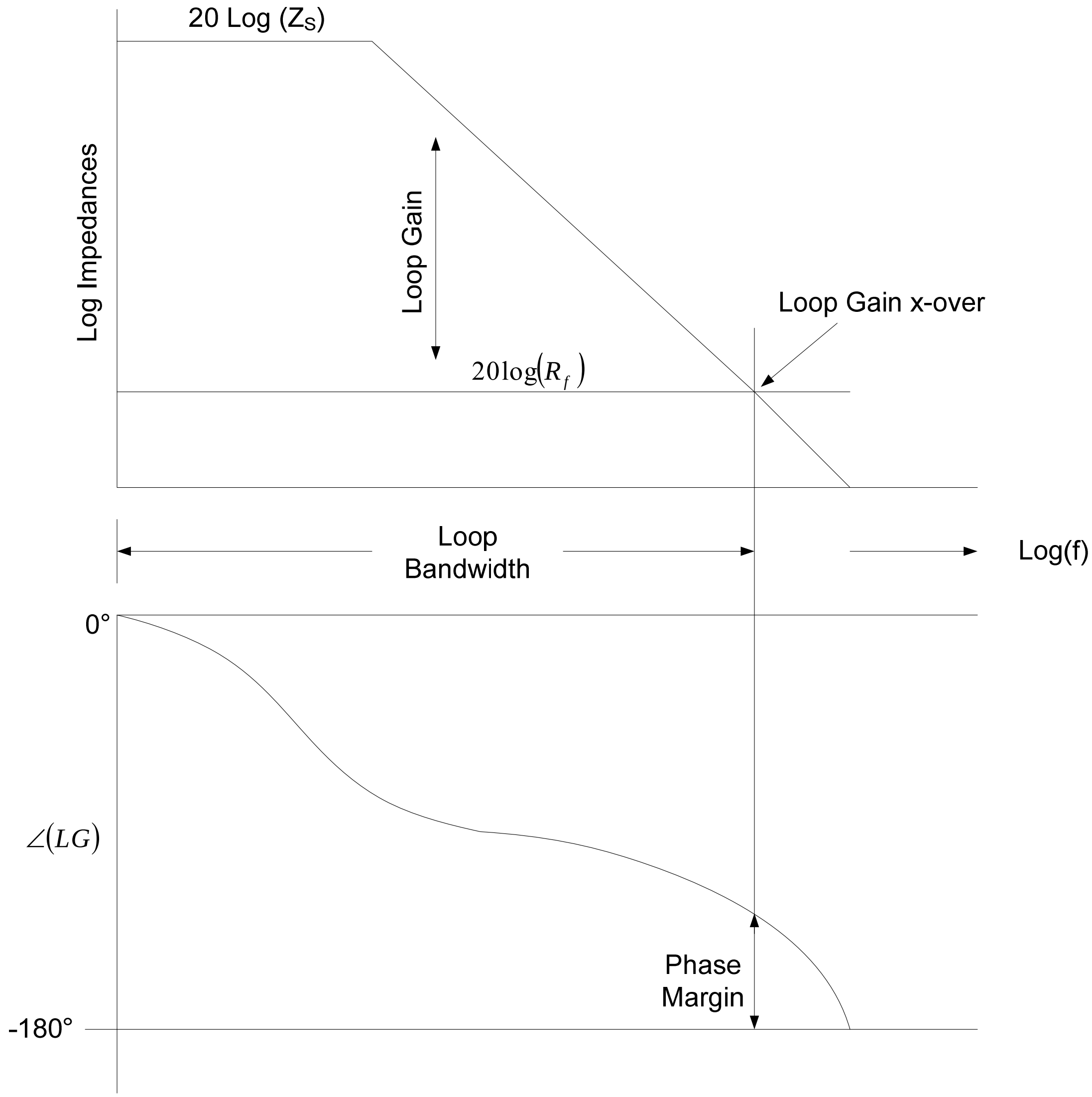
$V_o = Z(s) i_{err}$

i_{err} is the error <u>current</u>

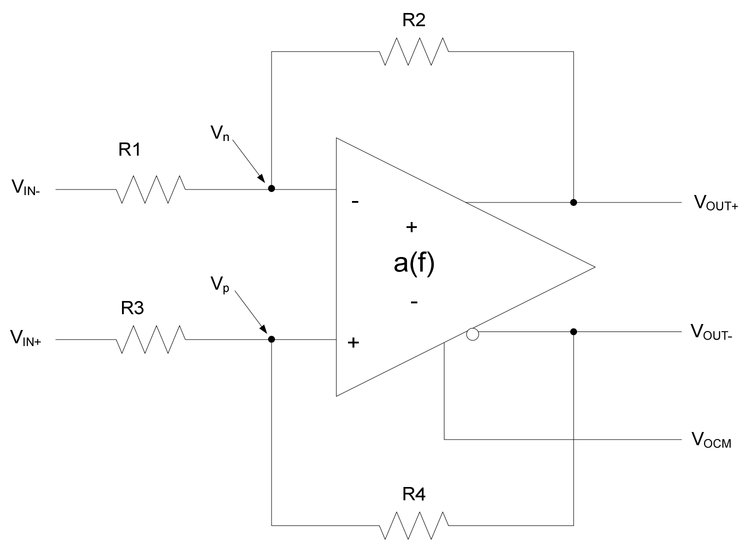


$$\frac{V_o}{V_i} = \frac{-\dfrac{R_2}{R_1}}{1+\dfrac{R_2}{Z(s)}}$$

Simplified CFB Loop Gain Analysis



Simplified FDA Analysis



$$\frac{(V_{OUT+})-(V_{OUT-})}{(V_{IN+})-(V_{IN-})}=\frac{(1-\beta)a(f)}{(1+a(f)\beta)}=\frac{1-\beta}{\beta}\mathrm{X}\frac{1}{\left(1+\frac{1}{a(f)\beta}\right)}$$

$$With\beta=\frac{R_1}{R_1+R_2}=\frac{R_3}{R_3+R_4}\equiv\frac{R_g}{R_g+R_f}$$

$$\frac{(V_{OUT+})-(V_{OUT-})}{(V_{IN+})-(V_{IN-})}=\frac{R_f}{R_g}\mathrm{X}\frac{1}{\left(1+\frac{\left(1+\frac{R_f}{R_g}\right)}{A(s)}\right)}$$

With the feedback ratios matched, this reduces to the same equation as an inverting VFB amplifier. Will have the same Loop gain Bode Plots.

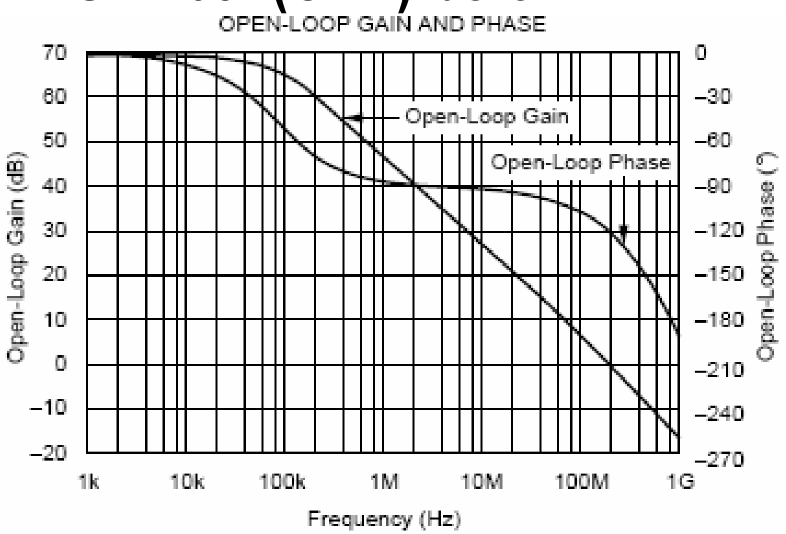
Considerable complexity in the analysis will result with imbalanced feedback ratios.

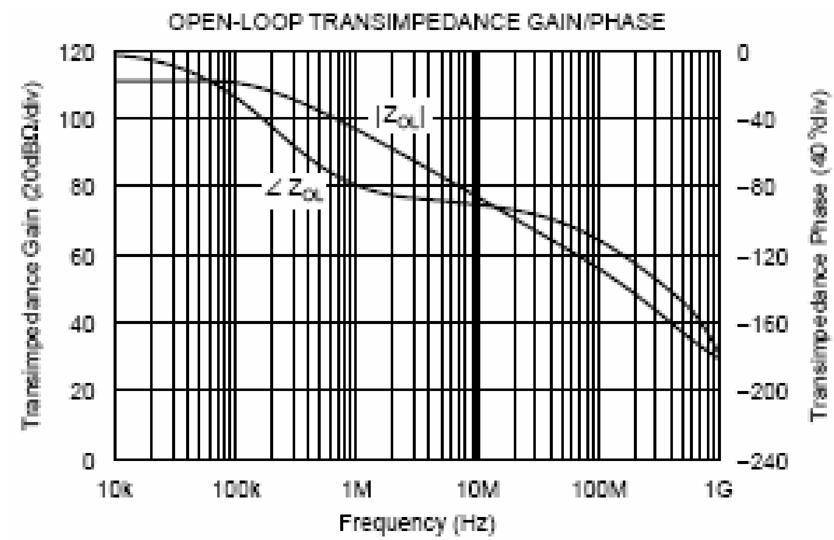
Refer to TI app. Note SLOA054 for details.

For this discussion, the FDA will be a subset of the VFB class of devices.

Comparing Voltage and Current Feedback Op Amps

- **Two parts on the same process, at the same quiescent power, will have pretty similar open loop gain curves for VFB and CFB devices – Compare the OPA690 (VFB) and the OPA691(CFB) below.**





OPA690 Voltage Feedback (VFB)

Dominant Pole at 80kHz

Gain of 2 (6dB) Loop Gain at 20Mhz is 14dB

OPA691 Current Feedback (CFB)

Dominant Pole at 200kHz

Gain of 2, Rf = 402ohms, Loop gain at 20Mhz is 16dB

The loop gain profile is just slightly higher over frequency for the CFB version due to the higher dominant pole location

Minimum Stable Gain for VFB Op Amps

- Classical Tradeoff's in selecting Voltage Feedback (VFB) Op Amps
  - Minimum Stable gain (primary IC circuit design variable) influences several key parameters.
    - Useable gain range
    - As minimum stable gain increases, input noise goes down and slew rate goes up.
  - Wideband, low gain, operation has been very difficult for VFB amplifiers. Newer parts, like the OPA690, use a high transconductance input stage that gives very high slew rate in a unity gain stable device – at the cost of higher input noise voltage

Selecting Current Feedback Op Amps

- Classical Tradeoff's in selecting Current Feedback (CFB) Op Amps
  - Although input voltage noise can be low, inverting input current noise is always much higher than VFB equivalents
  - Feedback element is constrained in its impedance range since it is the compensation element
  - Input bias currents are large and unmatched - limits achievable DC accuracy

Distortion Issues

- At lower frequencies, the lowest distortion will be given by voltage feedback amplifiers
  - We believe this is due to a linearity floor set by the error sensing point in the CFB topology. The CFB inverting input linearity sets a floor to distortion much higher than the best VFB designs. This is normally a 2nd harmonic term.
  - CFB will, however, give relatively constant distortion vs. Gain setting and hold better numbers to higher frequencies due to considerably more slew rate margin.

