LINEAR INTEGRATED CIRCUITS

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Current feedback amplifier

- *Current feedback* refers to any closed-loop configuration in which the error signal used for feedback is in the form of a current. A current feedback op amp responds to an error current at one of its input terminals, rather than an error voltage, and produces a corresponding output voltage
- The transfer function of a *transimpedance amplifier* is expressed as a voltage output with respect to a current input
- the open-loop "gain", v_O/i_{IN}, is expressed in ohms

Summary of points in current feedback op amps

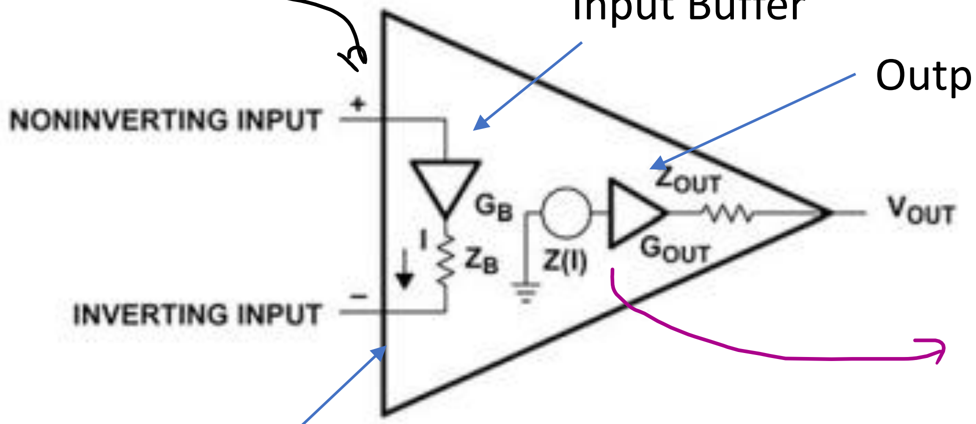
- Non inverting and Inverting gain circuits use the same formula for the gain that is $-R_F/R_G$ and $1+R_F/R_G$
- Use R_F as recommended by the data sheet, R_G can be as per the gain
- Use noninverting circuit, otherwise it will load source
- Never put capacitance across feedback resistor
- If only DC gain required, preferably use voltage feedback
- Current feedback op amps are choice for high speed and high current requirements
- For filters, voltage feedback op amp is preferred
- Current feedback op amps are best for high speed and high current circuits

Unit 3 Current feedback amplifier model

High impedance here

Input Buffer

Output Buffer(neglected for analysis)



Low impedance

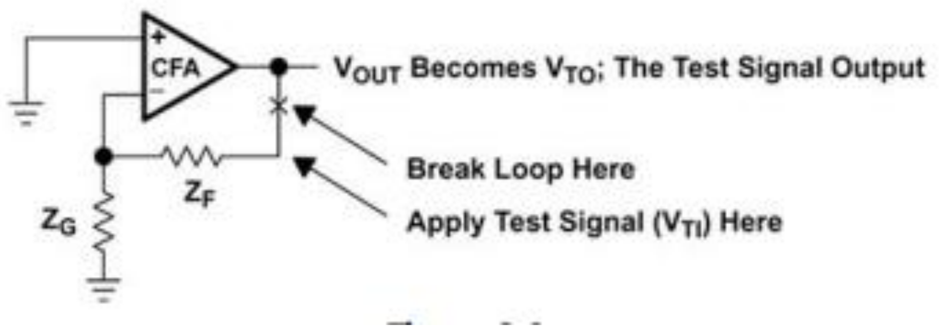
current controlled voltage device

Figure 9.1
Current-feedback amplifier model.

Low impedance here

Model

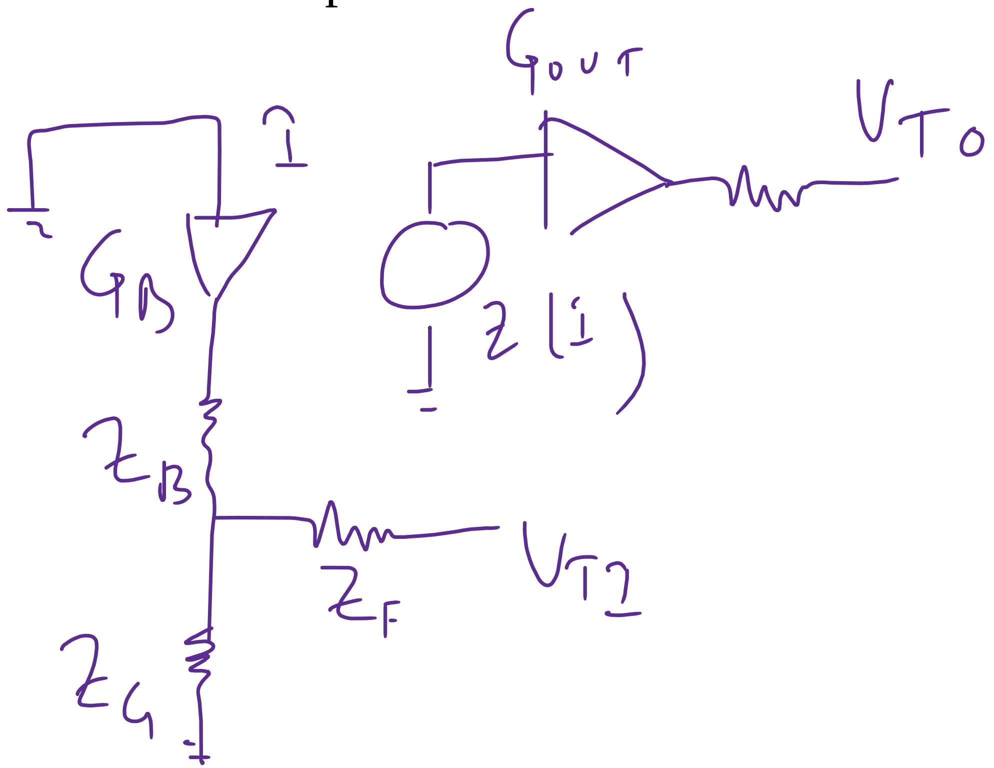
Unit 3 Development of stability equations



Loop gain

- Stability measurement done by loop gain
- Feedback circuit is seen at negative input terminal

Break the loop, apply test signal and measure output



Unit 3 Development of stability equations

- Break the loop, apply test signal and measure output
- Z is the transimpedance of the op amp which is nothing but gain in terms of impedance

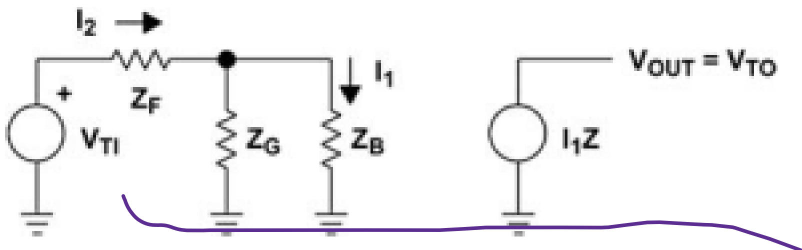


Figure 9.3
Stability analysis circuit.

$$V_{TO} = I_1 Z$$

$$V_{TI} = I_2(Z_F + Z_G \parallel Z_B) \quad — (1)$$

Loop gain

Use current divider theorem

$$I_2(Z_G \parallel Z_B) = I_1 Z_B \quad — (2)$$

$$I_2 = I_1(Z_G+Z_B)/Z_G$$

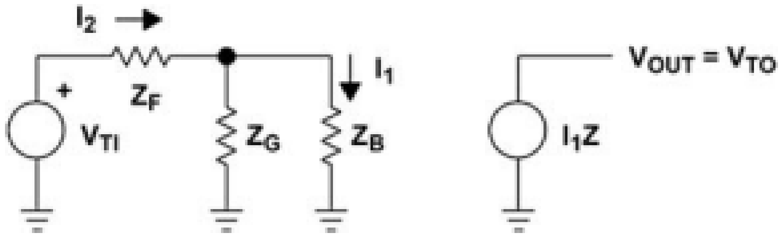


Figure 9.3
Stability analysis circuit.

$$V_{TO} = I_1 Z \quad \text{— (4)}$$

from (1) & (2)

$$V_{TI} = I_1(Z_F + Z_G \| Z_B)\left(1 + \frac{Z_B}{Z_G}\right)$$

Or

$$V_{TI} = I_1 Z_F\left(1 + \frac{Z_B}{Z_F \| Z_G}\right) \quad \text{— (3)}$$

From (3) & (4)

$$A\beta = \frac{V_{TO}}{V_{TI}} = \frac{Z}{\left(Z_F\left(1 + \frac{Z_B}{Z_F \| Z_G}\right)\right)}$$

