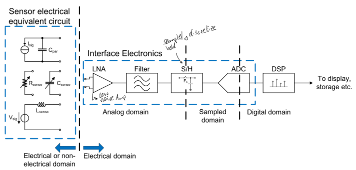
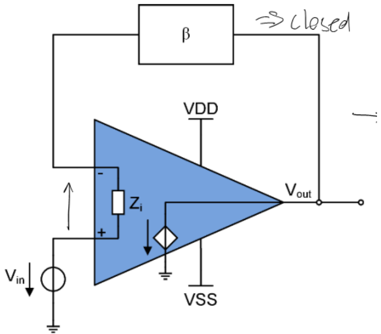
Sensor Principles

A generic sensor interface



OPAMP Basics

Opamps in feedback



Gain : $T(\omega)=\beta\cdot A_0(\omega)$
Phase Margin:
$PM=180°+\angle(T(\omega_1))|_{|T(\omega_1)|=1}$ Gain margin:$GM=20\cdot log_{10}(\frac{1}{T(\omega_2)})|_{\angle(T(\omega_2))=-180°}$ **Generic Transfer function**

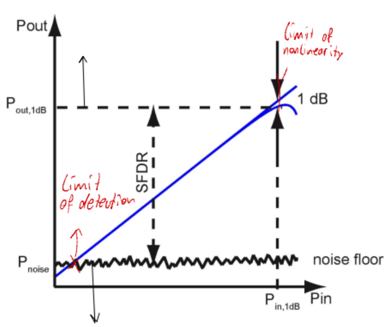
$V_x=\beta\cdot V_{out}=\beta\cdot A(\omega)\cdot(V_{in}-V_x)=\beta\cdot A(\omega)\cdot(V_{in}-\beta\cdot V_{out})$

$\frac{V_{out}}{V_{in}}=\frac{A(\omega)}{1+\beta\cdot A(\omega)}\overset{A(\omega)]\gg1}{\approx}\frac{1}{\beta}$ **Negative Feedback and linear operation**

$A(\omega)\gg1\Rightarrow$ virtual short at the input
$\Delta V\approx0$
$Z_i\to\infty\Rightarrow i_{oa}\approx0$
Voltage Drive $\to$ negative feedback
Current drive $\to$ positive feedback

Errors and Noise

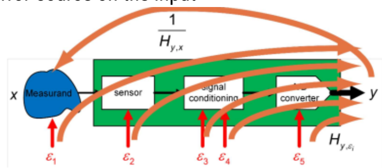
Limit of detection(LOD): minimum measurable input amplitude ($SNR\approx0$)
Dynamic range()DR: ratio of max and min amplitude within inaccuracy levels.



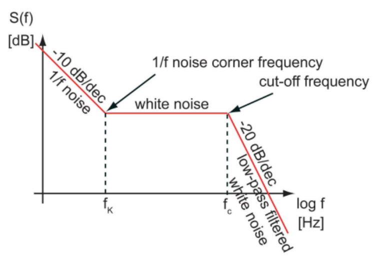
Errortypes:
Deterministic: source loading, offset, gain error
Random: thermal noise, 1/f noise
Quantification:
Absolute : $\Delta x=|\hat{x}-x_0|$
Relative: $\left|\frac{\Delta x}{x_0}\right|=\left|\frac{\hat{x}-x_0}{\hat{x}}\right|$
Max inaccuracy:
$\Delta x_{max}|x\in[\hat{x}-\Delta x_{\max},\hat{x}+\Delta x_{\max}]$
Error Propagation
$y=f\left(x_1,x_2,\ldots,x_N\right)$
Deterministic fluctuations of $x_i\to$ total error:
$\Delta y\approx\sum_{i=1}^N\frac{\partial f}{\partial x_i}\cdot\Delta x_i$
Partial derivative $\frac{\delta f}{\delta x_i}$ is called **sensitivity**
Additive errors are best specified absolute and multiplicative errors are best specified relative
Interference:
Unwanted coupling of external signal
Noise: random fluctuations from setup $\to$ can be modeled as error sources

