Analog Electronic Circuits

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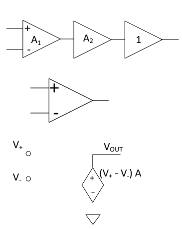
Lesson #2
Outline

- Basic OpAmp circuits
  - Summing, difference, integrator, differentiator
- Basic feedback
  - Feedback definition
  - OpAmp as feedback system
    - Non-inverting and inverting cases
- Static limitations
  - DC errors
    - Bias current, Offset voltage
  - Correction for offsets
  - Output voltage swing, input voltage range
- Dynamic limitations
  - Open-loop response
  - Gain-Bandwidth product

OpAmp characteristics

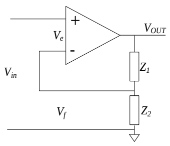


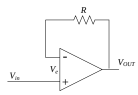
Ideal OpAmp primary features:

- Differential inputs
- Output product as function inputs $(V_+ - V_-)\,A$

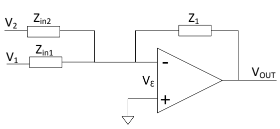
  $A = A_1 A_2 A_3$
- Infinite gain $A \to \infty$
- Infinite Bandwidth $BW \to \infty$
- Infinite input resistance $R_{in} \to \infty$
- Zero output resistance $R_{out} \to 0$

Non-inverting Amp



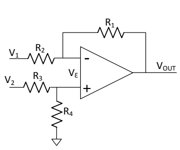


Summing Amp



$$V_{out} = -\left[V_1\left(\frac{Z_1}{Z_{in1}}\right) + V_2\left(\frac{Z_1}{Z_{in2}}\right)\right]$$

Difference Amp



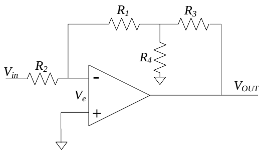
$$V_{out\_1} = -V_1\left(\frac{R_1}{R_2}\right)$$

$$V_{out\_2} = V_2\left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_1}{R_2}\right)$$

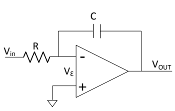
$$\frac{R_2}{R_1} = \frac{R_3}{R_4}$$

$$V_{out} = \frac{R_1}{R_2}(V_2 - V_1)$$

Feedback forces zero error state

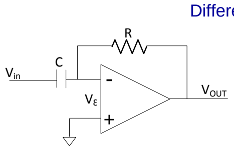


Integrator Amp



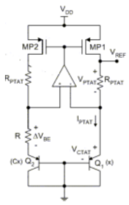
$$V_{out} = \frac{1}{SC} / \frac{1}{R} V_{in} = \frac{1}{SCR} V_{in}$$

Differentiator Amp

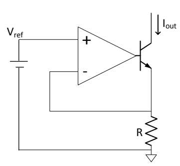


$$V_{out} = SC/RV_{in} = SCR\, V_{in}$$

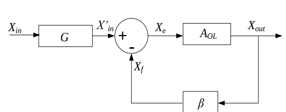
Voltage reference by OpAmp (Bandgap)



Current source by OpAmp



Negative Feedback



$$A_{CL} = \frac{X_{out}}{X_{in}} = G\frac{A_{OL}}{1+\beta A_{OL}}$$

$$A_{CL}\Big|_{\beta A_{OL}\gg 1} = \frac{G}{\beta}$$

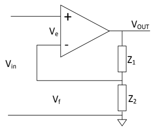
$$A_{CL}\Big|_{\beta A_{OL}\ll 1} = GA_{OL}$$

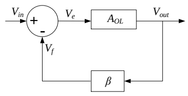
$$A_{OL} = \frac{X_{out}}{X_e}$$

$$G = \frac{X'_{in}}{X_{in}}\Big|_{X_{out}=0} = \frac{X_e}{X_{in}}\Big|_{X_{out}=0}$$

$$\beta = \frac{X_f}{X_{out}}\Big|_{X_{in}=0} = \frac{X_e}{X_{out}}\Big|_{X_{in}=0}$$

Feedback
Non-inverting Amp



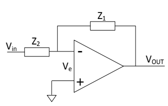


$$G = \left.\frac{V_e}{V_{in}}\right|_{V_{out}=0} = 1$$

$$\beta = \left.\frac{V_e}{V_{out}}\right|_{V_{in}=0} = \frac{Z_2}{Z_1+Z_2}$$

$$A_{CL}|_{\beta A_{OL}\gg 1} = \frac{G}{\beta} = \frac{1}{\frac{Z_2}{Z_1+Z_2}} = \frac{Z_1+Z_2}{Z_2} = 1+\frac{Z_1}{Z_2}$$

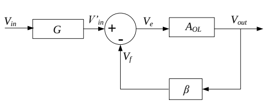
Feedback
Inverting Amp



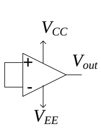
$$G = \left.\frac{V_e}{V_{in}}\right|_{V_{out}=0} = \frac{Z_1}{Z_1+Z_2}$$