General Applications Comments

- Catalogue Amplifier products can be generally broken into drive channel applications or receiver channel applications
  - In Drivers, can usually find a DAC somewhere upstream
  - In Receivers, can usually find an ADC somewhere Downstream.
- While there are numerous good exceptions - in general -
  - Drivers often benefit from the current feedback topology – this is changing with the advent of 3GHz FDA's
    - Better Distortion to high frequencies (slew rate margin vs. supply current much higher)
  - Receivers often benefit from the voltage feedback topology.
    - Lower input noise and better DC precision if needed
- Each product data sheet includes applications examples suited to that product.

General Applications Comments

- Most applications can also be characterized from the signal handling side by being either -
  - Time Domain, Pulse oriented applications
    - Key specs. become slew rate, settling time, DC precision
  - Frequency Domain, Modulated Carrier applications
    - Key Specs., become harmonic distortion, Noise Floor,
- Almost never require both types of signals in the same design - except -
  - ARB output stages
  - Non-specific data capture boards (Converter EVM's)

High-Speed “Hot Parts” List – sorted by operating voltage and topology

Note 1.	The supply voltage is the total across the device - these are in approx. ascending order of performance in each block
Note 2.	All of these devices are >50MHz Bandwidth and are unity (or low) gain stable (except where noted NUGS - Non-Unity Gain Stable)
Note 3.	In most cases the single channel version is shown - often there is also multi-channel and/or versions with disable not shown here, but will be shown in the single data sheets
Note 4.	In some cases, there is only a dual or quad of a part and that is what is listed. If not specifically stated otherwise, each part # here is a single.

NEW PARTS IN RED		**OPERATING SUPPLY VOLTAGE <5.5V**		**OPERATING SUPPLY VOLTAGE RANGE FROM 4V --> 12V (approx.)**		**OPERATING SUPPLY SUPPLY RANGE FROM 10V --> 32V (approx)**
VOLTAGE FEEDBACK OP AMPS (VFB)	OPA356	CMOS, RR output	OPA830	RR Output, Low power, low cost	THS4051	Moderate Speed, Low cost
	OPA357	CMOS, RRIO	OPA820	Low Noise, Low power, Low cost	THS4081	Low power,
	THS4304	Unity Gain Stable ,1GHz	OPA2613	Dual, low noise, High Io, DSL Driver	THS4031	Low Noise,
			OPA690	High Slew Rate, low power	THS4011	Highest Speed +/-15V VFB
			OPA698	Fast Recovery Output Limiting	THS4631	JFET Input
			OPA656	JFET Input, excellent DC precision		
			OPA842	Low noise, low harmonic distortion		
			THS4271	Very low harmonic distortion		
			OPA847	Lowest Noise, Highest Bandwidth -NUGS		
CURRENT FEEDBACK OP AMPS (CFB)			OPA684	Very Low power, low BW vs. Gain variation	THS3110	Low power, moderate speed, high Io
			OPA691	Low Power, high output current	THS3120	Medium speed
			OPA694	Low power >500Mhz	THS6132	Dual, Class G, DSL Driver
			OPA2674	Dual, with power control, DSL Driver, High Io	THS6182	Dual, Class AB, DSL Driver
			OPA695	Very wideband, high Intercept	THS6184	Quad, Class AB DSL Driver
					THS3091	Highest Speed +/-15V CFB
FULLY DIFFERENTIAL AMPLIFIERS (FDA)	THS4509	G>+2, Very wideband, very low distortion	THS4502	Wideband, Centered Input Range	THS4130	Audio speed, very low noise & distortion
	THS4508	G>+2, Very wideband, very low distortion				
		Input Voltage Range Includes Negative Supply				
	THS4511	Unity Gain Stable, Very wideband, very low distortion				
		Input Voltage Range Includes Negative Supply				
	THS4513	Unity Gain Stable, Very wideband, very low distortion				
	THS4520	Unity Gain Stable, Wideband, RRO, low distortion				
FIXED GAIN	THS4302	2.5GHz, Gain of 5V/V	OPA832	RR output Gain of 2 Video Line Driver		
	THS7303	Triple 2X1 Video Mux/driver with selectable filter	OPA693	>1.2GHz Gain of 2 Video Line Driver		
	THS7313	Triple 2X1 Video Mux/driver with selectable filter	BUF602	>1.4GHz Unity Gain Buffer with MidRef.		
	THS7353	Triple 2X1 Video Mux/driver with selectable filter				
	THS7327	Triple RGBHV Video Buffer w/I2C Control				
ADJUSTABLE GAIN	THS7530	Differential I/O, 300MHz BW, 35dB Gain adjust	VCA810	+/-40dB Range, 30MHz BW		

High-Speed Voltage Feedback Speed Comparisons

- Strong trend in recent years for competitive products to use Gain of 1 Bandwidth for promotional purposes.

- Where True Gain Bandwidth Product is >100MHz, several parasitic effects strongly influence this Gain of +1 SSBW - including -

  – Feedback pole formed by non-zero feedback resistor with the parasitic inverting input capacitance

  – Something <60deg. Phase margin at unity gain. This will always extend Bandwidth considerably - direct short as a feedback puts inverting input C onto output pin, almost always dropping phase margin.

  – Straight feedthru for >1Ghz and small packages.

High-Speed Voltage Feedback Speed Comparisons

- Where Gain of +1 BW >200Mhz for unity gain stable voltage feedback op amps, that bandwidth is often much > than the gain bandwidth product.

- For Example, the following RR output Single +5V supply parts illustrate this effect -

2nd & 3rd Generation PARTS	Vs = +5V AC Specifications –> Company	Gain Bandwidth Product (MHz) Typ	Slew Rate (V/us) Typ	Nominal Gain for Specs. (V/V)	Bandwidth at Nominal Gain ((MHz) typ
AD8061	ADI	270	800	1	300
LT1806	Linear Tech	100	140	1	325
EL5144	Elantec/Intersil	60	150	1	60
EL8102	Elantec/Intersil	180	600	1	500
MAX4212	Maxim	110	600	1	300
MAX4414	Maxim	180	200	1	400

High-Speed Voltage Feedback Speed Comparisons

- One good check for the usefulness of a Bandwidth number is to see if it correctly predicts the non-slew limited rise time.
- While $Tr = 0.35/F_{-3dB}$ is strictly only correct for the 10% to 90% rise time of a single pole response, it is also a good approximation for a well controlled 2nd order Butterworth frequency response.
- For example, the LT1806 shows 325Mhz SSBW on a +5V supply at Av = +1. This would imply a 1.1nsec rise time - deep in the plots, we find a scope photo showing 5nsec rise time - implying a 70MHz BW. This is much closer to the 100Mhz Gain Bandwidth product - this shows the 325Mhz to be little more than specmanship.

High-Speed Voltage Feedback Speed Comparisons

- For high speed voltage feedback parts, a gain of +1 bandwidth is impressive for promotional purposes but rarely useful for true performance comparisons. True Gain Bandwidth Product (GBP) is much more technically useful (and hard to hide). An easy way to get this real number out of the various data sheets is to look for the 40dB open loop gain frequency in the open loop plot, then multiply that frequency times 100.

Understanding Noise & Distortion Tradeoff's Between Op Amp Types and Application Topologies

- Loop Gain and other contributors to linearity
- Differential circuits and why
- Distortion dependence on external conditions
  - Voltage Feedback, Current Feedback, FDA's
- Noise models
  - Differences between amplifier types
- Example solutions and conclusions

Theoretical Determinants of Harmonic Distortion

- An Ideal amplifier would take an input spectrum and pass it on to the output with the same gain for each Fourier component and no added power in the spectrum.
  - We have not quite achieved that ideal, hence new amplifiers and techniques moving closer to this are still being introduced.
- Output spectral purity has many levels of consideration – the better you aspire to, the more of these levels you will have to consider.
- The first level is that, for a high open loop gain type of part, the closed loop output linearity will be the open loop linearity intrinsic to the output stage corrected by the loop gain at the fundamental frequency.
  - Low loop gain devices, like most RF amplifiers, achieve high linearity by making the signal power a very small part of the quiescent power. Hence you will see >80dBc SFDR type devices to very high frequencies using > 1.5W quiescent power

Distortion Analysis using Negative Feedback with Distortion modeled only as an Output Stage Distortion

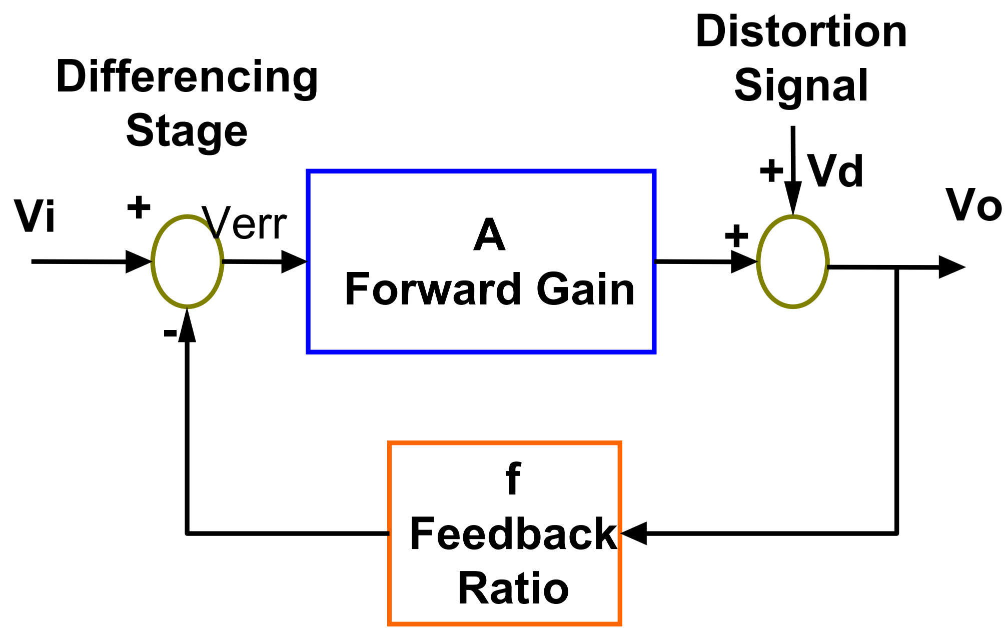
$$V_o = A \cdot V_{err} + V_d$$

$$V_{err} = V_i - f \cdot V_o$$

$$V_o = A \cdot V_i - A \cdot f \cdot V_o + V_d$$

$$(1 + A \cdot f) V_o = A \cdot V_i + V_d$$

$$V_o = A \frac{V_i}{(1 + A \cdot f)} + \frac{V_d}{(1 + A \cdot f)}$$



where Af ≡ Loop Gain.   Output stage non-linearities are corrected by loop gain.