Combining Error sources

Output referred noise
Effect of an error-source on the output
Input referred noise Equivalent effect of the error-source on the input



Find TF from ES to output
$y:H_{y,ES}\Rightarrow y_{out,\epsilon_2}=H_{y,\epsilon_2}\cdot\epsilon_2$
Refer result back to input wit
$H_{y,x}:x_{\epsilon_2}=\frac{y_{out,\epsilon_2}}{H_{y,x}}=H_{y,\epsilon_2}\cdot\frac{\epsilon_2}{H_{y,x}}$
Lin. System noise:
$PSD=S_y(f)=|H(f)|^2\cdot S_x(f)$



Noise Types

Thermal noise: excitation of charge carriers(white)
Shot noise: carriers randomly crossing the barrier, dependent on DC bias and white
Flicker Noise:, due to traps in semiconduct. 1/f spectral density. MOS trans at low freq.
Thermalnoise Theorem: Every closed system at temp. T has average. Energy of $kT/2\to$
$S_u(f)=2kTR($ double-sided $)$ math
$S_u(f)=4kTR($ single-sided $)$ physics

Langevin Approach kt/C noise

PSD noise voltage of V_n
$=S_{v_n}(f)=4kT\cdot\Re\{Z(j2\pi f)\}$
$\to\overline{V_n^2}=kT\left[\frac{1}{C_\infty}-\frac{1}{C_0}\right]=\frac{kT}{C}$
MOS IRN
$S_{\Delta V^2_{nG\text{-tot}}}=4kT\cdot R_{nG\text{-tot}}$, $R_{nG\text{-tot}}=\frac{\rho}{W\cdot L\cdot f}+\frac{\gamma_{nD}}{G_m}$ with GateExcess Noise factor
$:\gamma_{nD}=(n=1.3)\cdot[0.5WI;2/3SI]$
Bipolar Trans IRN:
$S_{\Delta V^2_{nR}}=4kT\cdot R_B$

Noise Aanalysis

small-signal-equivalent is valid.
Total ORN:
$S_{n,\,out}(f)=\sum_{k=1}^N|H_k(f)|^2\cdot S_{nk}(f)$
N uncorrelated NS.
$H_k(f)$ TF from NS ton output. IRN:
$S_{V_{neq,IRN}}(f)=\frac{S_{V_{nout}}(f)}{|A(f)|^2}$ with $A(f)$ is TF

Sensor types

Information domain $\to$ Electrical domain
Transduction: Converting a signal from the energy domain into another.
Sensors and actuators are transducers

Sources of eerror

Noise, sensitivity to unintended quantities, Noise, EMI

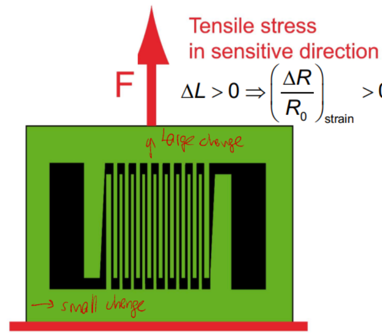
$$\begin{pmatrix}E_{mag}\\E_{mech}\\E_{therm}\\E_{opt}\\E_{chem}\\E_{elec}\end{pmatrix}=\begin{pmatrix}\alpha_{mag,mag}&\alpha_{mag,mech}&\alpha_{mag,therm}&\alpha_{mag,opt}&\alpha_{mag,chem}&\alpha_{mag,elec}\\\alpha_{mech,mag}&\alpha_{mech,mech}&\alpha_{mech,therm}&\alpha_{mech,opt}&\alpha_{mech,chem}&\alpha_{mech,elec}\\\alpha_{therm,mag}&\alpha_{therm,mech}&\alpha_{therm,therm}&\alpha_{therm,opt}&\alpha_{therm,chem}&\alpha_{therm,elec}\\\alpha_{opt,mag}&\alpha_{opt,mech}&\alpha_{opt,therm}&\alpha_{opt,opt}&\alpha_{opt,chem}&\alpha_{opt,elec}\\\alpha_{chem,mag}&\alpha_{chem,mech}&\alpha_{chem,therm}&\alpha_{chem,opt}&\alpha_{chem,chem}&\alpha_{chem,elec}\\\alpha_{elec,mag}&\alpha_{elec,mech}&\alpha_{elec,therm}&\alpha_{elec,opt}&\alpha_{elec,chem}&\alpha_{elec,elec}\end{pmatrix}\cdot\begin{pmatrix}E_{mag}\\E_{mech}\\E_{therm}\\E_{opt}\\E_{chem}\\E_{elec}\end{pmatrix}+\begin{pmatrix}E_{mag,os}\\E_{mech,os}\\E_{therm,os}\\E_{opt,os}\\E_{chem,os}\\E_{elec,os}\end{pmatrix}$$