This is Loop gain

 Noninverting current feedback amplifier

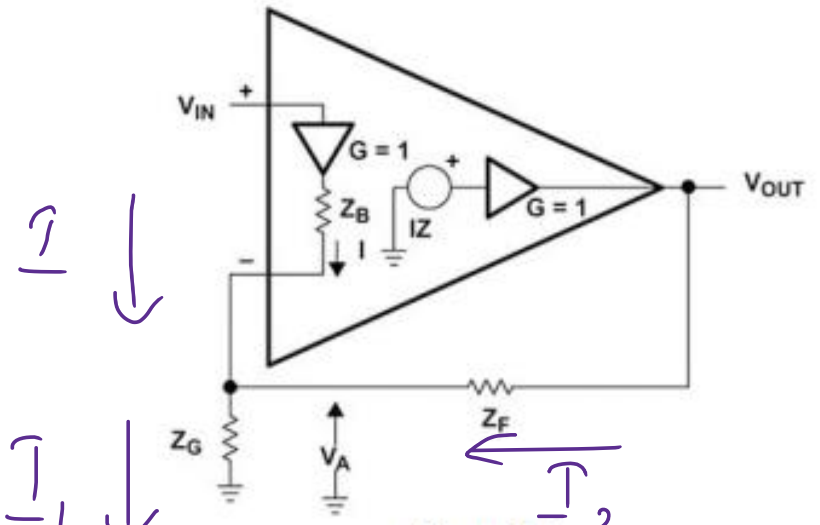


Figure 9.4
Noninverting current-feedback amplifier.

$$V_{OUT} = IZ \quad — (1)$$

$$I = I_1 – I_2$$

$$I_1 = V_A/Z_G$$

$$I_2 = (V_{OUT} – V_A)/Z_F$$

Circuit is nothing but non inverting amplifier

$$V_A = V_{IN} - IZ_B \quad — (3)$$

$$I = (V_A/Z_G) - (V_{OUT} – V_A)/Z_F \quad — (2)$$

Unit 3 Noninverting current feedback amplifier

From 1 2 & 3

$$\frac{V_{OUT}}{V_{IN}} = \frac{\dfrac{Z\left(1+\frac{Z_F}{Z_G}\right)}{Z_F\left(1+\frac{Z_B}{Z_F \| Z_G}\right)}}{1+\dfrac{Z}{Z_F\left(1+\frac{Z_B}{Z_F \| Z_G}\right)}}$$

$Z_B \simeq 0$

$$\frac{V_{OUT}}{V_{IN}} = \frac{\dfrac{Z\left(1+\frac{Z_F}{Z_G}\right)}{Z_F}}{1+\dfrac{Z}{Z_F}} = \frac{1+\dfrac{Z_F}{Z_G}}{1+\dfrac{Z_F}{Z}}$$

Unit 3 Noninverting current feedback amplifier

when Z = high

$$\frac{V_{OUT}}{V_{IN}} = \frac{\dfrac{Z\left(1+\frac{Z_F}{Z_G}\right)}{Z_F}}{1+\dfrac{Z}{Z_F}} = \frac{1+\dfrac{Z_F}{Z_G}}{1+\dfrac{Z_F}{Z}}$$

$$\frac{V_{OUT}}{V_{IN}} = 1 + \frac{Z_F}{Z_G}$$

Identical to Voltage Feedback amplifier

Unit 3 Inverting current feedback amplifier

$$I + I_2 = I_1$$

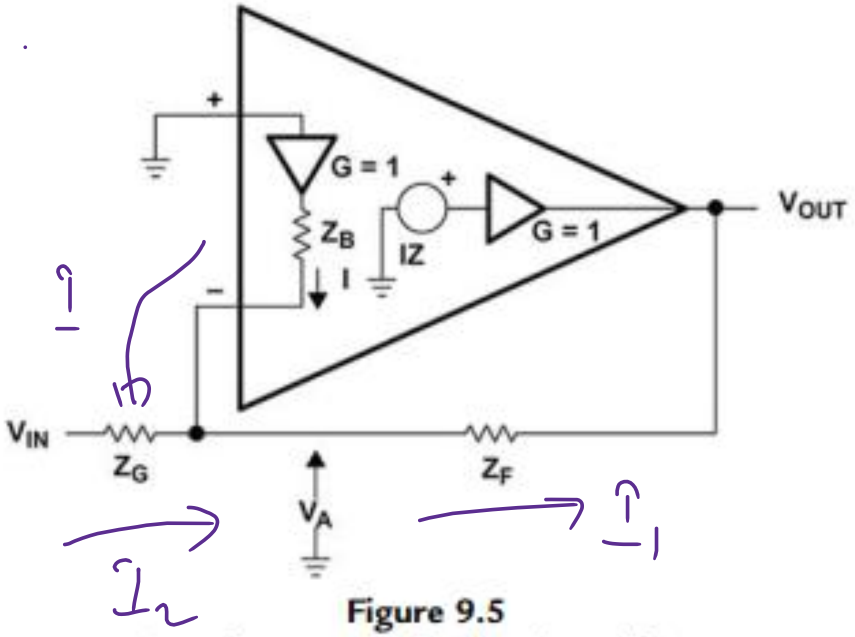


Figure 9.5
Inverting current-feedback amplifier.

$$I + (V_{IN} - V_A)/Z_G) = (V_A - V_{OUT})/Z_F \quad \text{— } 1$$

$$-V_A = IZ_B \quad \text{— } 2$$

$$V_{OUT} = IZ \quad \text{— } 3$$

Circuit is nothing but inverting amplifier

From 1 2 & 3

$$\frac{V_{OUT}}{V_{IN}} = -\frac{\dfrac{Z}{Z_G\left(1+\dfrac{Z_B}{Z_F \| Z_G}\right)}}{1+\dfrac{Z}{Z_F\left(1+\dfrac{Z_B}{Z_F \| Z_G}\right)}}$$

when $Z_B \simeq 0$

$$\frac{V_{OUT}}{V_{IN}} = -\frac{\dfrac{1}{Z_G}}{\dfrac{1}{Z}+\dfrac{1}{Z_F}}$$

Unit 3 Inverting current feedback amplifier

$$\frac{V_{OUT}}{V_{IN}} = -\frac{\dfrac{Z}{Z_G\left(1+\dfrac{Z_B}{Z_F \| Z_G}\right)}}{1+\dfrac{Z}{Z_F\left(1+\dfrac{Z_B}{Z_F \| Z_G}\right)}}$$

Z = high

$$\frac{V_{OUT}}{V_{IN}} = -\frac{Z_F}{Z_G}$$

Identical to Voltage Feedback amplifier

Unit 3 Stability analysis

$$A\beta = \frac{V_{TO}}{V_{TI}} = \frac{Z}{\left(Z_F\left(1 + \frac{Z_B}{Z_F \| Z_G}\right)\right)}$$

Stability equation (loop gain)

$$20\ \mathrm{LOG}|A\beta| = 20\ \mathrm{LOG}|Z| - 20\ \mathrm{LOG}\left|Z_F\left(1 + \frac{Z_B}{Z_F \| Z_B}\right)\right|$$

$$\phi = \mathrm{TANGENT}^{-1}(A\beta)$$

Gain and Phase equations for loop gain

Typical values

$$Z = \frac{\mathrm{IM}\Omega}{(1+\tau_1 S)(1+\tau_2 S)}$$

$$Z_B = 70\Omega$$

$$Z_G = Z_F\ \ 1\ \mathrm{k}\Omega$$

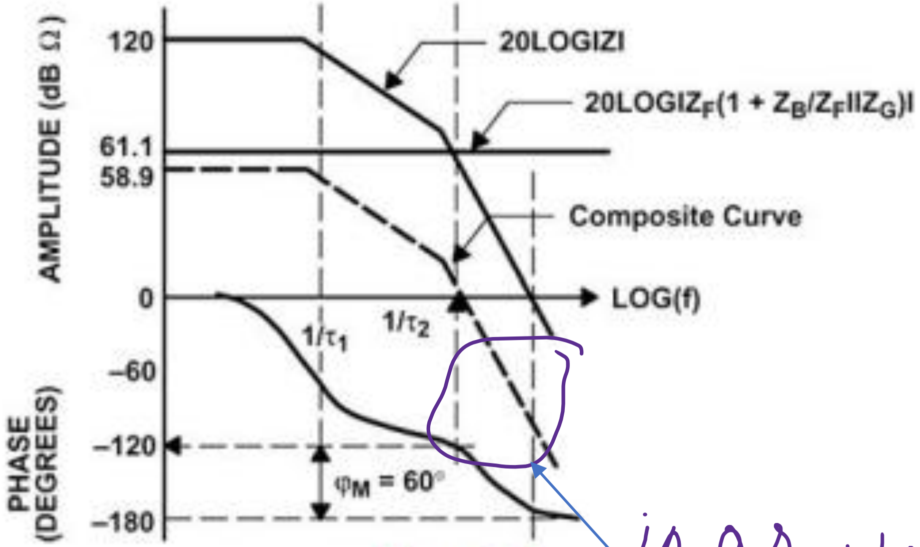


Figure 9.6
Bode plot of stability equation.

improved phase margin

- Open loop Gain is measured in terms of Z which trans-impedance
- Loop gain too measured in terms of impedance
- Assumed open loop gain to have two poles
- Loop gain reduces gain. As a result phase margin improves

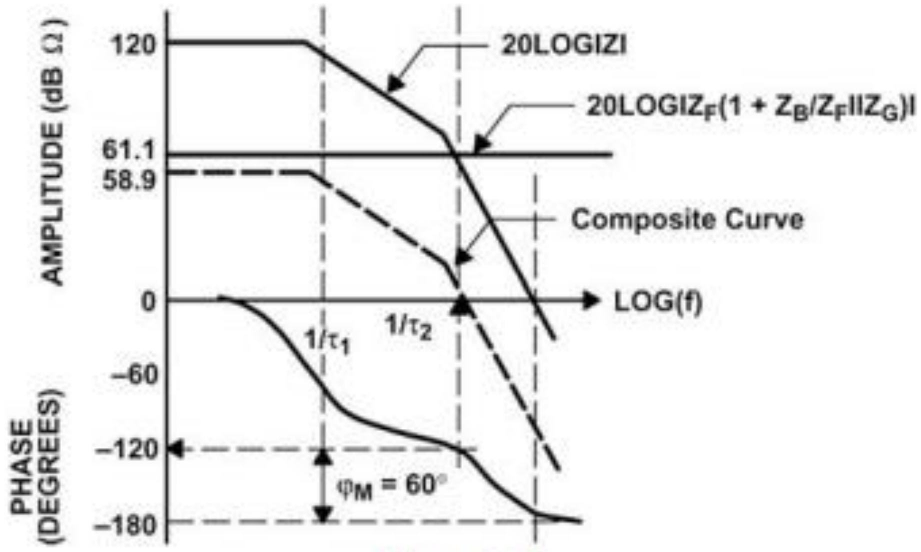


Figure 9.6
Bode plot of stability equation.

