Introduction to Interface Electronics

- Lumped Circuit Elements
- General Amplifiers
- Operational Amplifiers

Reading: Senturia, Chapter 14, p.353-395
## Lumped Circuit Elements

- **Linear 1-port (2-terminal) passive devices**
  - Resistor: energy dissipation
  - Capacitor: energy storage
  - Inductor: energy storage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Basic Relationship</th>
<th>Voltage-Current Relationships</th>
<th>Energy</th>
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<tbody>
<tr>
<td>$R$</td>
<td>$v = Ri$</td>
<td>$v_R = Ri_R$</td>
<td>$w_R = \int_{-\infty}^{t} v_R i_R , dt$</td>
</tr>
<tr>
<td>$G = \frac{1}{R}$</td>
<td></td>
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<tr>
<td>$L$ (or $M$)</td>
<td>$\psi = Li$</td>
<td>$v_L = L \frac{di_L}{dt}$</td>
<td>$w_L = \frac{1}{2} L i^2$</td>
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<td>$C$</td>
<td>$q = Cv$</td>
<td>$v_C = \frac{1}{C} \int_{-\infty}^{t} i_C , dt$</td>
<td>$w_C = \frac{1}{2} C v^2$</td>
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<td>$D = \frac{1}{C}$</td>
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</table>
Lumped Circuit Elements

- Non-linear 1-port (2-terminal) passive devices
  - P/N junction diode
  - Nonlinear I-V characteristic

\[ i_D = I_S \left( \frac{qv_D}{e^{kT}} - 1 \right) \]

Note: Diode voltage, \( v_D = V_D + v_d \)

\[ DC: \quad I_D = I_S \left( \frac{qV_D}{e^{kT}} - 1 \right) \]

\[ Small - signal: \quad i_d = \left( \frac{qI_D}{kT} \right) v_D = \frac{1}{r_d} v_d \]

Ref. Sedra and Smith, Microelectronic Circuits, p. 132.
Low-frequency large-signal equivalent circuit

High-frequency small-signal equivalent circuit

Bias point: \( I_D, V_D \)

\[
r_d = nV_T/I_D
\]

\[
C_d = \left( \tau_T/V_T \right) I_D
\]

\[
C_j = C_{j0}/\left( 1 - \frac{V_D}{V_0} \right)^m \quad \text{for } V_D < 0
\]

\[
C_j \approx 2C_{j0}, \text{ for } V_D > 0
\]

Ref. Sedra and Smith, Microelectronic Circuits, p. 170.
Zener Diode

- Exploits very sharp current-voltage characteristic at reverse breakdown for voltage regulation

\[ \Delta V = \Delta I \cdot r_z \]

Ref. Sedra and Smith, Microelectronic Circuits, p. 172.
Diode Circuits

AC-to-DC converter

Ref. Sedra and Smith, Microelectronic Circuits, p. 176, 184.
Active Devices

Sources

- Energy supplied into system from external source (sometimes not shown)
  - Independent voltage source
    - with series source resistance
  - Independent current source
    - with shunt source resistance
Active Devices

- Sources
  - Dependent sources
    - Dependent voltage source
    - Dependent current source

Ref. Van Valkenbur, Network Analysis, p. 38.
Active Devices -- BJT & MOSFET

- Cross-section
  - N/P/N Bipolar Junction Transistor (BJT)
  - n-channel Metal Oxide Semiconductor Field Effect Transistor (n-channel MOSFET)

Active Devices -- BJT & MOSFET

- Common-emitter configuration
  - $i_C$ vs. $v_{CE}$ DC characteristics with base-emitter voltage (or base current) as parameter
- Other configurations are common-base and common-collector

- Common-source configuration
  - $i_D$ vs. $v_{DS}$ DC characteristics with gate-to-source voltage as parameter
- Other configurations are common-gate and common-drain

Active Devices -- BJT & MOSFET

- BJT High-Frequency Small-signal Equivalent Circuit

- MOSFET High-Frequency Small-signal Equivalent Circuit

● Signal Amplification

Voltage gain, $A_v \equiv \frac{v_o}{v_i} \quad (20 \log |A_v| \ dB)$

Current gain, $A_i \equiv \frac{i_o}{i_i} \quad (20 \log |A_i| \ dB)$

Power gain, $A_p \equiv \frac{P_o}{P_i} = \frac{v_o i_o}{v_i i_i} \quad (10 \log A_p \ dB)$

Note: We will discuss the frequency response later.

Ref. Sedra and Smith, Microelectronic Circuits, p. 11.
General Amplifiers

- **Amplifier Saturation**
  - hard limit at power supply limits
  - Jargon: “rail” = power supply
    - rail-to-rail

- **Amplifier Nonlinearity**

  \[
  A_v = \left. \frac{dv_O}{dv_I} \right|_{\text{At operating point (known also as Quiescent point)}}
  \]

  Ref. Sedra and Smith, Microelectronic Circuits, p. 16.
• **Voltage Amplifier Equivalent Circuit**

\[ R_i \equiv \text{input resistance} \]
\[ R_O \equiv \text{output resistance} \]
\[ A_{V0} \equiv \text{open circuit voltage gain} \]

• **Voltage amplifier with signal source and load connected**

\[ v_O = (A_{V0}v_i) \frac{R_L}{R_L + R_O} \]
\[ v_i = v_S \frac{R_i}{R_i + R_S} \]

Overall gain:
\[ \frac{v_O}{v_S} = A_{V0} \frac{R_i}{R_i + R_S} \frac{R_L}{R_L + R_O} \]

General Amplifiers

- Frequency Response of Amplifiers

For a linear circuit, for a sinusoidal input, $v_i(t) = V_i \sin \omega t$, the output is sinusoidal with the same frequency:

$v_o(t) = V_o \sin(\omega t + \phi)$

Amplifier transfer function, $T(\omega)$:

$|T(\omega)| = \left| \frac{V_o}{V_i} \right|_{\text{function of } \omega}$

$\angle T(\omega) = \phi_{\text{function of } \omega}$

Analyze amplifier circuit in the complex frequency variable (s- or Laplace-domain).