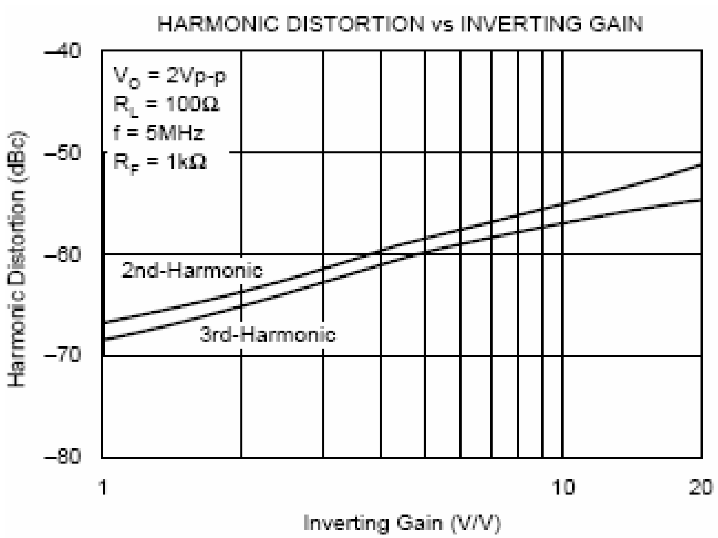
Paths to Improved Distortion Suggested by the Control Theory Model

- At a first level, output linearity is the open loop distortion of the output stage, corrected by the loop gain. So, improving either of these will improve distortion.

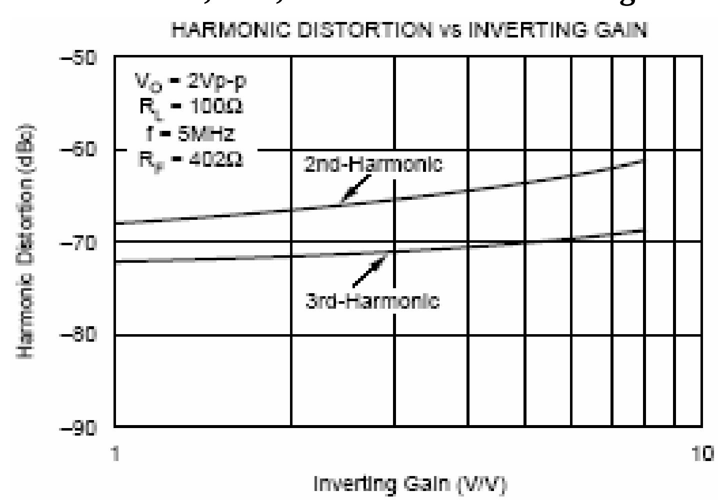
- One key conclusion from the Loop Gain comparison between VFB and CFB is that the CFB holds a more constant loop gain over signal gain (Gain Bandwidth Independence). This should hold more constant distortion to higher gains than VFB.

- Comparing those plots for the VFB OPA690 and CFB OPA691 -

OPA690, VFB, HD linear with log gain



OPA691,CFB, HD more constant over gain

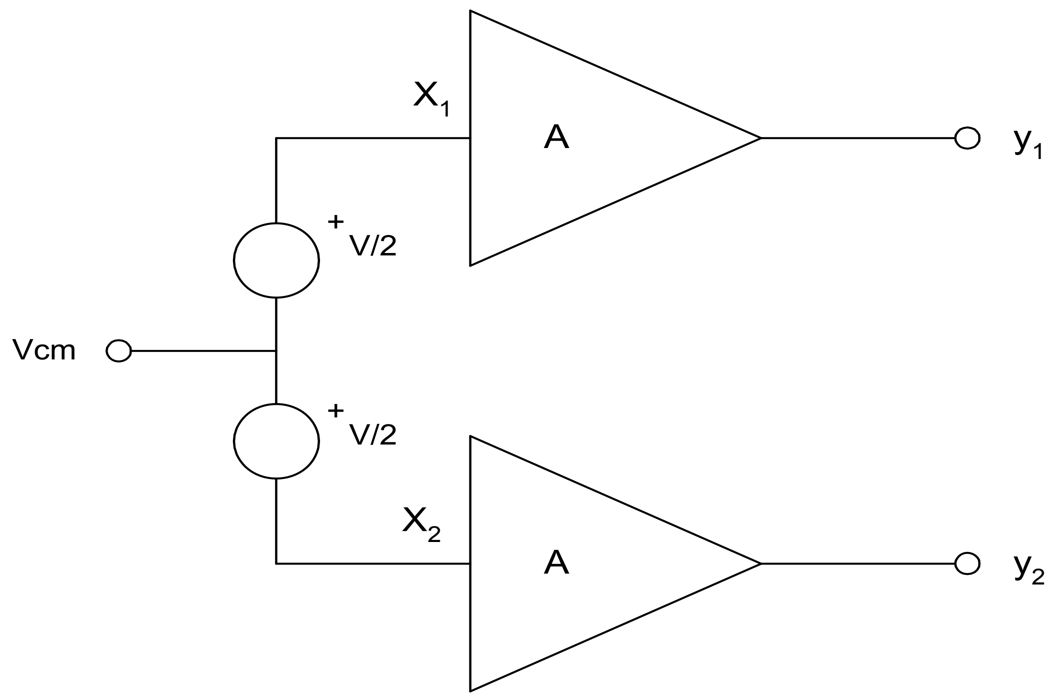


Continued Improvement in SFDR??

- The 2nd Harmonic typically does not follow this theory exactly. There are other, external, effects that come into play on the even order terms for a single ended amplifier.
- Even order distortion can be visualized as ½ cycle imbalance on a sine wave. Odd order distortion can be visualized as curvature through zero on a sine wave or a very balanced deviation on each ½ cycle.
- Anything that will take a purely balanced output sine wave and introduce perturbation on one ½ cycle but not the other, will be generating even order distortion terms.
- Suspects include –
  - Mutual coupling in the negative supply pin to the non-inverting input.
  - Slightly imbalanced ground return currents getting into the input signal paths.
  - Imbalanced supply decoupling impedance.
- One of the best ways to eliminate this issue is to run the signal path differentially – but exactly why does that work??

Why is it that a Differential Configuration Suppresses the Second Harmonic??

Differential even order harmonic cancellation



Let both gain elements A have the same polynomial approximation to a transfer function

Why is it that differential configurations suppress the second harmonic??

$$y = A_o + A_1 X + A_2 X^2 + A_3 X^3$$

$$X_1 = V/2$$

$$\&$$

$$X_2 = -V/2$$

$$y_1 = A_o + A_1 \left(V/2\right) + A_2 \left(V/2\right)^2 + A_3 \left(V/2\right)^3$$

$$y_2 = A_o - A_1 \left(V/2\right) + A_2 \left(V/2\right)^2 - A_3 \left(V/2\right)^3$$

$$then$$

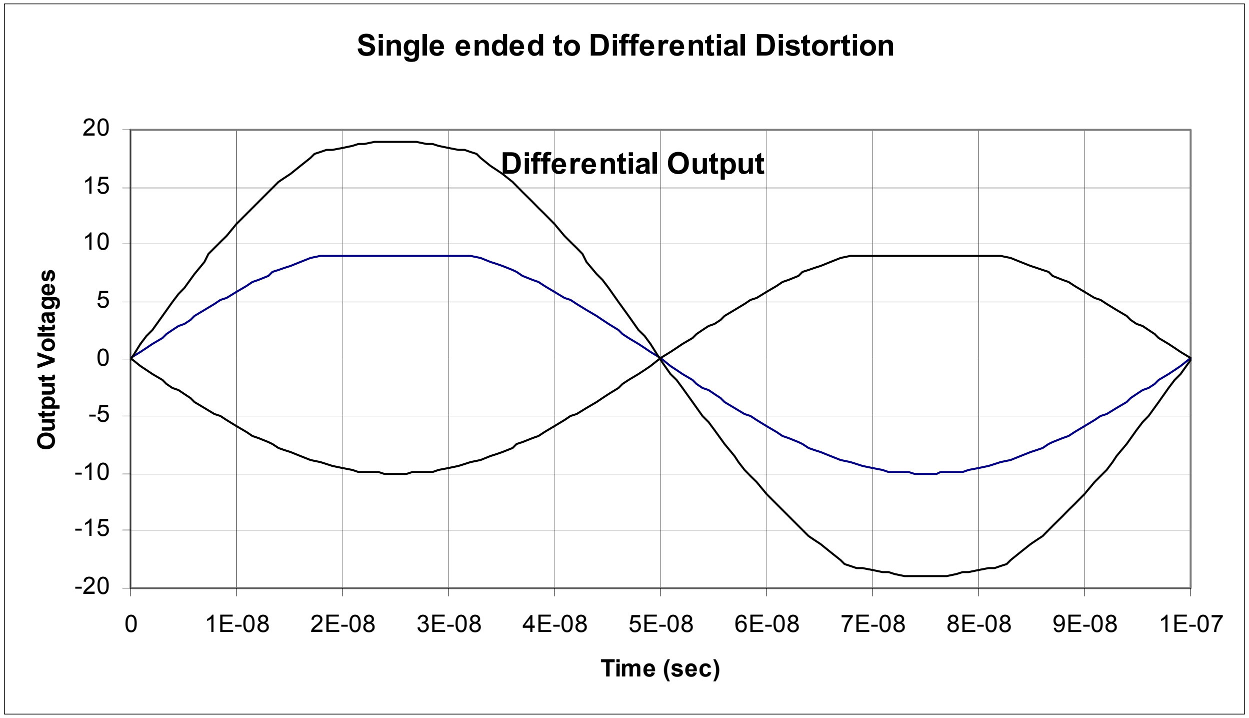
$$\left(y_1 - y_2\right) = 0 + A_1 V + 2 A_3 \left(V/2\right)^3$$

$$= A_1 V + \frac{A_3}{4} V^3$$

- Substituting in the two halves of differential input signal, getting to each output signal, then taking the difference - shows we are theoretically only left with the desired linear signal and the 3rd order term. Even if the A2 coefficient is not exactly matched between the two amplifiers, it is their difference that ends up being the gain for this 2nd order non-linearity at the output. We also see a reduction in the 3rd order coefficient - arising from only applying 1/2 of the input through each channel.