Summary of points

- R_F is usually recommended by the manufacturer
- R_F selection based on stability and bandwidth requirement

$$A\beta = \frac{V_{TO}}{V_{TI}} = \frac{Z}{\left(Z_F\left(1+\frac{Z_B}{Z_F \| Z_G}\right)\right)}$$

$$A\beta = \frac{Z}{Z_F + Z_B\left(1+\frac{R_F}{R_G}\right)}$$

Stability equation Different form

When $Z_B = 0$ and $Z_F = R_F$ → $A\beta = Z/R_F$

First method : Key points

- R_F defines stability of the amplifier
- It is important to select R_F properly
- R_F value range given by the manufacturer
- If different value to be used, results of loop gain are extrapolated assuming linear relation

Loop gain 1 value

Loop gain 2 value

$$\frac{Z}{Z_{F1} + Z_B\left(1 + \frac{Z_{F1}}{Z_{G1}}\right)} = \frac{Z}{Z_{FN} + Z_B\left(1 + \frac{Z_{FN}}{Z_{GN}}\right)}$$

$$Z_{FN} = Z_{F1} + Z_B\left(\left(1 + \frac{Z_{F1}}{Z_{G1}}\right) - \left(1 + \frac{Z_{FN}}{Z_{GN}}\right)\right)$$

New value of feedback resistor

Unit 3 Selection of feedback resistor

Second method

We can also use graphical method to select R_F value

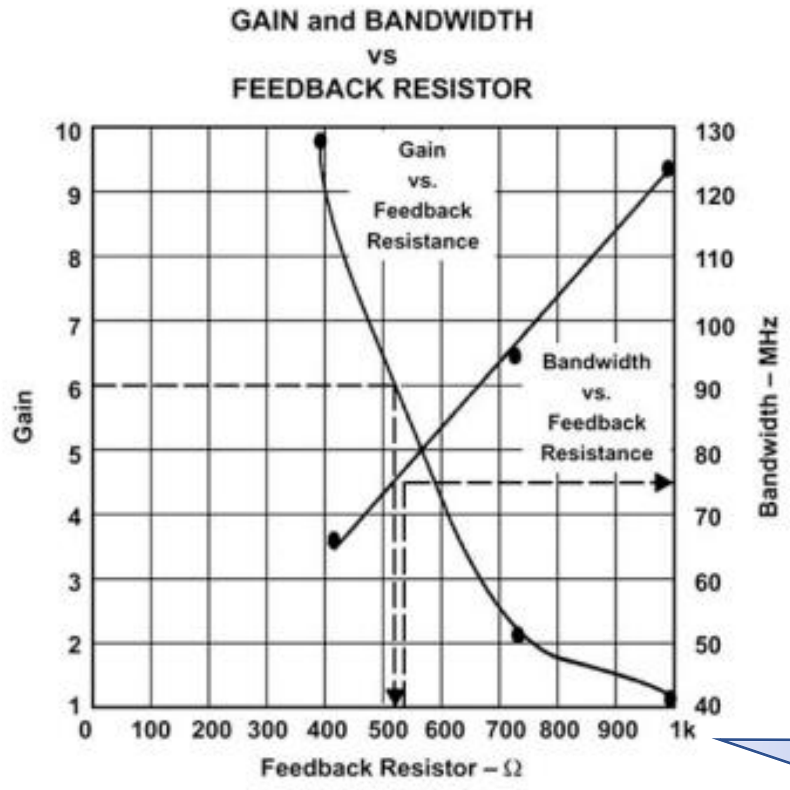


Figure 9.7

Plot of current-feedback amplifier R_F, G, and BW.

Graph taken from the data sheet of CFA

For a given gain, calculate R_F and from R_F calculate Bandwidth of the amplifier

Table represents different gain R_F and Bandwidth values

Table 9.1: Data Set for Curves in Fig. 9.7

Gain (A_{CL})	R_F (Ω)	Bandwidth (MHz)
+1	1000	125
+2	681	95
+10	383	65

Unit 3 Stability and feedback capacitance

Stray capacitance gets introduced across feedback resistor Hence Z_F becomes reactive

$$Z_F = \frac{R_F}{1 + R_F C_F s} \quad \text{1}$$

Loop gain is given by,

$$A\beta = \frac{V_{TO}}{V_{TI}} = \frac{Z}{\left(Z_F\left(1 + \frac{Z_B}{Z_F \| Z_G}\right)\right)}$$

$$Z_B = R_B \quad Z_G = R_G \quad \text{2}$$

From 1 and 2, loop gain is given by,

$$A\beta = \frac{Z(1 + R_F C_F s)}{R_F\left(1 + \frac{R_B}{R_F \| R_G}\right)(1 + R_B \| R_F \| R_G C_F s)}$$

Loop gain added with one pole and one zero,

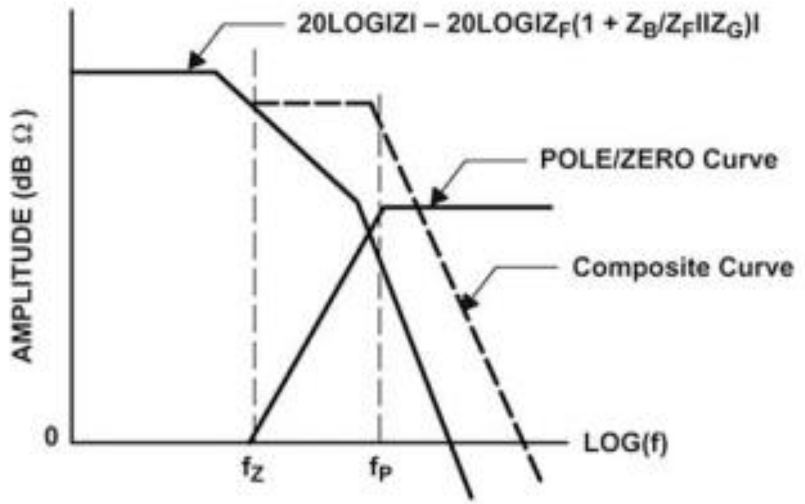


Figure 9.9

Gain plot with and without addition of poles and zeros

Unit 3 Stability and input capacitance

Stray capacitance gets introduced across input resistor
Hence Z_G becomes reactive

$$Z_G = \frac{R_G}{1 + R_G C_{GS} s} \qquad 1$$

From 1 and 2, loop gain is given by,

Loop gain is given by,

$$A\beta = \frac{Z}{Z_B + \dfrac{Z_F}{Z_G^2 + Z_B Z_G}}$$

$$A\beta = \frac{Z \qquad 2}{R_F\left(1 + \dfrac{R_B}{R_F \| R_G}\right)(1 + R_B \| R_F \| R_G C_{GS} s)}$$

$Z_B = R_B \quad Z_G = R_G \qquad 2$

Loop gain added with one pole

Unit 3 Stability and feedback capacitance

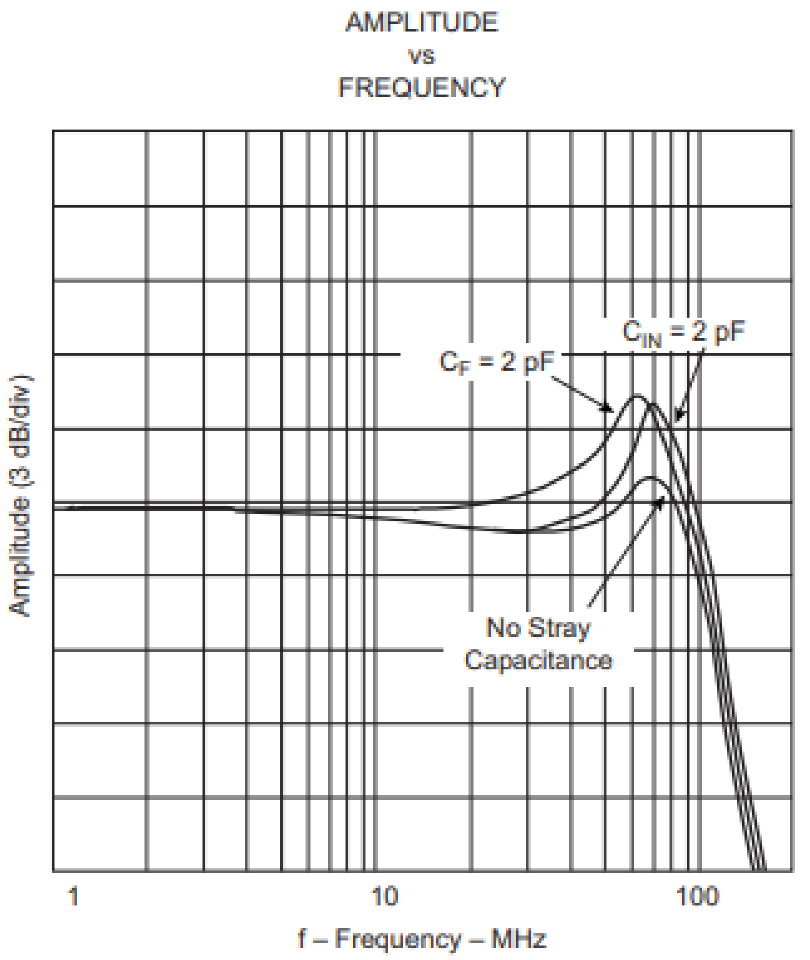


Figure 9.8

Effects of stray capacitance on current-feedback amplifiers.