Tandem transducers: Multiple steps to target domain.
cross-sensitivity, sensitivity to undesired quantity

Sensor classification:

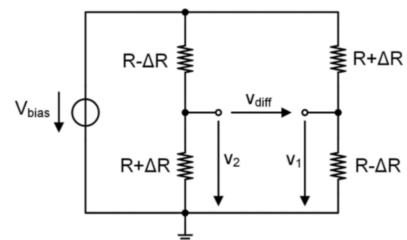
Active Sensors:
Require external source of excitation
Passive / self-generating sensors:
Generate their own electrical output signal
Draws all required energy from the measurand(source loading) E: Potentiometer for angle measurements. **Modulating sensors:**
Measure desired quantity by modulating
Additional source with modulated energy. Also adds error. E: Non0contact displacement measrement (rotating disk)
Analog vs. Digital:
Analog: time and value continuous
Digital: Discrete outputs
Deflection mode sensors:
Response to an output is a deviation from the equilibrium position
Null mode sensors:
Sensor or instruments exert an influence the measured system opposing the effect of the measurand. Ideally the result is a 0 measurement, typically achieved by feedback. The opposing influence is then the sensor output. Slower than deflection, but more accurate.
Resistive sensors - strain gauges
Change in geometry under mechanical stress produces associated resistance change
Volum. == const. $\to$
$\frac{\partial V}{V_0}=\frac{L_0}{V_0}\cdot\partial A+\frac{A_0}{V_0}\cdot\partial L\wedge\frac{\partial V}{V_0}=0\Rightarrow$
$\frac{\partial A}{A_0}=-\frac{\partial L}{L_0}\to\frac{\partial R}{R_0}=\frac{\partial\rho}{\rho_0}+2\frac{\partial L}{L_0}$
$\to\frac{\partial R}{R_0}=\alpha\cdot\frac{\partial L}{L_0}+2\frac{\partial L}{L_0}=\underbrace{(\alpha+2)}_{\triangleq k}\cdot\frac{\partial L}{L_0}$

k: gauge factor
α proportionality factor $\frac{\partial\rho}{\rho_0}\propto\frac{\partial L}{L_0}$



Readout resistive sensors

Use a half bridge resistive divider
top element sensing resistor
$\frac{v_{out}}{V_{bias}}=\frac{R}{2R+\Delta R}\Leftrightarrow\frac{\Delta R}{R}=\frac{V_{bias}}{v_{out}}-2$
Full bridge to remove offset, 2 sensing elements more sensitive,
remove nonlinearity by implementing differential measurements
Best use 4point full bridge



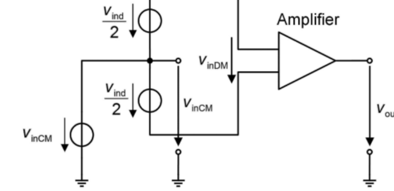
$V_{diff}=v_2-v_1=\frac{\Delta R}{R}\cdot V_{bias}$
Sensitivity $S=45mV/V$ excitation for 1V input
Accuracy $A=\frac{v_{diff}\left(\frac{\Delta R}{R}\right)-V_{diff,\,lin}\left(\frac{\Delta R}{R}\right)}{V_{diff}\left(\frac{\Delta R}{R}\right)}$
Deviation from the ideal bridge