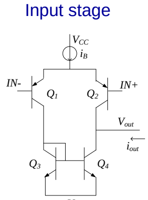
$$\beta = \left.\frac{V_e}{V_{out}}\right|_{V_{in}=0} = \frac{Z_2}{Z_1+Z_2}$$

$$A_{CL}|_{\beta A_{OL}\gg 1} = \frac{G}{\beta} = -\frac{\frac{Z_1}{Z_1+Z_2}}{\frac{Z_2}{Z_1+Z_2}} = -\frac{Z_1}{Z_2}$$



Static limitations
Input stage





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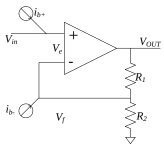
Bias current
Non-inverting Amp



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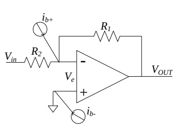
Bias current
Inverting Amp



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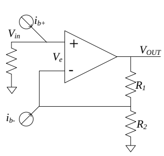
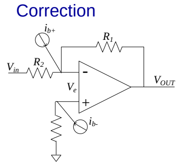
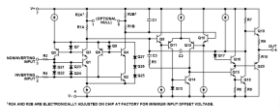
Bias current
Correction

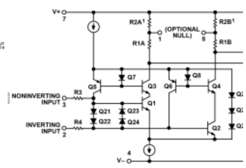




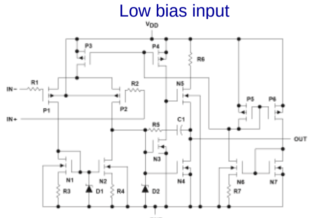
Bias current
Input bias cancellation



OP-07 (Analog Devices)

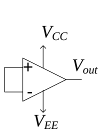


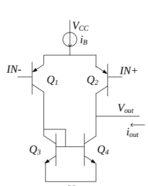
Bias current
Low bias input



TL08x (Texas Instruments)

Static limitations
Offset voltage





$$\beta = \frac{V_e}{V_{out}}\bigg|_{V_{in}=0} = \frac{Z_2}{Z_1+Z_2}$$

$$i_{out} = g_m(V_+ - V_-) \qquad g_m = \frac{i_B}{2V_T}$$

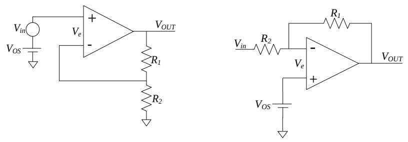
$$i_{C1} + i_{C2} = i_B$$

$$i_C = I_S e^{\left(\frac{V_{BE}}{V_T}\right)}$$

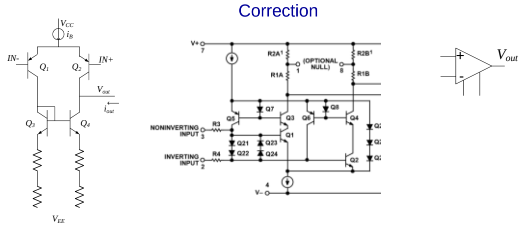
$$\frac{i_{C1}}{i_{C2}} = \frac{I_{S1}}{I_{S2}} e^{\left(\frac{V_{BE1}-V_{BE2}}{V_T}\right)}$$

$$I_{S1} = I_{S2}, V_{E1} = V_{E2} \quad ; \quad \frac{i_{C1}}{i_{C2}} = e^{\left(\frac{V_+ - V_-}{V_T}\right)}$$

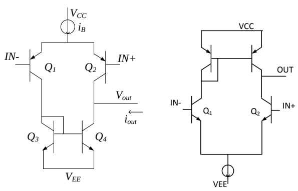
Offset voltage



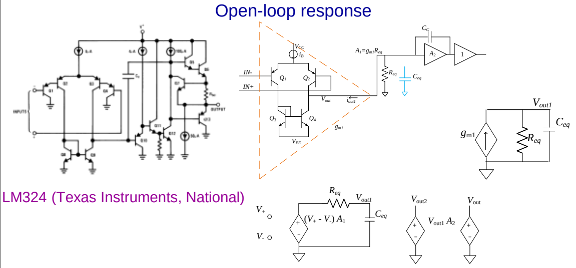
Offset voltage
Correction



Maximum ratings (Basic)

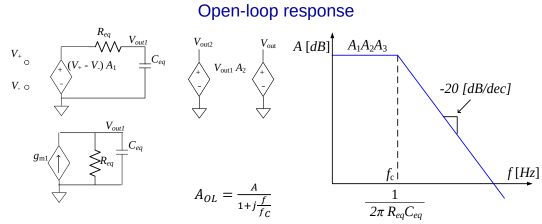


Open-loop response



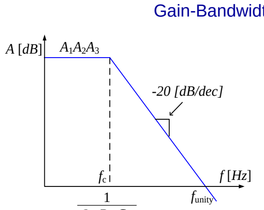
LM324 (Texas Instruments, National)

Open-loop response



$$A_{OL} = \frac{A}{1 + j\frac{f}{f_C}}$$

Gain-Bandwidth Product - GBW



$$A_{CL} = G\frac{A_{OL}}{1 + \beta A_{OL}}$$

$$\beta = 1, G = 1$$

$$A_{CL} = \frac{A_{OL}}{1 + A_{OL}}$$

$$GBW = f_{unity}$$