Unit 3 Stability with input capacitance and feedback capacitance

Z_F becomes reactive and Z_G also becomes reactive

Loop gain equation becomes,

$$A\beta = \frac{Z(1 + R_F C_F s)}{R_F\left(1 + \frac{R_B}{R_F \| R_G}\right)(R_B \| R_F \| R_G (C_F + C_G)s + 1)}$$

- when pole = zero
- when $R_F >> R_G$ & R_B

$$R_F C_F = C_G (R_G \| R_B)$$

To make circuit to cancel pole and zero, we need to keep

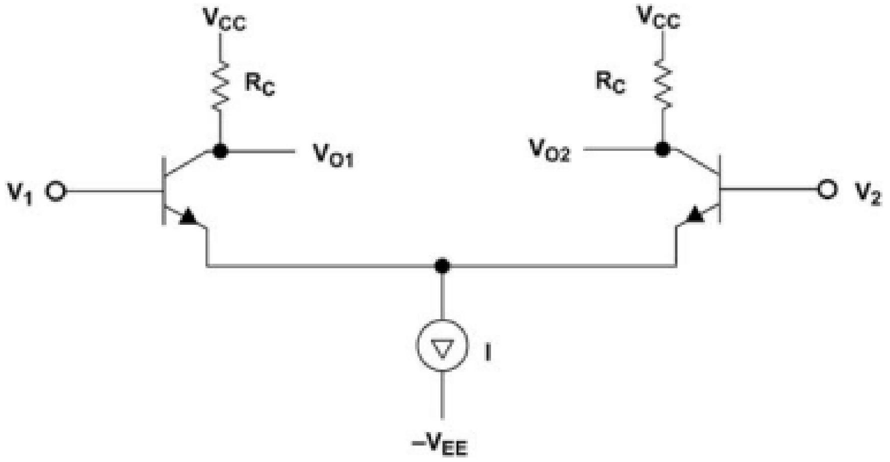
when $R_B << R_G$

$$R_F C_F = R_B C_G$$

Unit 3 Comparison between VFA and CFA - Precision

- **Traditional op amps are voltage feedback type whereas current feedback amps are recent**

- **VFA input comes from differential pair**

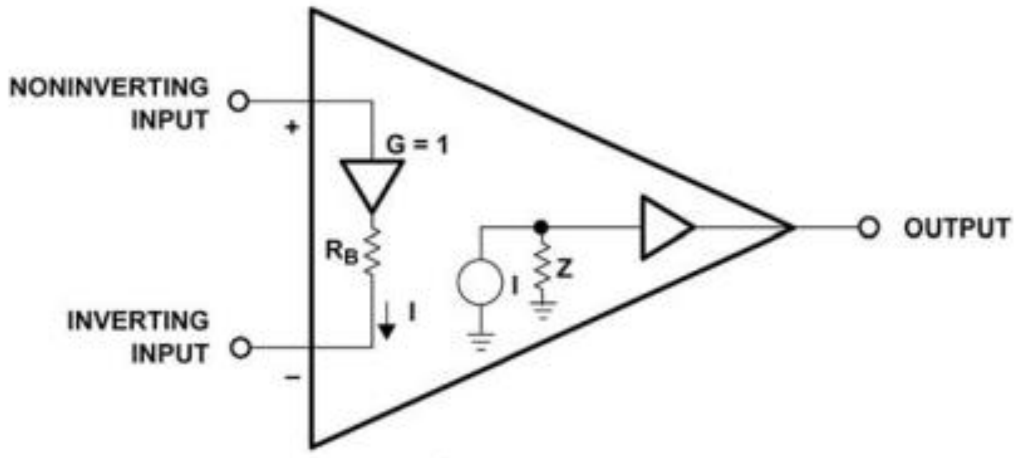


Differential pair are perfectly matched

- V_{BE} are matched
- Q_1 and Q_2 are matched
- Transistor current gains are matched
- Matched for layout equality

Unit 3 Comparison between VFA and CFA - Precision

- **CFA inputs are at different impedance levels**



CFA

- Input impedance for inverting and non inverting are different
- Common mode rejection is not good
- Overall precision is bad compared to VFA

Unit 3 Comparison between VFA and CFA - Bandwidth

- **VFA bandwidth not good**

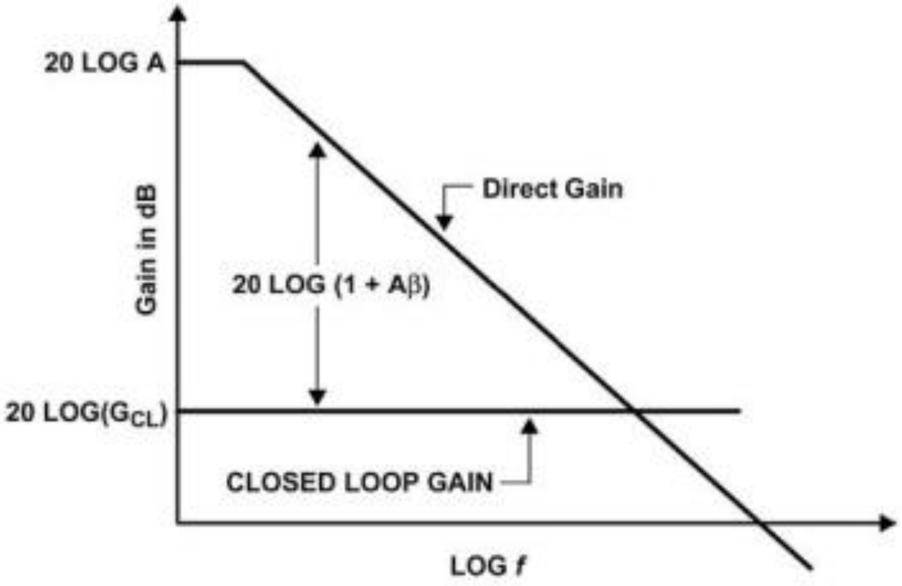
$$A\beta = \frac{aR_G}{R_F + R_G}$$

$$A\beta = \frac{a}{\frac{R_F + R_G}{R_G}} = \frac{a}{G_{CLNI}}$$

$$A\beta = \frac{a}{\frac{R_F + R_G}{R_G}} = \frac{a}{G_{CLI} + 1}$$

VFA

- Loop gain decreases for an increase in bandwidth
- Error is directly related to the bandwidth



Unit 3 Comparison between VFA and CFA - Bandwidth

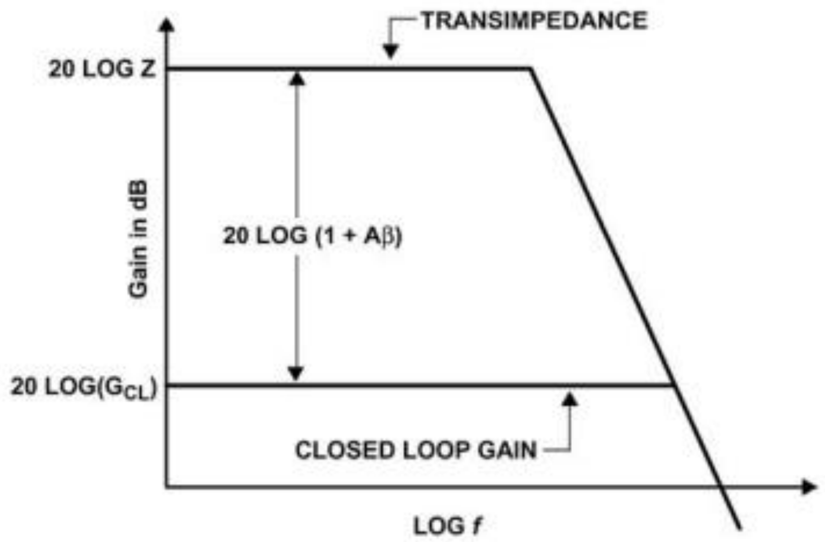
- **CFA bandwidth good**

$$A\beta = \frac{Z}{R_F\left(1 + \dfrac{R_B}{R_F \parallel R_G}\right)}$$

$$A\beta = \frac{Z}{R_F}$$

CFA

- No low frequency pole
- Loop gain does not depend on closed loop gain



Unit 3 Comparison between VFA and CFA - Stability

- **VFA stability**

$$A\beta = \frac{aR_G}{R_F + R_G}$$

Stability depends on a, R_G and R_F
Stray capacitance does not change stability significantly

