Fully Differential OPAMP

It's generally operated with Balance Input and produces Balance Output

Diagram of the Fully Differential OPAMP
For single output OPAMP, an amplifier is

\[ V_0 = -\frac{R_2}{R_1} V_{in} \]

\[ V_{common} = \frac{V_{omax} + V_{omin}}{2} \]

i.e. \( V_{om} = 0 \) if \( V_{omax} = -V_{omin} \)

In case of Balanced (Symmetric) Fully Differential system, \( V_{o1} \) & \( V_{o2} \) look like:
Difference Mode Output

Common Mode Output

\[ V_{CM} = 0 \]

If \( V_{OMAX} = -V_{OMIN} \)
We may need Amplifier with

1. Higher Gain
2. Higher SNR (Signal to Noise Ratio)

where \( \text{SNR} = \frac{\text{Max. Signal Output Power} \ (\ \overline{V_{\text{sym}}}^2/2)}{\text{Output Noise Power} \ (\ \overline{V_{\text{on}}}^2)} \)

where \( \overline{V_{\text{on}}} \) (Single ended) = \( 4 (1 + \frac{R_2}{R_1})^2 4 kT R_1 f_n \)

\( \overline{V_{\text{on}}} \) (Full Differential) = \( 2 (1 + \frac{R_2}{R_1})^2 4 kT R_1 f_n \)

\( \overline{V_{\text{signal}}} \) (Peak) for Single ended = \( V_{\text{max}} - V_{\text{min}} \)

\( \overline{V_{\text{signal}}} \) (Peak) for Full Differential = \( 2 (V_{\text{max}} - V_{\text{min}}) \)
Thus SNR of Fully Differential Amplifier is twice that of Single output Amplifier.

We can model the input side of Fully Differential Amplifier (FDA) as
COMMON MODE FEEDBACK (CMFB)

For fully Differential Amplifier with need of Higher Gains, we use Current Source Loads instead of Diode Connected Loads.

\[ \text{Then:} \]
\[ V_{\text{out}} = V_{\text{ol}} - V_{\text{o2}} \]
\[ V_{\text{id}} = \frac{(V_{\text{in1}} - V_{\text{in2}})}{2} \]
\[ V_{\text{ic}} = \frac{V_{\text{in1}} + V_{\text{in2}}}{2} \]
For Dittamp, with \( M_1 \) & \( M_2 \) identical,
\[
I_{DS1} = I_{DS2} = \frac{I_{SS}}{2} \quad (= \frac{I_{DSS}}{2})
\]

Since we have connected inputs to outputs
\[
\therefore \quad V_{CM} = \frac{I_{SS}}{2} \cdot (\gamma_{o3} \| \gamma_{o1}) = \frac{I_{SS}}{2} \cdot (\gamma_{o4} \| \gamma_{o2})
\]

However, if \( \gamma_{o3} \) is governed by \( I_{DS2} \) (same as \( \gamma_{o4} \))

and \( \gamma_{o1} \) by \( I_{DS6} \) (not minor), then the issue may come that, in case \( M_{2a} \) & \( M_{2b} \) are generally minor current \( I_{SS} \) and \( \gamma_{o3} \) (\( \gamma_{o4} \)) created by \( M_{6} \), are not generally

\[
I_{DS6} = I_{DS2}
\]

Then we have two cases \( I_{DS3,4} \geq \frac{I_{SS}}{2} \) or \( I_{DS3,4} < \frac{I_{SS}}{2} \).
Case 1: If $I_{DS_{3,4}} > \frac{I_{SS}}{2}$

i.e. $I_p = I_{DS_7}$ is larger than $I_n = I_{DS_5} = I_{SS}$

Then $(I_p - I_n)$ current flows in Route 7 (Route 6 creating a voltage, which may not be small

For $I_{DS_{3,4}} > \frac{I_{SS}}{2}$, the natural case will be to restore $I_{DS_{3,4}} = \frac{I_{SS}}{2}$

Which means $V_{01}$ & $V_{02}$ to be same as normal case, currents in $M_3$ & $M_4$ must reduce. This may bring these transistors Out of Saturation

This may reduce $R_{03}$, $R_{04}$ & hence fall in Gain

$\text{Graph:}$

$I_{DS_{3,4}} \rightarrow \frac{I_{SS}}{2} \text{ and } I_{03}$
Case II: $I_{DS_{34}} < \frac{I_{SS}}{2}$

Now $I_{SS}$ is supplied by MS.
If $I_{DS_{34}}$ is smaller, then MS must supply smaller current to restore 
$I_{DS_{34}} = \frac{I_{SS}}{2}$

This may bring out MS from Saturation.

