The Common-Mode Feedback (CMFB) circuit controls $V_{OC}$ so that it sits close to a given ref value (chosen by the designer) $V_{OCref}$, typically halfway between the upper and lower limit of $V_{OC}$

$$V_{OCref} = \frac{V_{DD} - 1V_{OS} + V_{IC} - V_{TN}}{2}$$

Small-signal analysis

Differential mode: $V_{IC} = 0$, $V_{ID} \neq 0 \Rightarrow V_{I1} = \frac{V_{ID}}{2}$ $V_{I2} = -\frac{V_{ID}}{2}$
the ST-OTA is equivalent to two common-source stages (identical) driven by opposite inputs $\Rightarrow$ opposite outputs
Common-mode input: $\nu_{ic} \neq 0, \quad \nu_{id} = 0 \Rightarrow \nu_{i1} = \nu_{i2} = \nu_{ic}$
The two half-circuits are identical and they are driven by the same input $V_{ic}$

$\Rightarrow V_{o1} = V_{o2} = V_{oc}$

At low frequency ($\omega = 0$):

$\text{Acc} = \frac{V_{oc}}{V_{ic}} \bigg|_{\text{Vid=0}} = \frac{q_{m1} R_o}{1 + q_{m1} 2 R_o}$

$|\text{Acc}| << |\text{Add}|$

What happens at $\omega > 0$:

$r_{o3} \Rightarrow r_{o3} \parallel \frac{1}{sC_0} = \frac{r_{o3}}{1 + s R_{o3} C_0}$

$C_{s1} = C_{sb1} + G_{m1} + \frac{C_{obs} + C_{ds}}{2}$

$2 R_{os} \rightarrow 2 R_{os} \parallel \frac{1}{s C_{s1}} = \frac{2 R_{os}}{1 + s 2 R_{os} C_{s1}}$

$\text{Acc}(s) = \frac{q_{m1} R_{o3}}{1 + s R_{o3} C_0} \frac{2 R_{os}}{1 + q_{m1} 2 R_{os}} \frac{1 + s 2 R_{os} C_{s1}}{1 + s R_{os} C_0 (1 + q_{m1} 2 R_{os} + s 2 R_{os} C_{s1})}$

$= \frac{q_{m1} R_{o3}}{1 + q_{m1} 2 R_{os}} \frac{1 + s 2 R_{os} C_{s1}}{1 + s R_{os} C_0 (1 + q_{m1} 2 R_{os} + s 2 R_{os} C_{s1})}$
One important Figure of Merit (FoM) of the OTA is the
\[ CNRR = \left| \frac{\text{Add}}{\text{Acc}} \right| \quad \frac{u=0}{\frac{R_{OS}}{R_{OS} + R_{OS}}} = \frac{g_{m1} - 2R_{OS}}{g_{m1} - 2R_{OS}} \]

The expression of \( \text{Acc}(s) \) above does not take into account the effect of the CMFB circuit, whose task is to keep \( V_{OC} \) at the reference value \( V_{OC_{ref}} \), thus countereacting any variation of \( V_{OC} \).
Single-ended 5-Transistor OTA (SE-5T-OTA)

Using the same circuit of the fully-differential 5T-OTA and using either $V_{o1}$ or $V_{o2}$ as output voltage referenced to ground is not a good idea since we throw away half the signal.

Transforming $M_3$ and $M_4$ into a 1:1 current mirror allows to transfer the current signal generated by $M_1$ to the right half of the circuit, where it adds up in phase with the current signal generated by $M_2$.
Consider the Norton equivalent circuit of the SE-ST-OTA at the OTA output port:

\[ I_{sc} = \text{short-circuit current} \]

\[ Z_0 = \text{impedance at the output port with all independent sources turned-off.} \]

\[ I_{sc} : \text{ the } M_3-M_4 \text{ current mirror features a very large bandwidth (see Lecture #3)} \text{ so we may assume that } g_{m1} \cdot \frac{V_{id}}{2} \text{ is mirrored to an identical current flowing out of the drain of } M_4 \text{ into the OTA output. The current generated by } \]

\[ n_2, -g_{m2} \cdot \frac{V_{id}}{2}, \text{ flows directly to the OTA output, so that} \]
\[
V_{sc} = \alpha_{m1} V_{id}/2 + \alpha_{m2} V_{id}/2 = \alpha_{m} V_{id}
\]

since \( \alpha_{m2} = \alpha_{m1} \)

\[
Z_o = R_o \parallel \frac{1}{sC_o}
\]

\[
R_o = R_{o2} \parallel R_{o4} = R_o \parallel R_{o3}
\]

\[
C_o = C_{db2} + C_{gd1} + C_{db4} + C_{gd4}
\]

At low frequency \((w \to 0)\):

\[
V_o = \alpha_{m1} R_o V_{id} \implies A_{dm0} = \frac{V_o}{V_{id}} \bigg|_{V_{ic} = 0} = \alpha_{m1} R_o
\]

At \(w > 0\):

\[
A_{dm}(s) = \frac{\alpha_{m1} R_o}{1 + s R_o C_o}
\]

The \( M_3 - M_4 \) current mirror behavior is ideal up to very high frequency:

\[
I_{d4} = I_{d3} = -\alpha_{m1} V_{id}/2
\]

low impedance \((L3)\) node

high impedance \((H2)\) node

up to very high frequency

When we take into account the parasitic capacitances connected
At node D1 - D3 (draw of N1 and N3) then

\[ C_{d4} = C_{db1} + C_{gs1} + C_{db3} + C_{gs3} + C_{gs4} + C_{gd4} \left( 1 - \frac{V_{ds}}{V_{th1}} \right) \]

Neglect Miller’s effect on Cgd4 for simplicity (small relative error)

\[ I_{d4} = I_{g4} \frac{V_{g4}}{2} = I_{g4} \left( - \frac{V_{id}}{2} \right) \frac{1}{R_{ym3}} \left( \frac{1}{sC_{d4}} \right) \]

\[ = - \frac{I_{g4} V_{id}}{\frac{1}{sC_{d4}} + \frac{1}{R_{ym3}}} \]

\[ \omega_{ym3} = \omega_{ym4} \text{ since } \omega_{N3} = \omega_{N4} \text{ and } I_{D3} = I_{D4} = I_{B} / 2 \]

So:

\[ V_0 = \left[ - \omega_{ym2} \left( - \frac{V_{id}}{2} \right) - I_{d4} \right] R_0 \left( \frac{1}{sC_0} \right) \]

\[ = \omega_{ym1} \frac{V_{id}}{2} \left( 1 + \frac{1}{1 + s \frac{C_{d4}}{R_{ym3}}} \right) \frac{R_0}{1 + s R_0 R_0 C_0} \]

\[ = \omega_{ym1} \frac{V_{id}}{2} \left( \frac{1}{1 + s \frac{C_{d4}}{R_{ym3}}} \right) \left[ \frac{1}{1 + s R_0 C_0} \right] \]

Dominant pole: \( \omega_1 = \frac{1}{R_0 C_0} \)

Non-dominant pole: \( \omega_2 = \omega_{ym1} / C_{d4} \)

Zero: \( \omega_0 = 2 \omega_{ym3} / C_{d1} \)