BridgeParameters

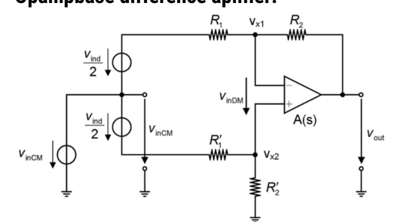
Bridge resistance: Unloaded R across the signal terminals
Offset error Outputvoltage at 0 input
Drift: Outputchange conditioned on environmental condition

Differential/ Commonmode signals

Recall: $V_1=\frac{1}{2}\cdot\left(1-\frac{\Delta R}{R}\right)\cdot V_{bias}$, $v_2=\frac{1}{2}\cdot\left(1+\frac{\Delta R}{R}\right)\cdot V_{bias}$
Differential signal:
$V_{diff}=V_2-V_1=\frac{\Delta R}{R}\cdot V_{bias}$
Common-mode signal:
$V_{CM}=\frac{v_2+v_1}{2}=\frac{V_{bias}}{2}$



DiffGain: $V_{out}=A_{DM}\cdot V_{inDM}$
CMMGain: $V_{out}=A_{CM}\cdot v_{inCM}$
Ideally A_{cm} is 0 or $A_{cm}\ll A_{dm}$
Commonmode rejection ratio(CMRR):
$CMRR\triangleq\left|\frac{A_{DM}}{A_{CM}}\right|=\left|\frac{dv_{out}/dv_{inDM}}{dv_{out}/dv_{inCM}}\right|$
Often in **dB**
Opampbase difference aplifier:



1st: $A(s)=\infty,R_2=R_2'=\alpha\cdot R_1=\alpha R_1'$
$A_{DM}=-\alpha,A_{CM}=0,CMRR=\infty$
2nd assume $A(s)=\infty,R_2=\alpha\cdot R_1$, $R_2'=(\alpha+\Delta\alpha)\cdot R_1',R_1'=R_1+\Delta R$
$A_{DM}=-\left(\alpha+\frac{\Delta\alpha}{2\cdot(1+\alpha+\Delta\alpha)}\right)$
$A_{CM}=\frac{\Delta\alpha}{1+\alpha+\Delta\alpha}$
$CMRR=-\frac{1}{2}+\frac{\alpha\cdot(1+\alpha+\Delta\alpha)}{\Delta\alpha}$
3d: $A(s)=A_{DC}/\left(1+s\cdot\frac{A_{DC}}{GBW}\right)$
$A_{DM}=-\left(\alpha+\frac{\Delta\alpha}{2\cdot(1+\alpha+\Delta\alpha)}\right)\cdot\frac{1}{1+\frac{1}{A_{DC}}+\frac{\alpha}{A_{DC}}+(1+\alpha)\cdot\frac{s}{GBW}}$
$A_{CM}=\frac{\Delta\alpha}{1+\alpha+\Delta\alpha}\cdot\frac{1}{1+\frac{1}{A_{DC}}+\frac{\alpha}{A_{DC}}+(1+\alpha)\cdot\frac{s}{GBW}}$
$CMRR=-\frac{1}{2}+\frac{\alpha\cdot(1+\alpha+\Delta\alpha)}{\Delta\alpha}$

Magnetic Field Sensors

$V_{hall}=G\cdot\frac{\mu\cdot\rho}{h}\cdot l\cdot B=G\cdot\frac{1}{e\cdot n\cdot h}\cdot l\cdot B=S_l\cdot l\cdot B$ G: geometry factor **Noise sources:**
- Thermal noise
-1/f noise
-Noise of conditioning electronics
Noise power: $V_{noise}\sqrt{4kT\cdot R\cdot\Delta f}$
Signal power: $V_{hall}S_I\cdot I\cdot B$