Single-Ended Even-Order Terms become Odds in the Differential Configuration

- In the time domain, this effect can be seen by producing a clipped waveform for the two outputs, then taking the difference. The individual outputs would have a very high even order harmonic content, while the differential signal will still be distorted, but will give rise to only odd harmonics since the clipping is now symmetric on each 1/2 cycle of the sinusoid.



Single-Ended vs. Differential SFDR

- To illustrate the power of differential designs in suppressing HD2, the plots on the next slide show the HD2 and HD3 for a low noise, low distortion VFB dual amplifier in both single ended and differential configurations. The test conditions give the same loop gain, but the differential test had a 35ohm load to each output while the single ended was a 100ohm – which raised the HD3 quite a bit.

- The single ended performance is HD2 dominated, while running the same part differentially, pushes the 2nd down to be on the order of the HD3 number.

Single-Ended vs. Differential SFDR

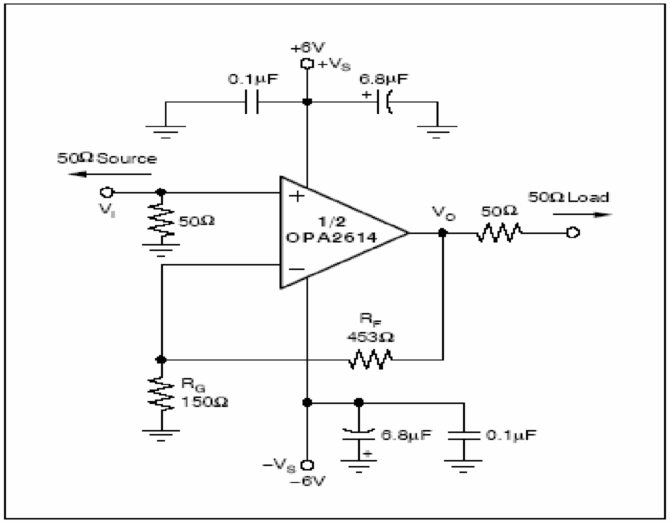
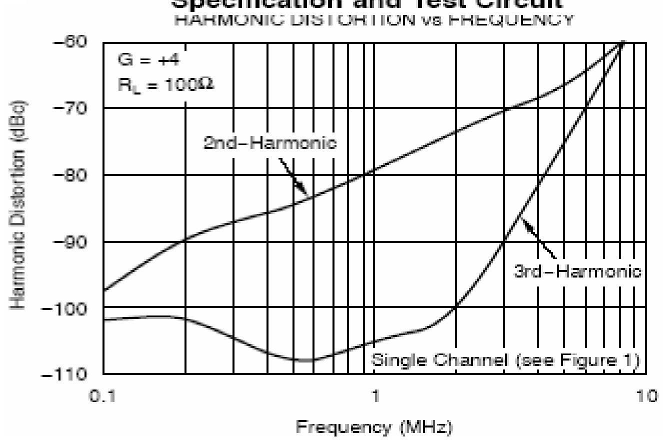


Figure 1. DC-Coupled, G = +4, Bipolar Supply, Specification and Test Circuit



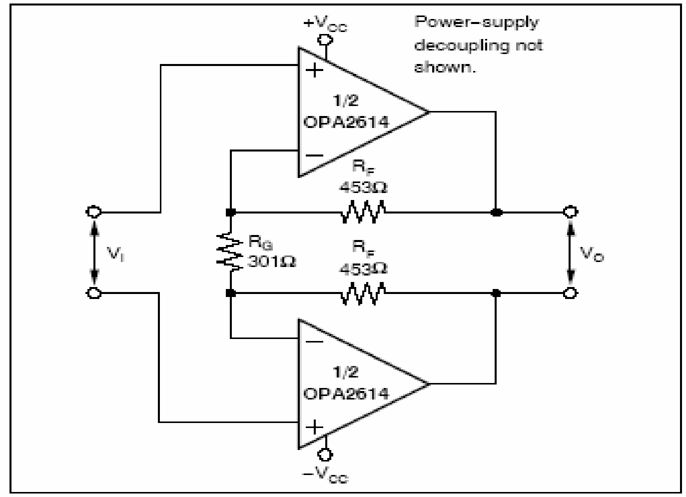
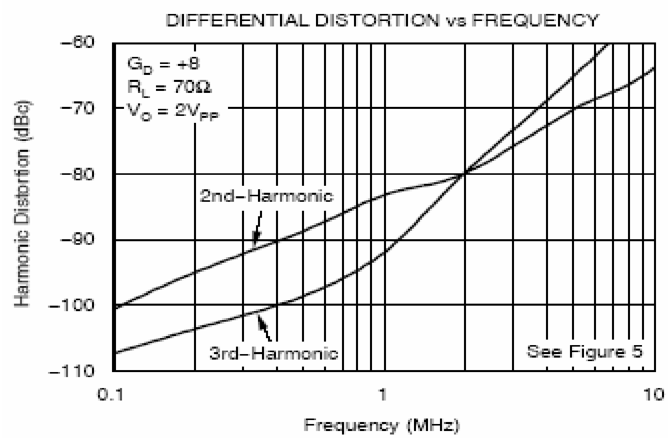


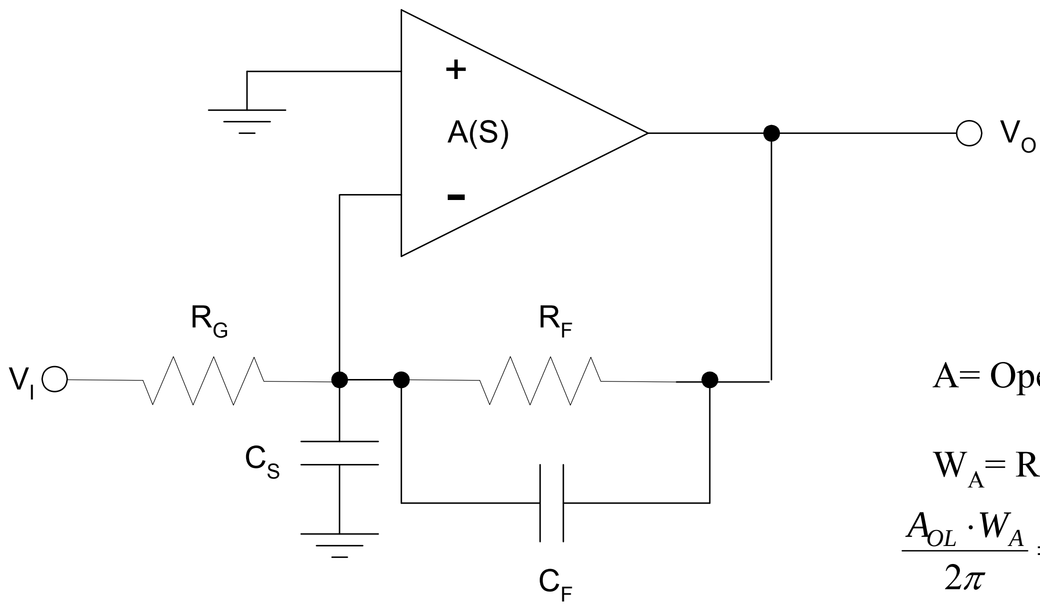
Figure 5. Noninverting Differential I/O Amplifier



Key Elements to Understanding and Improving Distortion

- External conditions that will influence distortion
  - Required Output Voltage and Current as a portion of the quiescent power and design the output stage
    - This is including loading and supply voltage effects as well.
    - Adding a higher standing current in the output stage will often lower distortion with no effect on noise. This Class A current can pick up about 10dB on the 3rd.
  - Loop gain – use a VFB designed for the desired gain setting or, at higher gains use a CFB device.
  - Frequency – since loop gain changes with frequency, a fixed output stage non-lineari will give a changing distortion over frequency.
  - Layout and Supply Decoupling
    - This is covered in detail in TI – app. Note SBAA113
- To improve distortion, we can perhaps shape the loop gain over frequency to get enhance low frequency distortion while holding a stable response.