- **CFA stability**

$$A\beta = \frac{Z}{R_F}$$

Stability depends on R_F
Stary capacitance play role in stability significantly

Unit 3 Comparison between VFA and CFA - Impedance

- **VFA impedance**

Input impedance is high and matched at both terminals
Even in CMOS input impedance is high

- **CFA impedance**

Not high compared to VFA
Two input impedances are not matched
Because of low input impedance at inverting terminal

Unit 3 Comparison Table on equations

Table 10.1: Tabulation of Pertinent Voltage-Feedback Amplifier and Current-Feedback Amplifier Equations

Circuit Configuration	Current-Feedback Amplifier	Voltage-Feedback Amplifier
Noninverting		
Forward or direct gain	$\dfrac{Z\left(1+\frac{Z_F}{Z_G}\right)}{Z_F\left(1+\frac{Z_B}{Z_F \parallel Z_G}\right)}$	a
Ideal loop gain	$\dfrac{Z}{Z_F}\left(1+\dfrac{Z_B}{Z_F \parallel Z_G}\right)$	$\dfrac{aZ_F}{(Z_G+Z_F)}$
Actual closed-loop gain	$\dfrac{\dfrac{Z_F\left(1+\frac{Z_B}{Z_G}\right)}{Z_F\left(1+\frac{Z_B}{Z_F \parallel Z_G}\right)}}{1+\dfrac{Z}{Z_F\left(1+\dfrac{Z_B}{\frac{1+Z_B}{Z_F \parallel Z_G}}\right)}}$	$\dfrac{a}{1+\dfrac{aZ_G}{Z_F \parallel Z_G}}$
Closed-loop gain	$1+Z_F/Z_G$	$1+Z_F/Z_G$
Inverting		
Forward or direct gain	$\dfrac{Z}{Z_G\left(1+\frac{Z_B}{Z_F \parallel Z_G}\right)}$	$\dfrac{aZ_F}{(Z_F+Z_G)}$
Ideal loop gain	$\dfrac{Z}{Z_F}\left(1+\dfrac{Z_B}{Z_F \parallel Z_G}\right)$	$\dfrac{aZ_G}{(Z_G+Z_F)}$
Actual closed-loop gain	$\dfrac{-Z_G\left(1+\frac{Z_B}{Z_F \parallel Z_G}\right)}{1+\dfrac{Z}{Z_F\left(1+\frac{Z_B}{Z_F \parallel Z_G}\right)}}$	$\dfrac{\dfrac{-aZ_F}{Z_F+Z_G}}{1+\dfrac{aZ_G}{Z_F \parallel Z_G}}$
Closed-loop gain	$-Z_F/Z_G$	$-Z_F/Z_G$

Unit 3 Fully Differential op amp

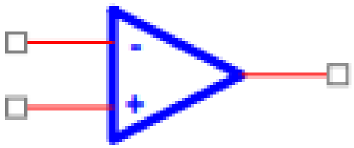


Figure 11.1
Single-ended op amp schematic symbol.

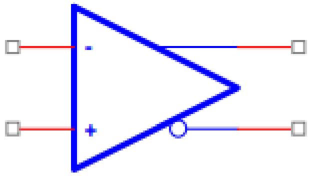


Figure 11.2
Fully differential op amp schematic symbol.

- Differential input (Two inputs), single output(One output)

- Differential input(Two inputs), differential output(One output)

Unit 3 Fully Differential op amp

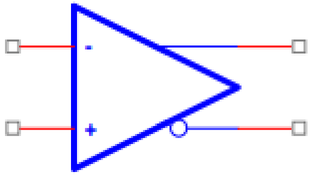
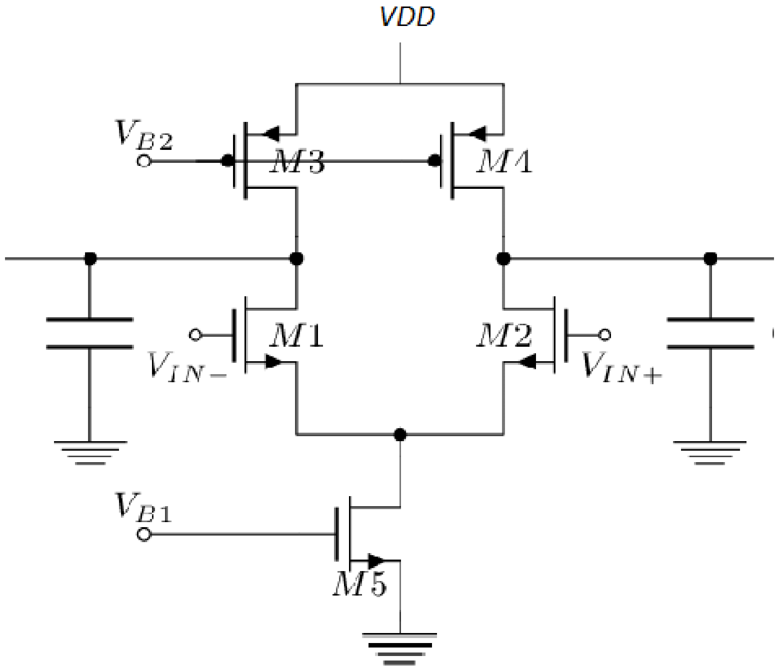


Figure 11.2
Fully differential op amp schematic symbol.



- Differential input(Two inputs), differential output(One output)

- Typical circuit inside fully differential amplifier

Unit 4 Fully Differential op amp

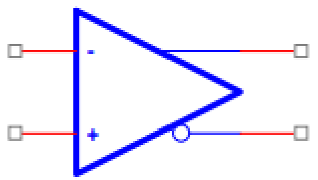


Figure 11.2
Fully differential op amp schematic symbol.

- Two closed loop feedbacks are required for feedback circuit
- Both loops to be matched
- Here, each loop is a inverting type

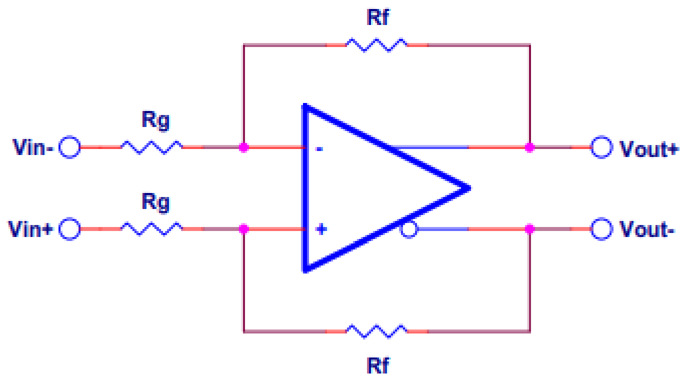


Figure 11.4
Closing the loop on a fully differential op amp.

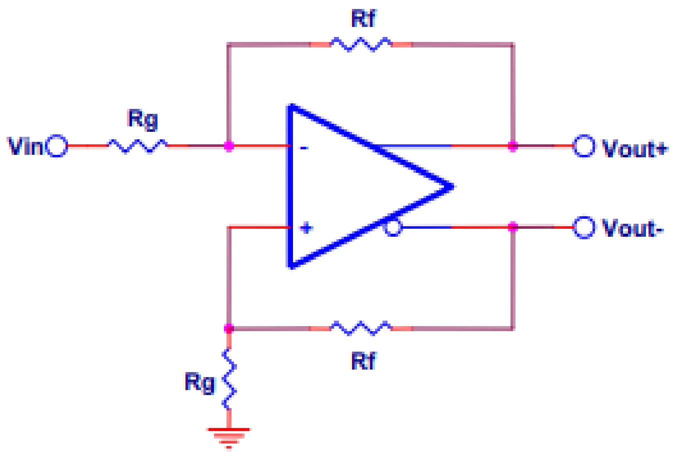
Ideal fully differential op amp gain is

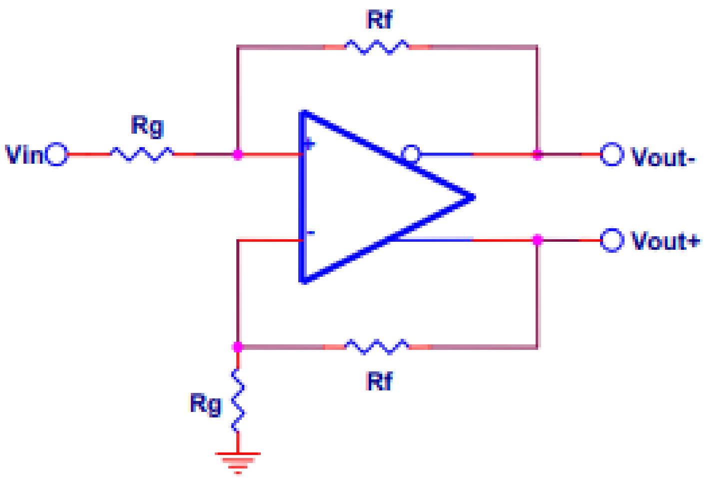
$$\frac{V_O}{V_I} = \frac{R_F}{R_G}$$

Unit 3 Fully Differential op amp

- **Single Ended to Differential Conversion**

- *In some applications, it is necessary to have two output, which can be derived from single input*





- Gain of single ended to differential is

$$\frac{V_O}{V_I} = \frac{R_F}{R_G}$$

- In many cases, fully differential output is expressed as **(V_{out+} - V_{out-})**

- **Single Ended to Differential Conversion**
  - Gain plot when R_F is equal to R_G that is when gain is one.

