

Prof. Mor M. Peretz Analog Electronic Circuits 361-1-3671 [1]
 THE CENTER FOR POWER ELECTRONICS AND MIXED-SIGNAL IC, BEN-GURION UNIVERSITY

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

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OpAmp characteristics

Ideal OpAmp primary features:

- Differential inputs
- Output product as function inputs $(V_+ - V_-) A$
 $A=A_1A_2A_3$
- Infinite gain $A \rightarrow \infty$
- Infinite Bandwidth $BW \rightarrow \infty$
- Infinite input resistance $R_{in} \rightarrow \infty$
- Zero output resistance $R_{out} \rightarrow 0$

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Non-inverting Amp

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Summing Amp

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

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Difference Amp

$$V_{out,1} = -V_1 \left(\frac{R_3}{R_2} \right)$$

$$V_{out,2} = V_2 \left(\frac{R_4}{R_3 + R_4} \right) \left(1 + \frac{R_3}{R_2} \right)$$

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

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

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Feedback forces zero error state

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Integrator Amp

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

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Differentiator Amp

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

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Voltage reference by OpAmp (Bandgap)

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Current source by OpAmp

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Negative Feedback

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

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

$$\beta = \left. \frac{X_f}{X_{out}} \right|_{X_{in}=0} = \left. \frac{X_e}{X_{out}} \right|_{X_{in}=0}$$

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

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

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

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Feedback Non-inverting Amp

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

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

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

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Feedback Inverting Amp

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

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

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

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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**

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Bias current Input bias cancellation

OP-07 (Analog Devices)

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Bias current Low bias input

TL08x (Texas Instruments)

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Static limitations Offset voltage

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

$$i_{out} = g_m(V_+ - V_-)$$

$$i_{c1} + i_{c2} = i_B \quad g_m = \frac{i_B}{2V_T}$$

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

$$\frac{i_{c1}}{i_{c2}} = \frac{I_{S1}}{I_{S2}} e^{\left(\frac{V_{BE1} - V_{BE2}}{V_T}\right)}$$

$$I_{S1} = I_{S2}, V_{BE1} = V_{BE2} \quad ; \quad \frac{i_{c1}}{i_{c2}} = e^{\left(\frac{V_+ - V_-}{V_T}\right)}$$

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Offset voltage

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Offset voltage Correction

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Maximum ratings (Basic)

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Open-loop response

LM324 (Texas Instruments, National)

V_{i1}
 V_{i2}
 V_{out1}
 V_{out2}
 V_{out}

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Open-loop response

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

$A_{OL} = A_1 A_2 A_3$
 $f_c = \frac{1}{2\pi R_{cp} C_{cp}}$

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Gain-Bandwidth Product - GBW

$A_{CL} = G \frac{A_{OL}}{1 + \beta A_{OL}}$
 $\beta = 1, G = 1$
 $A_{CL} = \frac{A_{OL}}{1 + A_{OL}}$
 $GBW = f_{unity}$