New Compensation Technique for Non-Unity Stable Voltage Feedback Op Amps



$$A(s) = \frac{A_{OL} \cdot W_A}{s + W_A}$$

A= Open Loop Gain

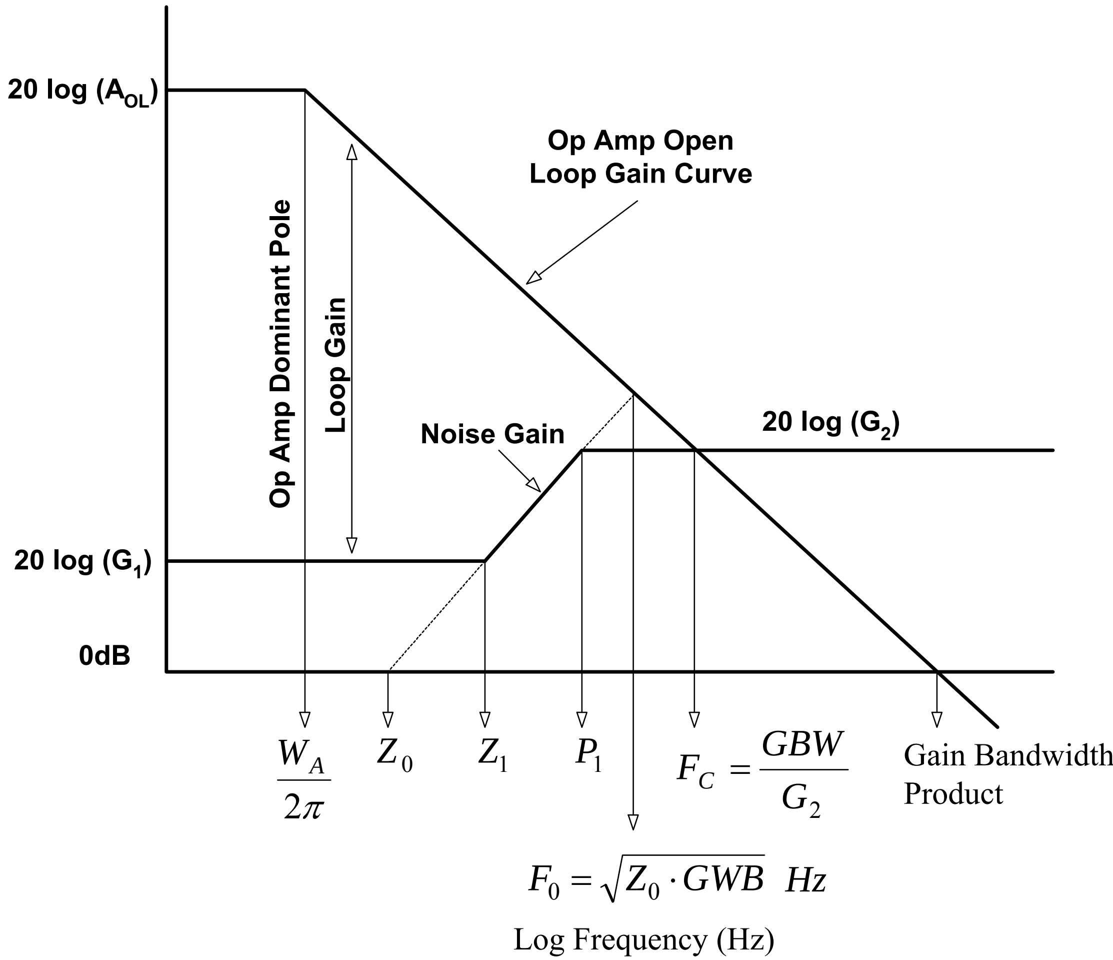
W_A= Radian Dominant Pole

$$\frac{A_{OL} \cdot W_A}{2\pi} = \text{ Gain Bandwidth Product (GBW) Hz}$$

This is an inverting mode circuit that will shape the noise gain to transition from the resistive divider at low frequencies to a capacitive divider at loop gain x-over. It has proven very effective at improving low frequency distortion where very non-unity gain stable VFB devices can be applied at low gains with excellent results.

This circuit and its performance is developed in detail in “Unique Compensation Technique Tames High Bandwidth Voltage Feedback Op Amps”, EDN, August 1st, 1997, pp133-150

Bode Analysis for the New Compensation Circuit



$$G_1 = 1 + \frac{R_F}{R_G}$$

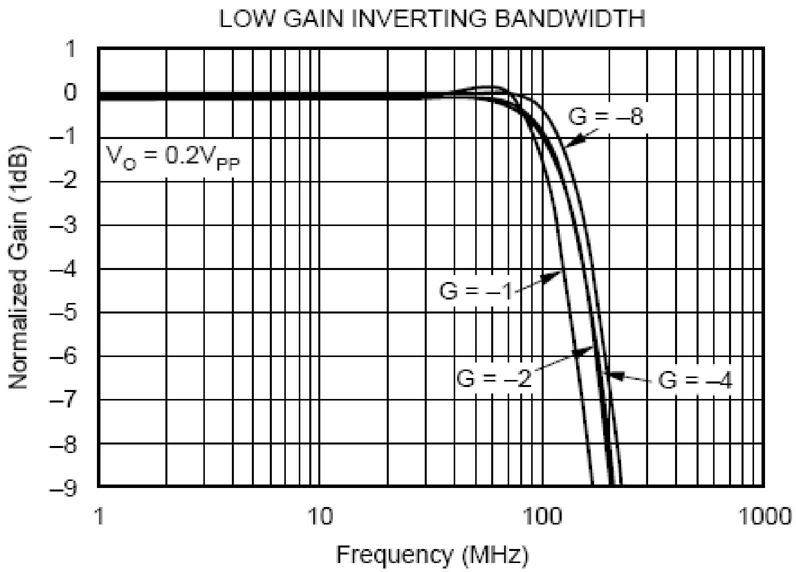
$$G_2 = 1 + \frac{C_S}{C_F}$$

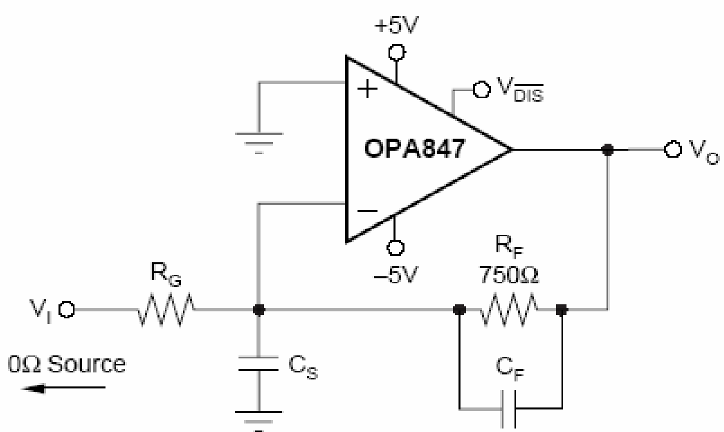
$$Z_0 = \frac{1}{R_F\left(C_F + C_S\right)2\pi}$$

$$Z_1 = \frac{1}{\left(R_F \parallel R_G\right)\left(C_F + C_S\right)2\pi} = G_1 \cdot Z_0$$

$$P_1 = \frac{1}{R_F \cdot C_F \cdot 2\pi} = G_2 \cdot Z_0$$

Application of Inverting External Compensation to 3.9GHz GBP VFB Op Amp





For each of these plots the Rg was changed to step the gain up and Cs, Cf adjusted to get a Butterworth response. Each of these shows about 140Mhz BW but hiding inside the response is exceptional loop gain below Z1 in the Bode plot. This gives extremely low distortion for this circuit below 10Mhz.

Without these comp. caps, the OPA847 is specified as minimum stable gain of 14V/V.

There is an analogous technique for CFB devices

Input and Output Noise Calculations

- 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.

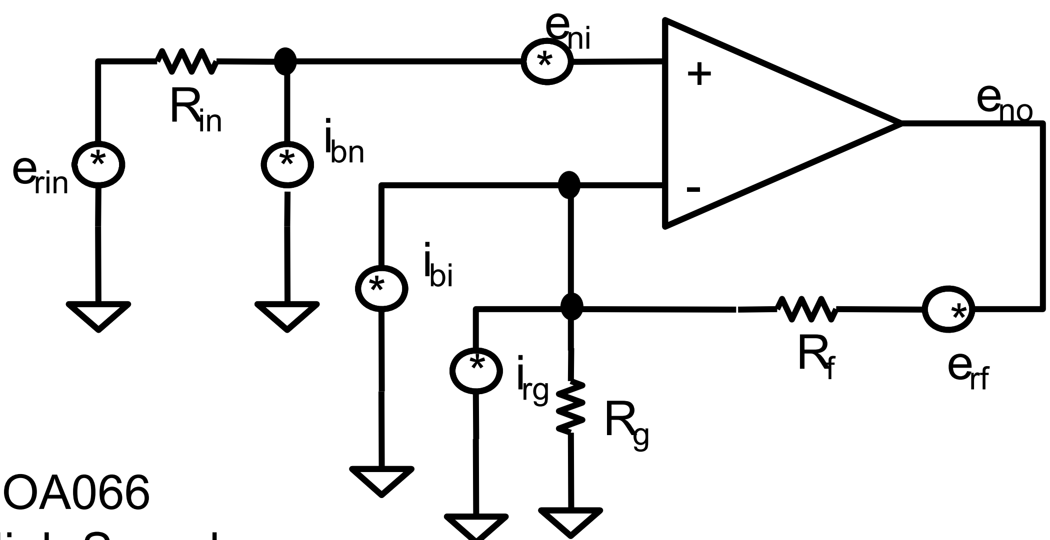
Noise Analysis for any Op Amp

$$e_{no}^2 = \left[(e_{rin}NG)^2 + (i_{bn}R_{in}NG)^2 + ((e_{ni}NG)^2 + (i_{bi}R_f)^2 + (i_{rg}R_f)^2 + e_{rf}^2\right]$$

$$e_{no}^2 = \left[e_{ni}^2 + (i_{bn}R_{in})^2 + 4kTR_{in}\right]NG^2 + \left[(i_{bi}R_f)^2 + (4kTR_f)NG\right]$$

4kT=16.4E-21 J at T = 298 °C

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



See TI App. Note SBOA066 “Noise Analysis for High Speed Op Amps” for more detail.

Non-Inverting Input Referred Total Noise

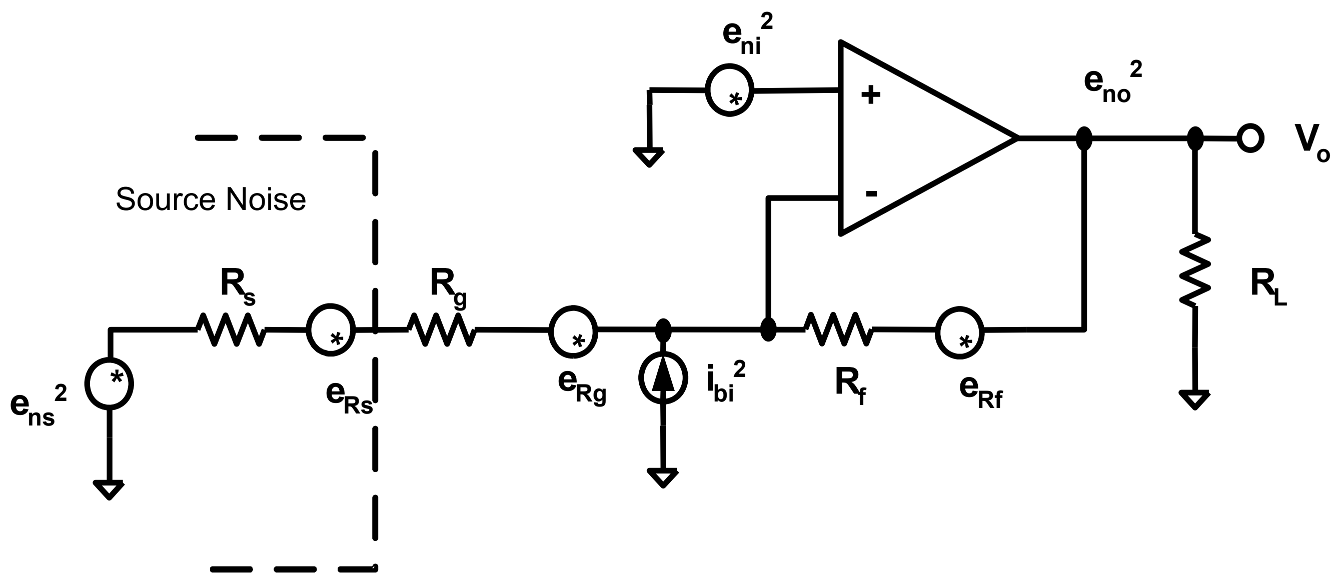
- Dividing the total output noise by the non-inverting gain will mathematically develop an input noise that, if this term were placed at the input of a noiseless amplifier of the same gain - you would get the same total output noise.

$$e_{no} = \sqrt{e_{ni}^2 + \left(i_{bn} R_s\right)^2 + 4kTR_s + \left(\frac{i_{bi} R_f}{NG}\right)^2 + \frac{4kTR_f}{NG}}$$

Where NG = 1 + Rf/Rg = Noise Gain

This shows that, as gain increases, the non-inverting input referred noise approaches just those terms present at the non-inverting input. Conversely, at low gains, the apparent input noise can be dominated by the terms at inverting input - this is commonly the case for current feedback op amps.