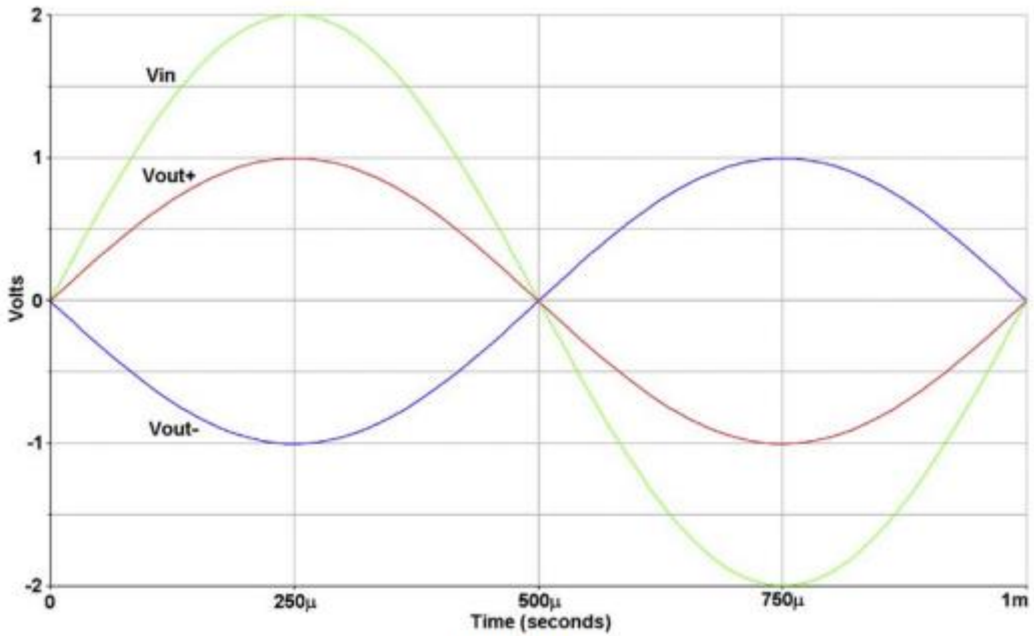


Figure 11.6
Relationship between V_{IN}, V_{OUT+}, and V_{OUT-}.

- Value of differential gain is always equal to one which is
- $V_{IN} = V_{OUT+} - V_{OUT-}$

Unit 3 Fully Differential op amp

- **Concept of V_{OCM}**

  - A new pin is added called V_{OCM}
  - V_{OCM} is called voltage output common mode
  - This is specific to TI chips

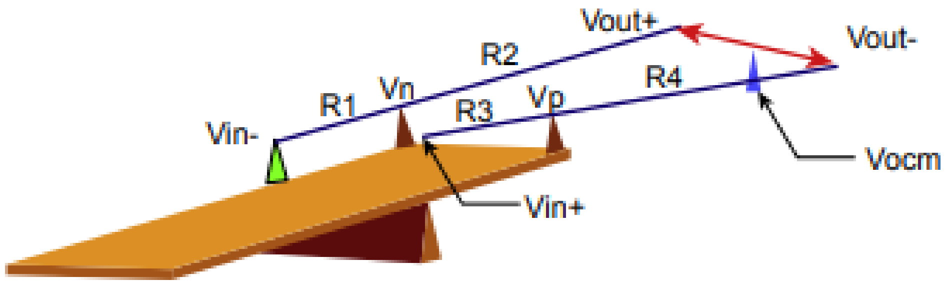


Figure 11.8
Mechanical model of V_{ocm}.

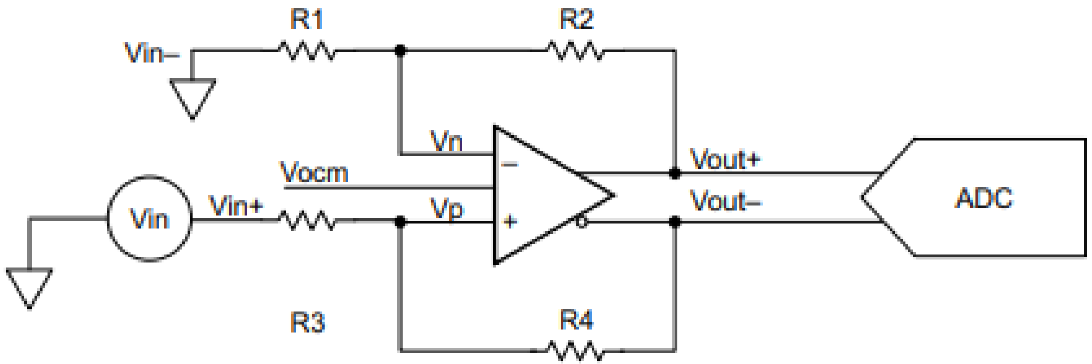


Figure 11.7
Electrical model of V_{ocm}.

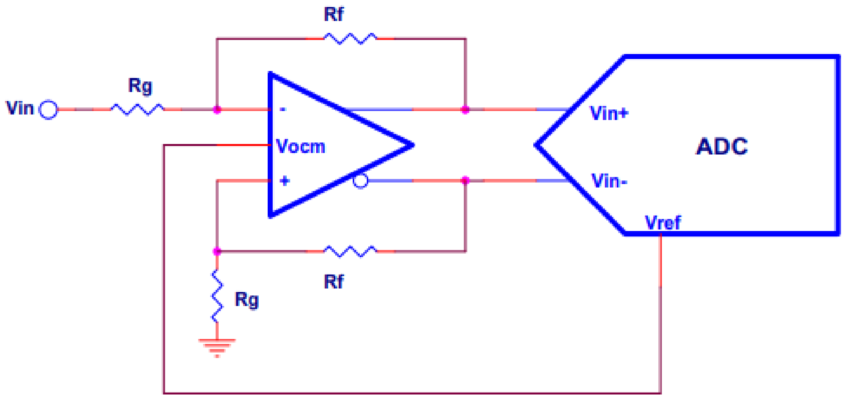


Figure 11.10
Using a fully differential op amp to drive a analog-to-digital converter

Unit 3 Fully Differential op amp

- **Instrumentation amplifier**

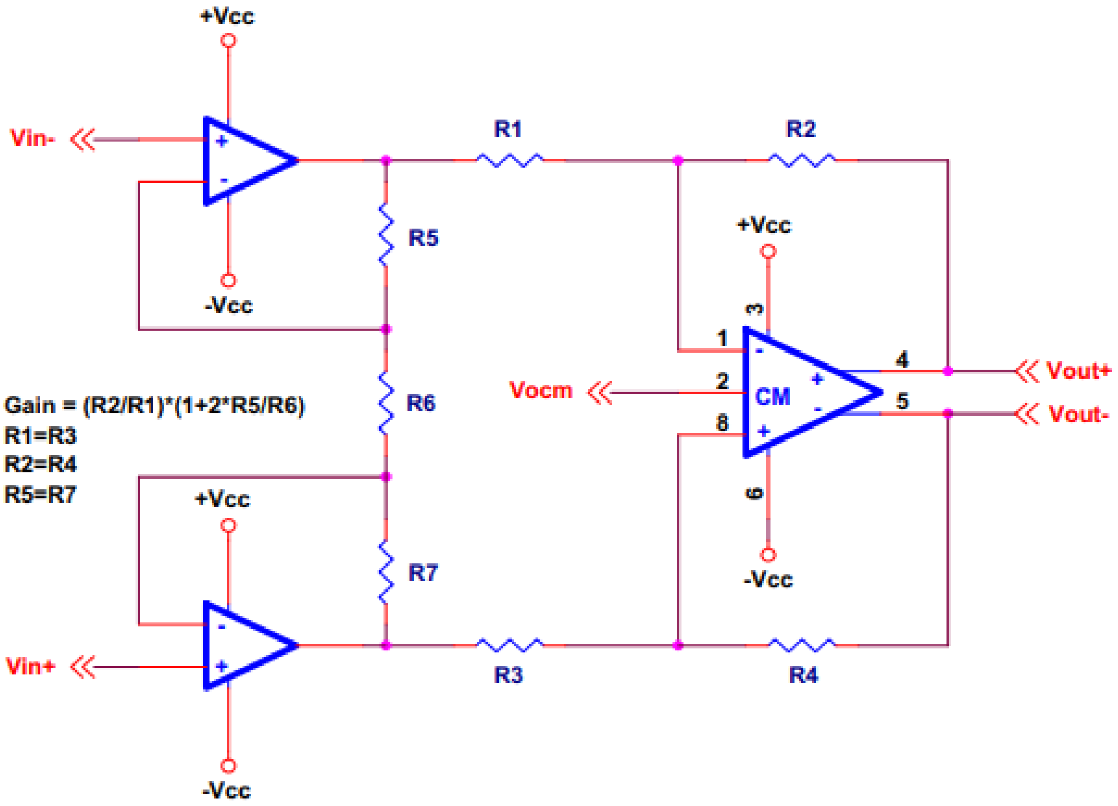
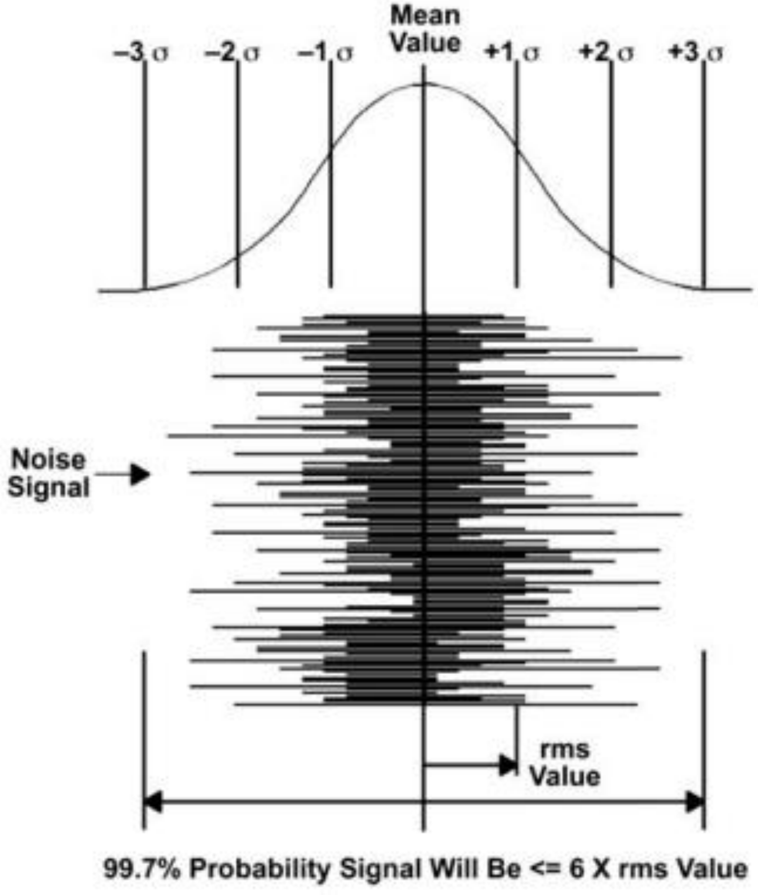