Reduction in $R_{os}$ of MS will reduce CMRR as common mode gain will reduce increase.
Average of OPAMP outputs is termed of Common-Mode Output

\[ V_{CM} = \frac{V_{o^+} + V_{o^-}}{2} \]

If \( V_{DD} = 1 - V_{SS} \) \& \( V_{o^+} \rightarrow V_{DD} \) \& \( V_{o^-} \rightarrow V_{SS} \)

Then \( V_{CM} = \frac{V_{DD} + V_{SS}}{2} = \frac{2.5 - 2.5}{2} = 0 \)

But if \( V_{DD} = 5 \) \& \( V_{SS} = 0 \) \( V_{CM} = 2.5 \) V

It is necessary that for FD Amplifier to be stable, just Differential Feedback is not good enough but one needs Common Mode Feedback. This allows a fixed value of \( V_{CM} \).
Typical Common Mode Feedback works like

We sense \( V_{o1} \) and \( V_{o2} \) and generate \( V_{CMFB} \). This is compared with Set \( V_{CM} \) (\( V_{ref} \)) and depending upon \( V_{CMFB} > a \) or \( V_{CMFB} < V_{CM} \) we increase or decrease bias for Tail Current Source \( I_{SS} \).
A CMFB Circuit using CMOS technology

M7 to M10 are providing constant current sources.

1. \( V_{o^+} \) & \( V_{o^-} \) are such that average value > \( V_{CM} \)
2. \( V_{o^+} \) & \( V_{o^-} \) are such that their average value < \( V_{CM} \).
"NOISE"

1. Concept
2. Types of Noise
3. MOS Models for Noise
Noise: Any unwanted or undesired signal couples with desired signal is termed as Noise.

"Noise is generated due to a random process and limits the minimum signal (desired) level that a circuit can process with reasonable but acceptable quality."

In Analog Circuit, the design trade-off is between:

- Noise
- Power Dissipation
- Bandwidth (Speed)
- Linearity
If we have Signal $x(t)$, which is periodic
then we can deterministically
say that at $t=t_1$
\[x(t) = x(t_1)\]

However, if the Signal is random in nature
we can predict $x(t_1)$ or $x(t_2)$. We then say
that Signal is 'Noise Signal'.

\[x(t)\]
It is interesting that most noise sources show constant average power over a period, i.e.

\[ P_{av} = \frac{1}{T} \int_{-T/2}^{T/2} \frac{v^2(t)}{R_L} dt \]

That is, averaging is done over a long period of time.

\[ \int_{-T}^{T} \approx \frac{1}{T} \int_{-T/2}^{T/2} v(t)^2 dt \]

\[ \sqrt{P_{av}} = \text{Voltage which is called Noise (rms) Voltage) / Load.} \]
Concept of Noise Spectrum

If Noise avg. power is defined in frequency domain, we get Noise Spectrum, which is called Power Spectral Density (PSD).

PSD is defined as $S_x(f)$ of a noise waveform $x(t)$. Avg. power here is carried by $x(t)$ in bandwidth of $1\,\text{Hz}$, around center frequency $f$. 

\[ x(t) \xrightarrow{\text{BPF}} S_x(f) \xrightarrow{\text{Square}} x_f^2(t) \]
\( (x(f, t))^2 \)

Then we can evaluate Power Spectral Density \( S_x(f) \) if we obtain PSD at various values of \( f \): \( f = f_1, f_2, \ldots, f_n \)

\( S_x(f) \) is expressed as \( V^2/Hz \)

\[ \sqrt{S_x(f)} \] has units of \( V/\sqrt{Hz} \)
White Noise has spectrum

\[ S_n(f) \rightarrow \infty \] \quad \rightarrow f

Generally we limit the spectrum frequency to large values.

Response of PSD input to a system with Transferfn \( H(f) \).

\[ S_f(f) = S_x(f) \cdot |H(f)|^2 \]

where \( H(f) = H(S=2\pi jf) \)

If White noise spectrum is inputted to Transferfn \( S_n(f) \)

\[ S_n(f) \times (H(f)) \rightarrow S_y(f) \]
Two sided symmetric spectral function can be transformed to single sided Sp. fn by doubling the magnitude.

\[ S_n(x) \quad \Rightarrow \quad \text{sn}(f) \]
Distinction between Device Noise, Distortion and Interference due to signals.

1. Distortion: If the output signal waveform departs from expected waveform which should have occurred due to input signal operated on a Transfer function. Example:

For \( V_{in} \) between \(-V_{in1}\) to \(V_{in1}\)

\[ V_0 = \text{Gain} \cdot V_{in} \quad \text{where} \quad \text{Gain} = \frac{dV_0}{dV_{in}} \]

However beyond \( V_{in} > V_{in1} \) or \( < -V_{in1} \),

\( \frac{dV_0}{dV_{in}} \) keeps changing. This is due to non-linear behavior of the System. The Output will then have Non-linear Distortion.
Thus Distortion occurs due to

1. Nonlinearities in the Transfer Function of Active Devices

2. Distortion due passive components like cable or by inhomogeneities in the propagation path.

2. Interference:

In a spectrum, nearby signal frequency interferes in the interest band

Eg. Intermodulation in a RF receiver input leads to interference.
3. Noise:

Electronic components produce combination of three noise spectra:

i. $S_n(f) = \text{const.}$ White Noise

ii. $S_n(f) \propto \frac{1}{f}$ 1/f Noise

iii. $S_n(f) \propto \frac{1}{f^2}$ Popcorn Noise

However, we have another class of noise which are categorised as Thermal Noise types. Overall we have numbered noises:

(a) Shot Noise (b) Johnson Noise (Most commonly called Thermal Noise)

Third type of noise is called G-R noise and finally we have noise called $kT/C$ noise.