Inverting Amplifier Noise Model with Input Matching



$$e_{no} = \sqrt{e_{ni}^2 \cdot NG^2 + 4kT\left(\left(R_s + R_g\right)\|R_f\right) + \left(i_{bi} R_f\right)^2 + e_{ns}^2\left(NG - 1\right)^2}$$

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

$$4kT = 16.0 \times 1E-21J \quad \text{For T = 290K}$$

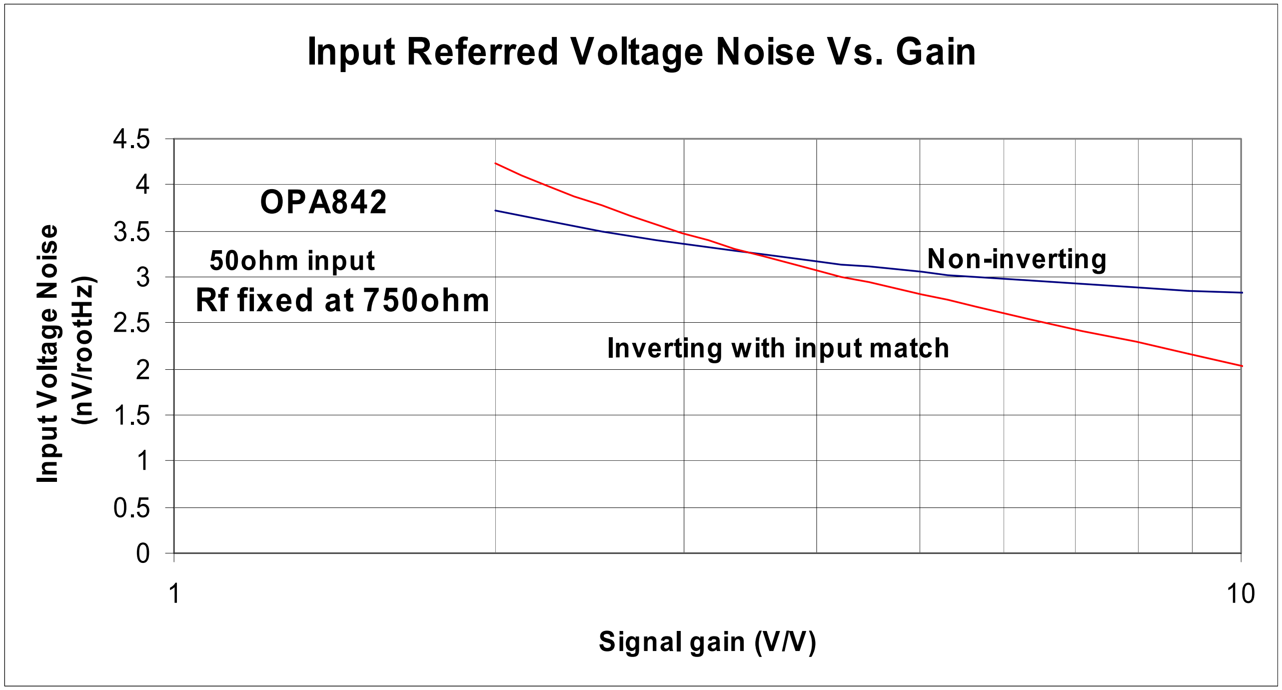
Inverting Input Referred Total Noise

- Dividing the total output noise by the inverting gain will mathematically develop an input noise that, if this term were placed at the input of a noiseless amplifier of the same gain - you would get the same total output noise.

- This is particularly useful for low input voltage noise parts when Rg = Rs. Total input referred noise in this case can be very low. (The VFB OPA842 and OPA847 and CFB OPA695 are good examples).

Input Referred Voltage Feedback Noise vs. Gain Setting

•The Inverting mode becomes lower noise when the equivalent gain from the En term at the non-inverting input to the inverting input signal point becomes <1. This applies when a finite source impedance is matched to the input impedance.

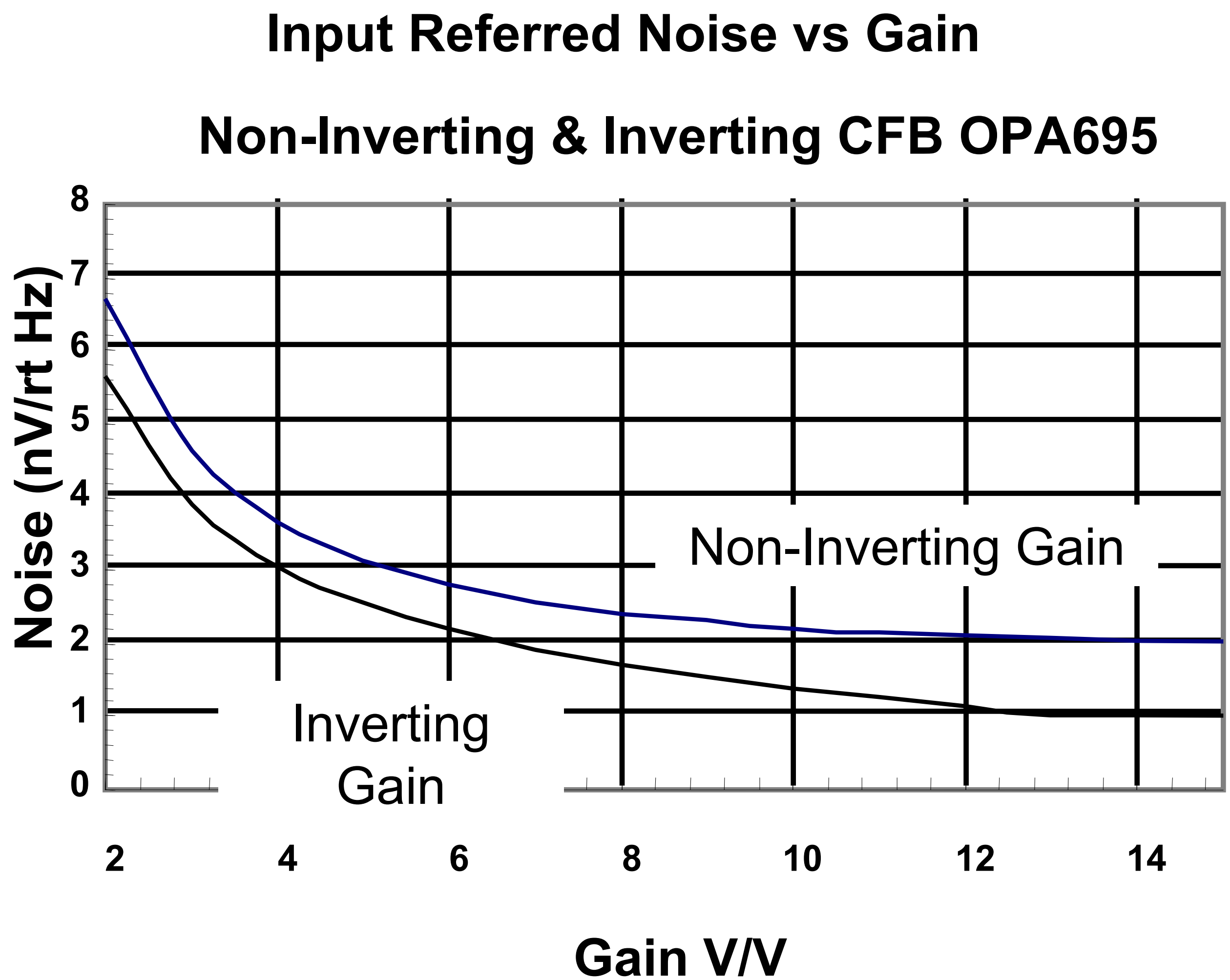


Input Referred Current Feedback Noise vs. Gain Setting

- CFB Amps at high gains can provide very low input referred noise

- Low Noise CFB amps in the Inverting mode will have even lower noise then non-inverting configuration

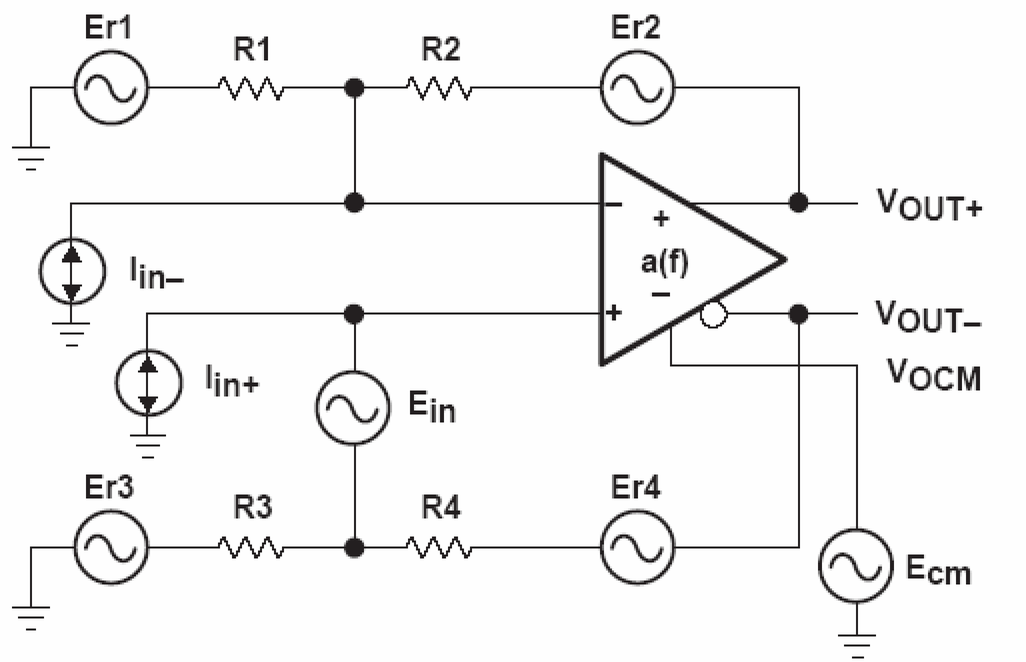
- Big increase at the lower gains is the effect of the higher inverting bias current noise times the feedback R.