Figure 11.11
Instrumentation amplifier.

Instrumentation amplifier with V_{OCM} concept at second stage

Unit 3 Op Amp Noise Theory

- Noise is a purely random signal
- Instantaneous value can not be predicted at any point of time
- Noise is created either internally or externally
- Instantaneous values are either positive voltage or negative voltage
- These can be plotted as Gaussian probability function
- Thermal noise and shot noise follow Gaussian function



Noise floor is the level of noise when there is no input given

- Signal to Noise Ratio

$$\frac{S_{(f)}}{N_{(f)}} = \frac{\text{rms signal voltage}}{\text{rms noise voltage}}$$

- When there are multiple noise sources, total noise will be

$$E_{\text{Total rms}} = \sqrt{e_{1\ \text{rms}}^2 + e_{2\ \text{rms}}^2 + \cdots e_{n\ \text{rms}}^2}$$

- **Example**
- If two noise sources are 2V rms, total value will be

$$E_{\text{Total rms}} = \sqrt{2^2 + 2^2} = \sqrt{8} = 2.83\ V_{\text{rms}}$$

Unit 3 Op Amp Noise Theory

- **Noise Units**

Normally expressed as rms volts(amps) per root hertz

$$V/\sqrt{Hz} \text{ or } A/\sqrt{Hz}.$$

For example:

- An op amp with a noise specification of 2.5 $nV/\sqrt{Hz}$ is used over an audio frequency range of 20 Hz–20 kHz, with a gain of 40 dB. The output voltage is 0 dB V (1 V).
- To begin with, calculate the *root Hz* part: $\sqrt{20000 - 20} = 141.35$.
- Multiplying this by the noise spec: $2.5 \times 141.35 = 353.38$ nV, which is the equivalent input noise (E_{IN}). The output noise equals the input noise multiplied by the gain, which is 100 (40 dB).

The signal-to-noise ratio can be now calculated:

$$353.38 \text{ nV} \times 100 = 35.3\ \mu\text{V}$$

$$\text{Signal-to-noise(dB)} = 20 \times \log(1 \text{ V} \div 35.3\ \mu\text{V}) = 20 \times \log(28329) = 89 \text{ dB}$$

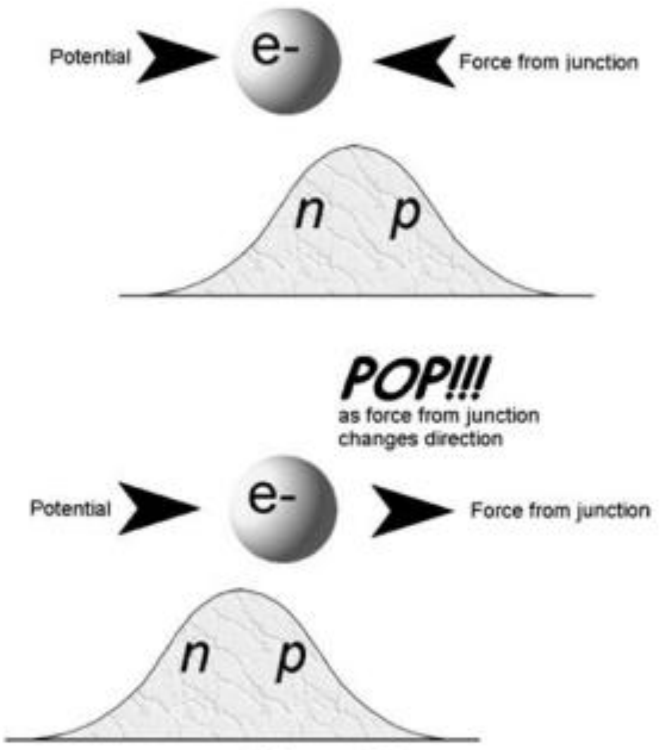
There are five types of noise in op amps and associated circuitry:

1. shot noise,
2. thermal noise,
3. flicker noise,
4. burst noise, and
5. avalanche noise.

Shot Noise

- Also called as quantum noise
- Caused by random movement of charge carriers in a conductor
- Few random electrons get energy and move randomly
- These noise independent of temperature
- These are always associated with current flow
- This noise is flat when plotted for spectral density
- They represent imperfections in a metal

Shot Noise



The rms shot noise current is equal to:

$$I_{sh} = \sqrt{(2qI_{dc} + 4qI_o)B}$$

where q = electron charge (1.6×10^{-19} C), I_{dc} = average forward dc current in A, I_o = reverse saturation current in A, and B = Bandwidth in Hz.

The rms shot noise voltage is equal to:

$$E_{sh} = kT\sqrt{\frac{2B}{qI_{dc}}}$$

where k is Boltzmann's constant (1.38×10^{-23} J/K); q is electron charge (1.6×10^{-19} C); T is temperature in K; I_{dc} is average dc current in A; and B is bandwidth in Hz.

Thermal Noise

- Also called as Johnson's noise
- It is due to thermal agitation of electrons
- It has uniform spectral density

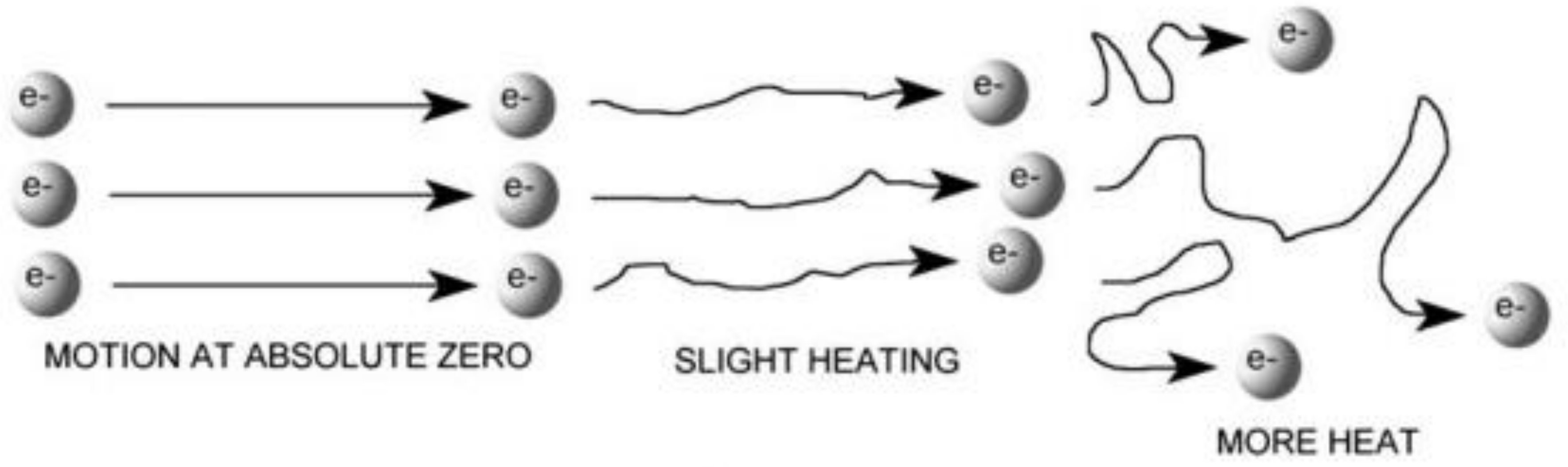
At frequencies below 100 MHz, thermal noise can be calculated using Nyquist's relation:

$$E_{th} = \sqrt{4kTRB}$$

$$I_{th} = \sqrt{\frac{4kTB}{R}}$$

where E_{th} is thermal noise voltage in volts rms; I_{th} is thermal noise current in amps rms; k is Boltzmann's constant (1.38×10^{-23}); T is absolute temperature in Kelvin; R is resistance in ohms; and B is noise bandwidth in Hertz ($f_{max} - f_{min}$).