Resolution: $B_{\min} \hat{\wedge} \frac{V_{\text{noise}}}{V_{\text{hall}}/B} = \frac{\sqrt{4kT \cdot R \cdot \Delta f}}{S_I \cdot I}$

With $S_I = \frac{\mu \cdot \rho}{h \cdot e \cdot n} \cdot G$

At $B = 0$ Hall plate can be modeled as wheatstone bridge, non-uniform stress causes intrinsic offset(5 to 30mT)

Cancel intrinsic offset by coupling ° turned sensors, current and sense ports are swapped

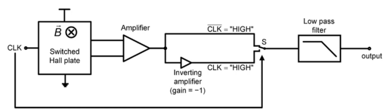
Idea: Hall voltage is in phase and gradient caused offsets are than $180°$ out of phase

Spinning current method:

Sense and current ports are switched every clock cycle

Idea: A DC component equal to the offset and a frequency component proportional to the hall voltage is produced **(Fourier Expansion of a square wave)**

By modulating the information to the clock frequency noise and offset are greatly mitigated.



Multiplying by 1 and -1 to demodulate back to low frequency.

Low pass stage to remove signal around the 2nd harmonic

This allow to see the base noise floor of the sensor not 1/f noise.

In the conventional implementation 2 bias currents are used in the low power configuration the bias form the plate is reused for the amplifier.

Temperature Sensors

Seebeck effect: Convert temp. gradient to electromotive force

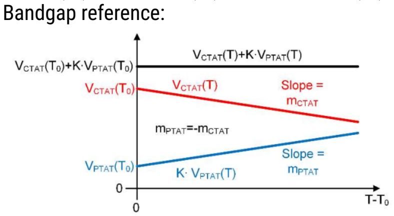
$F(T) \hat{=} \int_{T_{stand.}}^{T} (S_+(T') - S_-(T'))dT'$

$\rightarrow E_{emf} = F(T_{sense} - F(T_{ref})$

Temperature stable references:

$V_{\mathrm{REF}}(T) = V_{\mathrm{CTAT}}(T) + K \cdot V_{\mathrm{PTAT}}(T)$

Bandgap reference:



PTAT: Proportional to absolute temperature

CTAT: Complementary to absolute temperature

Scale one slope and add the function for a temp. constant reference

This can be built with a diode or a BJT with a shorted base and collector

Butt current is also temperature dependent so use diff pair.

$V_{\text{PTAT}} = \Delta V_{\text{EB}} = V_{\text{EB1}} - V_{\text{EB2}} \approx \frac{kT}{q} \cdot \ln\left[\frac{I_q \cdot I_S' \cdot A_{E2}}{I_S' \cdot A_{E1} \cdot I_q}\right] = \frac{kT}{q} \cdot \ln\left[\frac{A_{E2}}{A_{E1}}\right]$

Scale currents or diodes to make equal bias

$V_{\mathrm{EB}} = \underbrace{E_g/q}_{V_G} - \underbrace{\frac{kT}{q}}_{U_T} \cdot \ln\left(\frac{I_S'}{I_D}\right) =$

$V_G - U_T \cdot \ln\left(\frac{K_1 \cdot T^{\gamma}}{I_D}\right)$

$V_G \approx V_{G0K} - a \cdot T$

With $I_S' > I_D$ but also temperature dependent $\rightarrow$ curved CTAT.

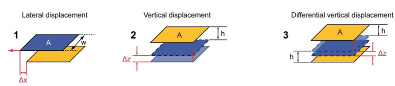
Combine CTAT and PTAT: Series:

$V_{\mathrm{REF}} = I_{\mathrm{PTAT}} \cdot R_2 + V_{\mathrm{CTAT}} = \frac{R_2}{R_1} \cdot V_{\mathrm{PTAT}} + V_{\mathrm{CTAT}}$

Parallel:

$V_{\mathrm{REF}} = (I_{\mathrm{PTAT}} + I_{\mathrm{CTAT}}) \cdot R_3 = \frac{R_3}{R_1} \cdot V_{\mathrm{PTAT}} + \frac{R_3}{R_2} \cdot V_{\mathrm{CTAT}}$