The Feedback R is adjusted here to get maximum flat bandwidth at each gain.

FDA Noise Model

•FDA's are essentially voltage feedback op amps – so have a very similar total differential output noise expression. The one added term is the common mode noise – this will get to the output as common mode normally – except when the feedback ratios are unmatched, when a conversion from common mode to differential will occur.



•If the feedback ratios, β1 & β2 are equal, this simplifies enormously to an expression very similar to the op amp equation.

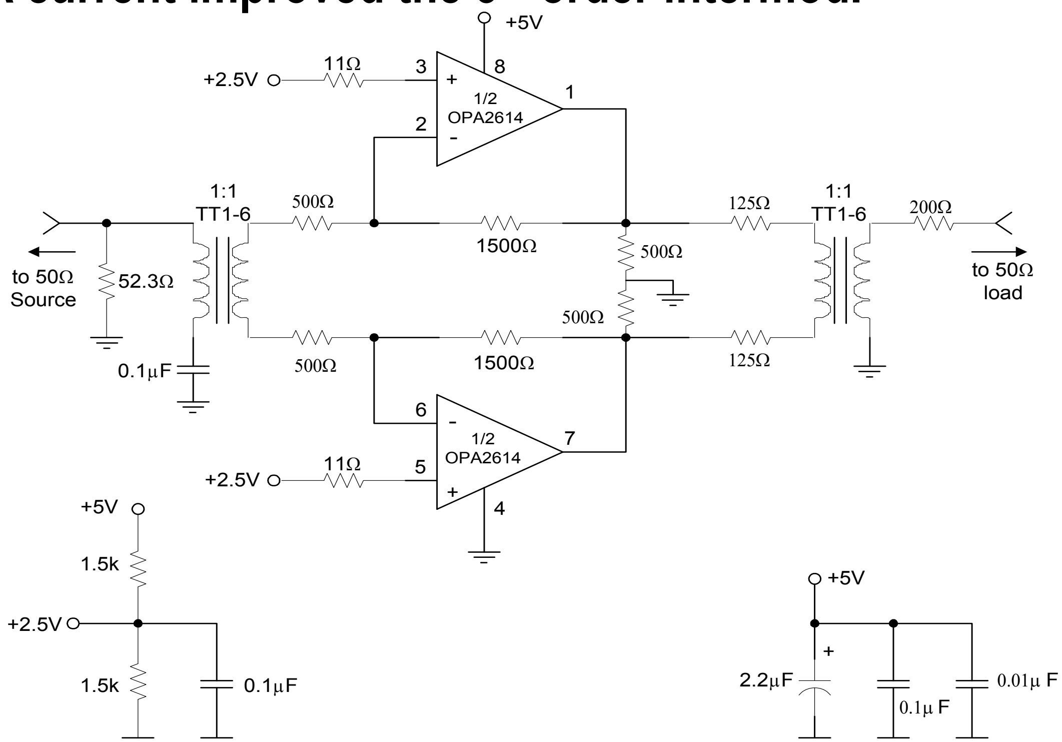
$$Eod = \sqrt{\frac{(2Ein)^2 + (2Iin \times Req1)^2 + (2Iin \times Req2)^2 + \left(2Ecm\left(\beta_1 - \beta_2\right)\right)^2 + \left(2(Er1)\left(1-\beta_2\right)\right)^2 + \left(2(Er3)\left(1-\beta_1\right)\right)^2}{\left(\beta_1 + \beta_2\right)^2} + Er2^2 + Er4^2}$$

Summary Suggestions to get the Lowest Noise and Distortion

- Differential signal paths allow much lower distortion versus quiescent power than single ended signal paths.
  - Making the last stage of gain before the converter a differential path will be moving in the direction of better SFDR. If the signal path is intrinsically single ended, make the conversion to differential at a lower power (voltage) level then use the last stage interface to get the remaining gain in a differential structure.
- At higher gains, where an input match is desired, the inverting topology can offer lower input referred voltage noise – this arises due the effective attenuation of the amplifiers voltage noise term when referred to the inverting input.
- At lower frequencies, VFB will probably get to the lowest distortion vs. Iq. At higher frequencies, the CFB has been used, but emerging high slew rate FDA's are also doing very well in this application.

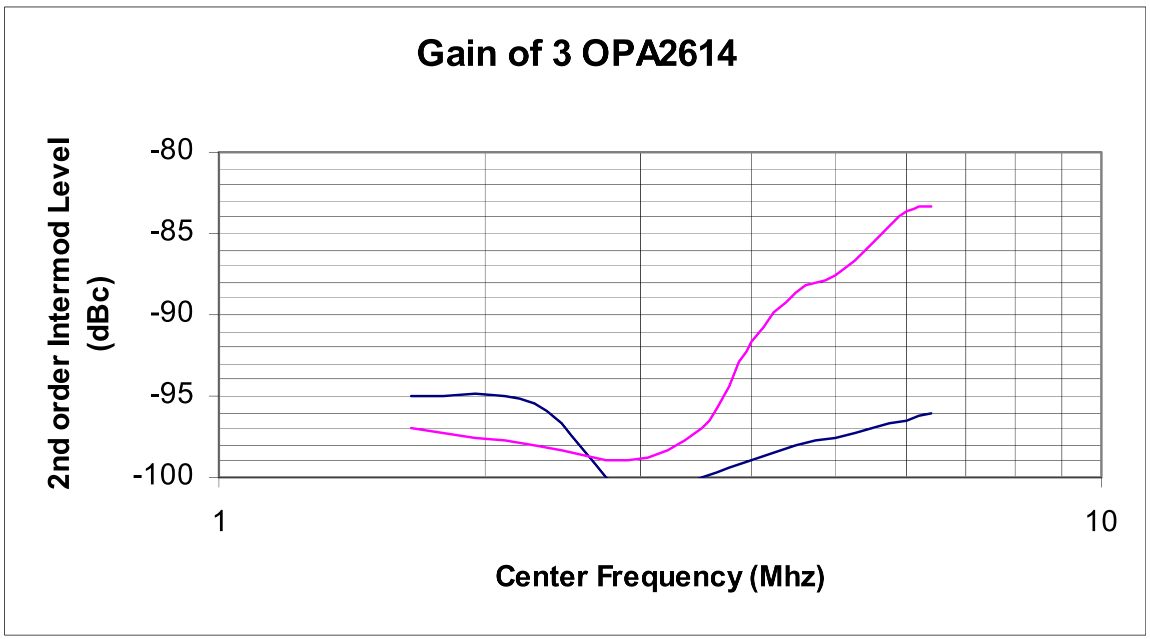
Example Design #1

Here – the input match was not done in the gain resistors – the circuit was eventually intended to show 1kohm differential load to the two outputs of a mixer. The 500ohm to ground on the outputs increased the supply current by adding a 2.5V/500Ω = 5mA in each output stage or another 10mA total – this class A current improved the 3rd order intermod.



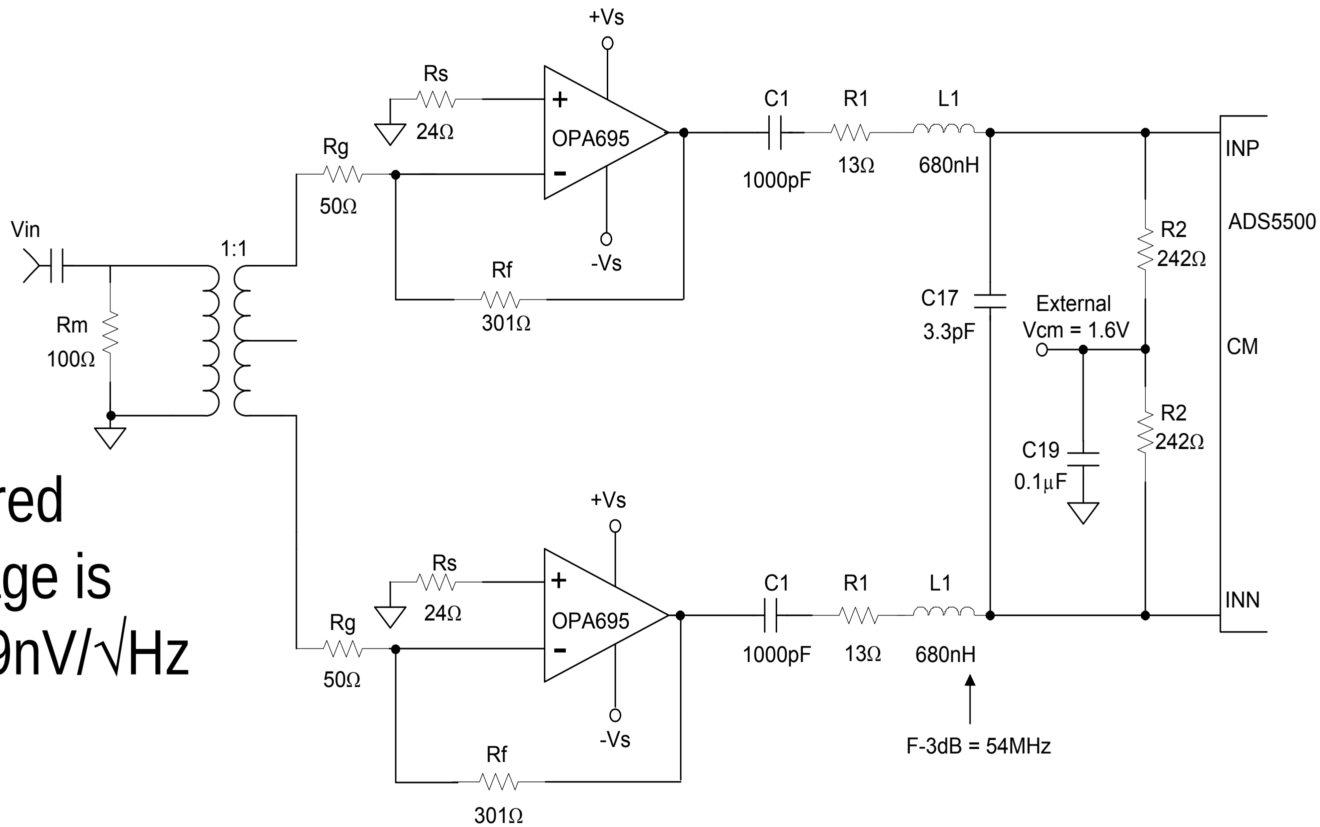
Example Designs

This first example needed very low noise to low frequencies (low 1/f corner) , single +5V operation, moderate gain and <-85dBc SFDR to 5Mhz for 2 tones at 2Vpp total envelope. The test circuit showed the differential source is emulated with a transformer and the output differential signal is converted to single ended to measure through another transformer. Neither transformer would have been used in the actual application. The lower trace is the 2-tone, even order intermod while the higher one is 3rd order. This dual uses 10.5mA on +5V along with another 10mA of output stage class A current.