Thermal Noise



Lowering temperature reduces thermal noise

Flicker Noise

- Also called as 1/f noise
- It is present in all active and passive elements
- It is in crystal structure this can be reduced by better structure
- This noise Increases with decrease in frequency
- It is associated with DC currents

$$E_n = K_e\sqrt{\left(\ln\frac{f_{max}}{f_{min}}\right)} \quad I_n = K_i\sqrt{\left(\ln\frac{f_{max}}{f_{min}}\right)}$$

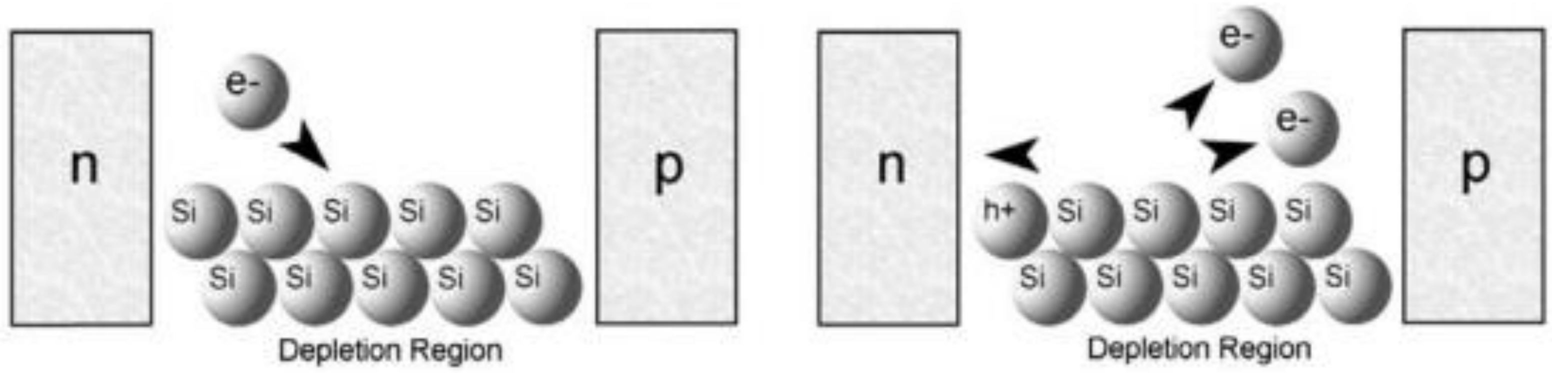
where K_e and K_i are proportionality constants (volts or amps) representing E_n and I_n at 1 Hz; and f_{max} and f_{min} are the maximum and minimum frequencies in Hz.

Burst Noise

- Also called as popcorn noise
- It is characterised by high frequency pulses
- It’s amplitude is several times the thermal noise
- Can be heard at frequency in around 100hertz in a speaker

Avalanche Noise

- Occurs at p n junction area
- Occurs when strong reverse field is applied to the junction
- Electrons will get kinetic energy and move, resulting in a current

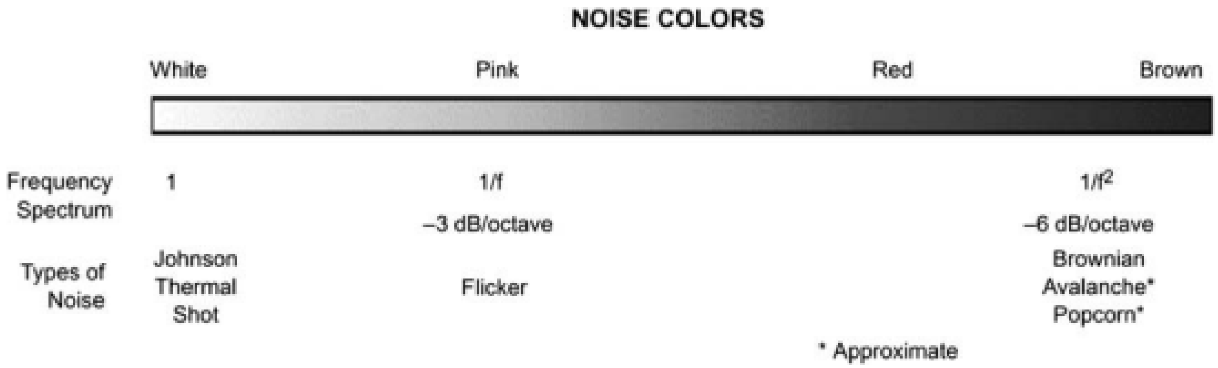


Noise Colours

- Colours describe type of noise and its frequency dependency

Table C.1: Noise Colors.

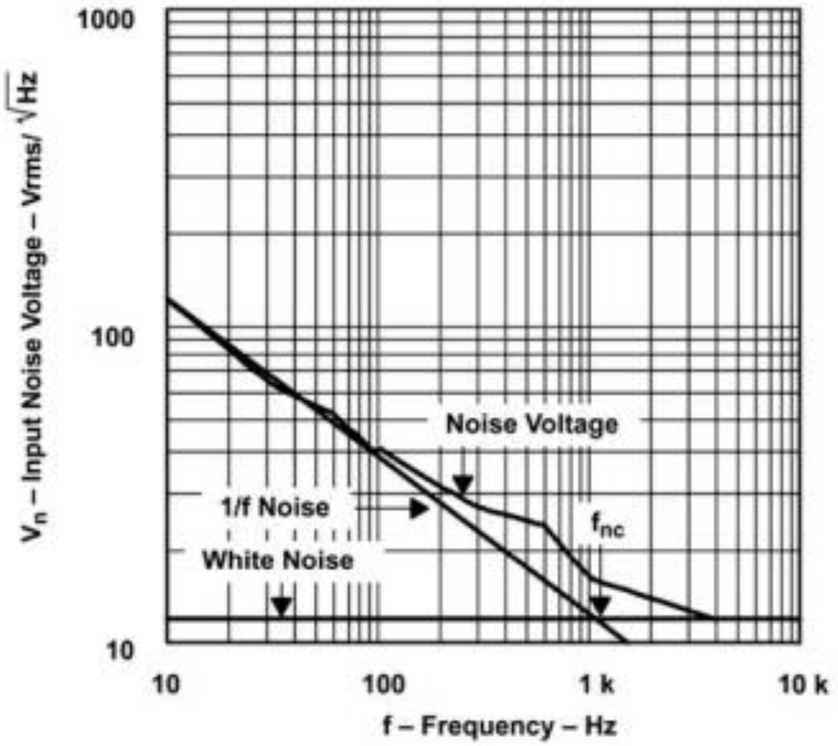
Color	Frequency Content
Purple	f^2
Blue	f
White	1
Pink	$\frac{1}{f}$
Red/brown	$\frac{1}{f^2}$



Unit 3 Op Amp Noise Theory

Op amp Noise

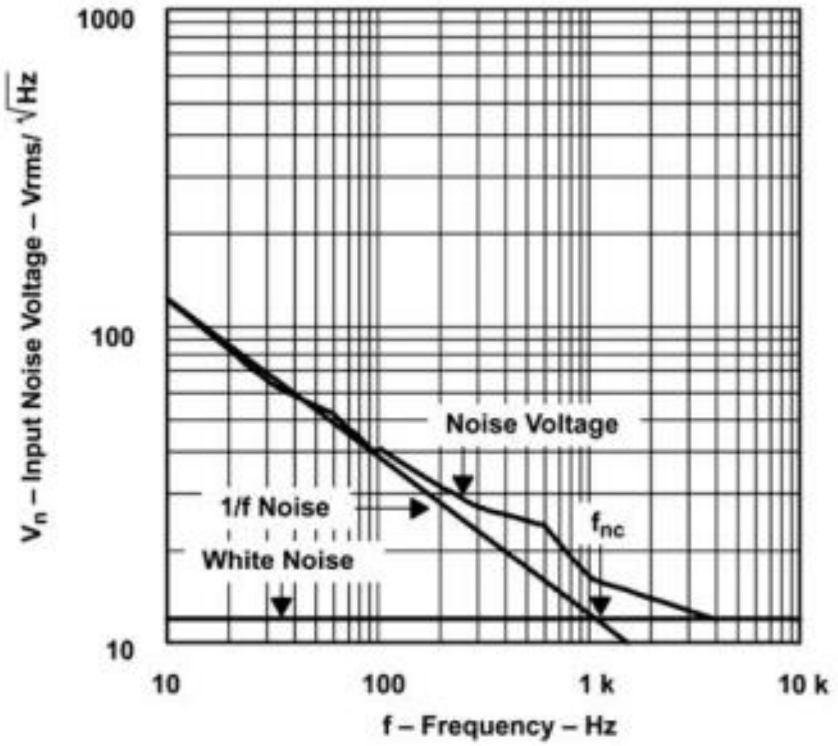
- Op amp noise described in a graph
- At low frequency, it is 1/f noise
- At high frequency, it is white noise



Unit 3 Op Amp Noise Theory

Op amp Noise

- The point where 1/f noise is same as white noise is called noise corner frequency



Textbook :

Op Amp for Everyone : Bruce Carter and Ron Mancini Fifth Edition 2017

THANK YOU

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