Capa. Sensor Readout

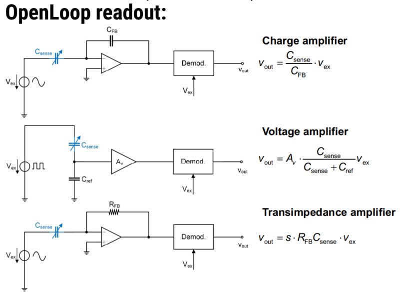


1: $\Delta C = C - C_0 = \varepsilon \cdot \frac{W}{h} \cdot \Delta x$

2: $\Delta C = \frac{\varepsilon \cdot A}{h} \cdot \frac{\Delta z/h}{1+\Delta z h} \approx \frac{\varepsilon \cdot A}{h^2} \cdot \Delta z$

3: $\Delta C = \varepsilon \cdot \frac{A}{h} \cdot \left(\frac{2 \cdot \Delta z/h}{1-[\Delta z/h]^2}\right) = \frac{2 \cdot \varepsilon \cdot A}{h^2} \cdot \Delta z$

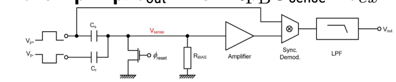
OpenLoop readout:



ChargeAmp: $V_{\text{out}} = \frac{C_{\text{sense}}}{C_{\text{FB}}} \cdot V_{\text{ex}}$ **ChargeAmp-Nonideal:** $\frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{j\omega \cdot R_{\text{FB}} C_{\text{in}}}{\left(1+\frac{j\omega}{\text{GBW}}\right) \cdot \left(1+\frac{j\omega}{\omega_{\text{FB}}}\right)}$

VoltAmp: $v_{\text{out}} = A_v \cdot \frac{C_{\text{sense}}}{C_{\text{sense}} + C_{\text{ref}}} V_{\text{ex}}$

TransImpAmp: $v_{\text{out}} = s \cdot R_{\text{FB}} C_{\text{sense}} \cdot v_{ex}$



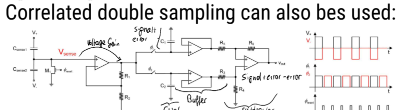
V_{Sense} not grounded sensitive to leakage currents

Bias resistor provides well defined DC-point.

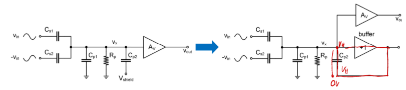
R_{Bias} needs to be large because of the highpass forming, corner frequency needs to be low enough compared to excitation freq.

Periodic reset can also be used where $V_{p+} = V_{p-} = 0$

Correlated double sampling can also bes used:



Bootstrapping: VoltAmp



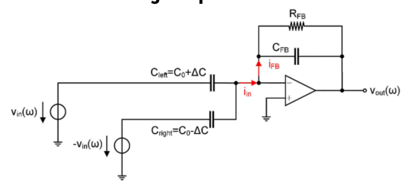
$C_{s1} = C_{s0} + \Delta C/2 C_{s2} = C_{s0} - \Delta C/2$, v_{out} becomes sensitive to parasitic capacitance

Can be bootstrapped out with voltage buffer driving V_{shield}

$v_{\text{out}} = \frac{\Delta C}{2C_{s0}+C_{p1}+(C_{p2})} \cdot A_v \cdot v_{\text{in}}$ C_{p2} gets removed by V_{shied}

Can also use TIA, the virtual ground helps with the parasitic capacitance, this also works in the charge amplifier

DiffReadoutChargeAmp:



Req V_{ex}:

Error will propagate to output directly

Accuracy more important for small ΔC

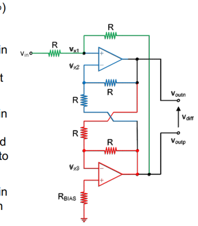
Mismatch or drift will introduce errors

Sinewave can be created with center-tapped transformer or active balun

Rectangular witch switched excitation schemes

DiffReadoutChargeAmp:

- Assuming ideal opamps ($A_{op} \mapsto \infty$)
  $\Rightarrow v_{x2} = v_{x1}, \ v_{x3} = 0$
- The part of the circuit highlighted in red is a simple inverting amplifier with input voltage v_{outn} and output voltage v_{outp}
- The part of the circuit highlighted in blue is a simple non-inverting amplifier with input voltage v_{x1} and with its reference potential pulled to v_{outp}
- The part of the circuit highlighted in green is a voltage divider between v_{in} and v_{outp}



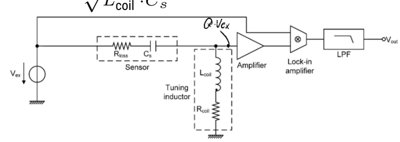
$V_{\text{outp}} = V_{\text{in}} = -V_{\text{outn}}$

Differential Capa sensing:

$\Delta v_{x,\text{ amp}} \approx -\frac{\Delta x}{x_0} \cdot V_{\text{ex}}$

Resonant readout:

$\omega_{\text{LC}} = \frac{1}{\sqrt{L_{\text{coil}} \cdot C_s}}$



DoubleDiffReadout:

$\Delta V_{\text{out}} = -\Delta V_{ex} \cdot \left(\frac{\Delta C_s}{C_i} \cdot \underbrace{\left[1 - \frac{C_s}{C_s + C_i + C_p}\right]}_{\text{gain error}} - \underbrace{\frac{\Delta C_i + \Delta C_p}{C_i} \cdot \frac{C_s}{C_s + C_i + C_p}}_{\text{offset error}}\right)$

Differential Measurements

- Inherent rejection to common-mode interference ans noise
- Wider Signal swing for a given supply voltage
- Minimum effect of even order distortion including DC offset
- Can lead to improved sensor linearity

But respond to some degree to common mode signal

Ideal DiffPair:

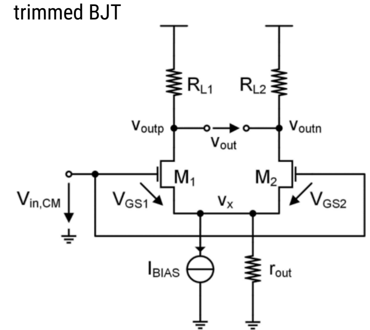
CMRR: $\triangleq 20 \cdot \log\left(\left|\frac{A_{\mathrm{DM}}}{A_{\mathrm{CM-to-DM}}}\right|\right) = 20 \cdot \log\left(\frac{2G_{\mathrm{mav}} \cdot r_{\mathrm{out}}}{\Delta R_L/R_{\mathrm{Lav}} + \Delta G_{\mathrm{m}}/G_{\mathrm{mav}}}\right]$

PSRR: $\triangleq 20 \cdot \log\left(\left|\frac{A_{\mathrm{DM}}}{A_{\mathrm{VDD}}}\right|\right) = 20 \cdot \log\left(\left|\frac{A_{\mathrm{DM}}}{\Delta V_{\mathrm{out}}/\Delta \mathrm{VDD}}\right|\right)$ Process variation causes mismatch between resistors and current source is not ideal

Input referred offset is the voltage needed to get zero volts differential output

IRO: $\Delta V_G = V_{\mathrm{OS}} = -\frac{I_{\mathrm{Dav}}}{G_{\mathrm{mav}}} \cdot \left(\frac{\Delta R_{\mathrm{L}}}{R_{\mathrm{Lav}}} + \frac{\Delta \beta}{\beta_{\mathrm{av}}}\right) - \Delta V_{\mathrm{TO}}$

OffsetVoltage: 10mV **MOS** ; 1mV **BJT**, 120 μ, trimmed BJT



$CMRR \cdot V_{os} \approx G_{mav} \cdot r_{out} \cdot V_{OV}$, $V_{OV} = \frac{I_{DAV}}{G_{mav}}$