Example Design #2

1st Nyquist zone design for low frequency through 40MHz with 122MSPS clock rate

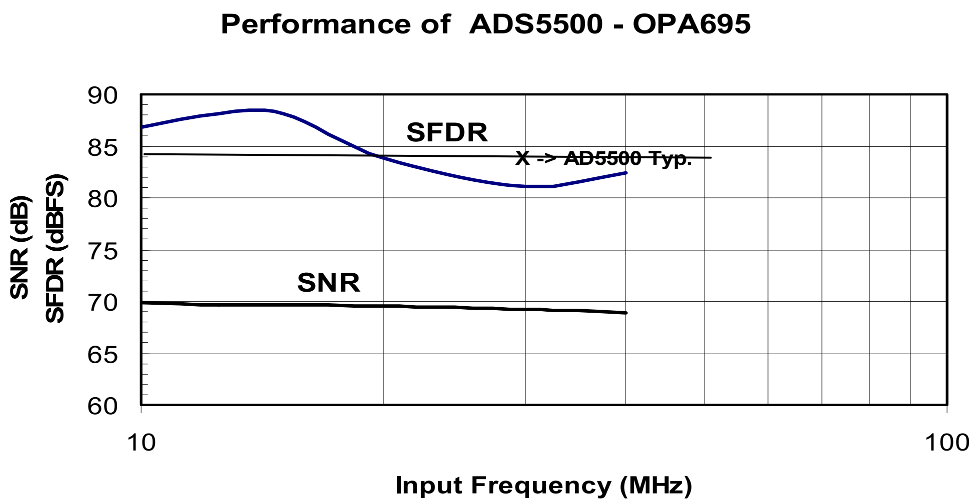


Input referred noise voltage is approx. 2.9nV/√Hz

This 2nd order RLC filter design is described in "RLC Filter Design for ADC Interface Applications" SBAA108A

Example Design #2

This 2nd example was similar to #1 but looking to achieve >80dB SFDR for an amplifier/converter combination through 40MHz at moderate gains (6V/V). Here a current feedback device was used to get good noise to high frequencies and better slew rate margin for the desired 2Vpp output signal. A 2nd order low pass at the output controlled the noise power bandwidth to hold minimal SNR degradation. This is using a 14-bit, 125MSPS converter.

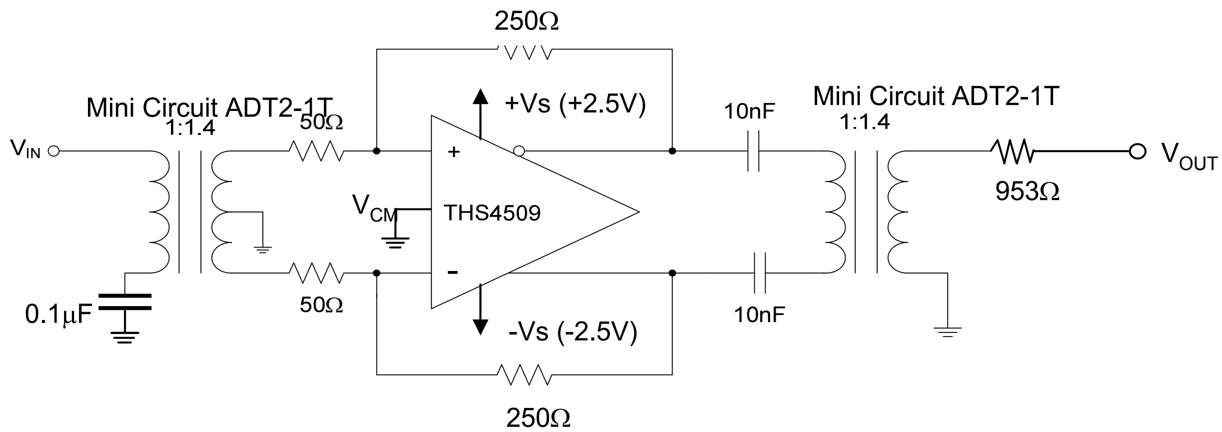


The ADS5500 has SNR = 70.5dBFS

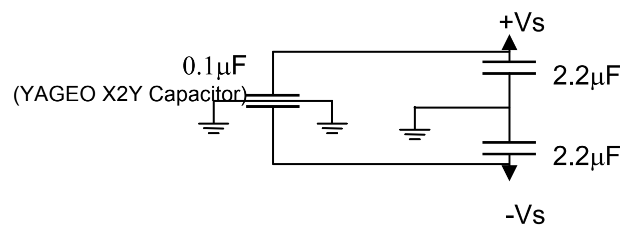
This circuit, layout, and performance is described in TI User Guide, SBOU028.

Example Design #3

IF interface application intended for narrowband undersampling.



Input noise figure
approx. 8.2dB

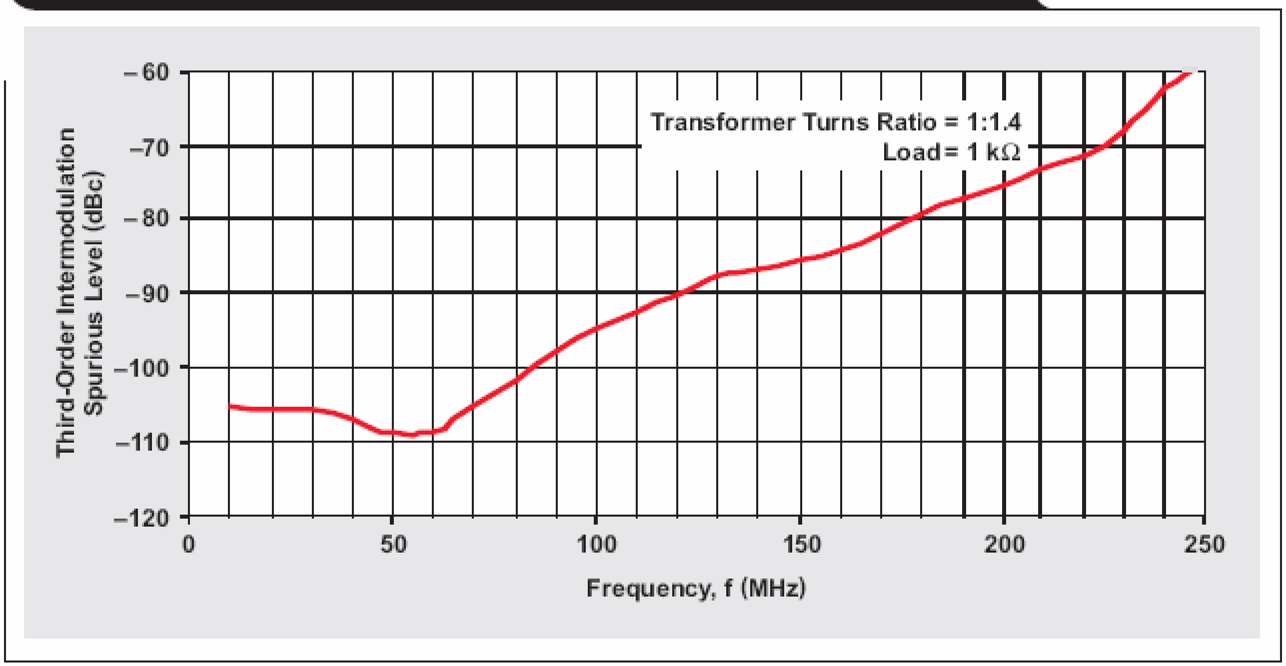


This circuit described in TI AAJ article “Low-power, high intercept interface to the ADS5424, 105MSPS converter for undersampling applications.” SLYT223

Example Design #3

Here the measured 3rd order intermodulation spurs for a 2Vpp output envelope (each tone 1Vpp) swept over frequency. This is a plot of how far below each carrier power level the spurious are for this THS4509 implementation.

Figure 10. Measured third-order intermodulation spurious signal level



Conclusions/Questions?

- **Most VFB devices are low gain stable and can give the lowest noise and distortion at low gains and frequencies. Non-inverting differential I/O stages work well but inverting will give lower noise if higher gains are needed. For moderate performance targets, all CFB devices are low gain stable and do well to very high output powers.**

- **CFB devices at higher gains, and particularly inverting, are probably lower noise and can deliver a lower distortion to higher gains. Inverting differential I/O configurations are the best for HD2 suppression.**

- **FDA devices at low gains can push the frequency envelope higher for very low distortion. They also provide an easy way to get DC coupled single ended to differential conversion with a common mode level shift. Should carefully consider matching the feedback ratios over frequency for best results.**

Conclusions

- Most VFB devices are low gain stable and can give the lowest noise and distortion at low gains and frequencies. Non-inverting differential I/O stages work pretty good here. For moderate performance targets, all CFB devices are low gain stable and do well to very high output powers.

- CFB devices at higher gains, and particularly inverting, are probably lower noise and can deliver a lower distortion to higher gains. Inverting differential I/O are the best for HD2 suppression.

- FDA devices at low gains can push the frequency envelope up for very low distortion. Also provide an easy way to get DC coupled single ended to differential conversion with a common mode level shift. Should carefully consider matching the feedback ratios over frequency for best results.