Ref. Sedra and Smith, Microelectronic Circuits, p. 20, 21.
Frequency Response of Amplifiers

Capacitively coupled ac-amplifier

Direct-coupled dc-amplifier

Tuned or bandpass amplifier

Ref. Sedra and Smith, Microelectronic Circuits, p. 26..
Review of Single Time-Constant Networks

- circuits that can be reduced to one reactive component (capacitance or inductance) and one resistive component

Ref. Sedra and Smith, Microelectronic Circuits, p. 22.
Low Pass Filter

Replacing the circuit elements with their impedances,

\[ R \rightarrow R \text{ and } C \rightarrow \frac{1}{sC} \]

\[ T(s) = \frac{V_o(s)}{V_i(s)} = \frac{1}{1 + sRC} = \frac{1}{1 + \frac{s}{\omega_0}} \]

where \( \omega_0 = \frac{1}{\tau} = \frac{1}{RC} \). Replacing \( s \) with \( j\omega \),

\[ |T(j\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_0}\right)^2}} \]

\[ \angle T(j\omega) = -\tan^{-1}\left(\frac{\omega}{\omega_0}\right) \]

Ref. Sedra and Smith, Microelectronic Circuits, p. 22.
Single Time-Constant Networks

- Magnitude and Phase Response of Low Pass STC Network

Ref. Sedra and Smith, Microelectronic Circuits, p. 32.


High Pass Filter

Replacing the circuit elements with their impedances,

\[ R \rightarrow R \text{ and } C \rightarrow \frac{1}{sC} \]

\[ T(s) = \frac{V_o(s)}{V_i(s)} = \frac{sRC}{sRC + 1} = \frac{s}{s + \omega_0} \]

where \( \omega_0 = \frac{1}{\tau} = \frac{1}{RC} \). Replacing \( s \) with \( j\omega \),

\[ |T(j\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega_0}{\omega}\right)^2}} \]

\[ \angle T(j\omega) = \tan^{-1}\left(\frac{\omega_0}{\omega}\right) \]

Ref. Sedra and Smith, Microelectronic Circuits, p. 22.
Single Time-Constant Networks

- Magnitude and Phase Response of High Pass STC Network

\[ T(j\omega) = \frac{1}{1 + j\omega RC} \]

Ref. Sedra and Smith, Microelectronic Circuits, p. 33.
Amplifier Frequency Response

Find the amplifier voltage transfer function, DC gain, and high frequency roll-off.

Ref. Sedra and Smith, Microelectronic Circuits, p. 33.
Single Time-Constant Networks

- **Direct-coupled amplifier with input capacitance**

\[
V_o(s) = \frac{R_L}{R_L + R_o} A_{V0} V_i(s) \quad \text{and} \quad V_i(s) = \frac{R_i // \frac{1}{sC_i}}{R_i // \frac{1}{sC_i} + R_S} V_s(s)
\]

\[
T(s) = \frac{V_o(s)}{V_i(s)} = \left[ A_{V0} \frac{1}{1 + \frac{R_o}{R_L}} \frac{1}{1 + \frac{R_s}{R_i}} \right] \left( \frac{1}{1 + sC_i \left( R_S // R_i \right)} \right)
\]

This voltage transfer function has the same form as the low pass STC network.

**DC gain:** \( T(s)_{s \rightarrow 0} = \left[ A_{V0} \frac{1}{1 + \frac{R_o}{R_L}} \frac{1}{1 + \frac{R_s}{R_i}} \right] \)

**High frequency rolloff:** \( \omega_0 = \frac{1}{\tau} = \frac{1}{C_i \left( R_S // R_i \right)} \)

Ref. Sedra and Smith, Microelectronic Circuits, p. 22.
Single Time-Constant Networks

- **Direct-coupled Amplifier with Input Capacitance**

Example: \( R_s = 20k\Omega, R_i = 100k\Omega, C_i = 60\, \text{pF} \)

\[
A_{V_0} = \frac{144}{V} \frac{V}{V}, \quad R_o = 200\Omega, \quad R_L = 1k\Omega
\]

DC gain:

\[
K = \left[ A_{V_0} \frac{1}{R_o} \frac{1}{1 + \frac{R_s}{R_L}} \frac{1}{1 + \frac{R_i}{R_i}} \right] = 100 \frac{V}{V}
\]

High frequency rolloff:

\[
\omega_0 = \frac{1}{\tau} = \frac{1}{C_i \left( \frac{R_s}{R_i} \right)} = 159kHz
\]

Capacitively-coupled Voltage Amplifier

Example: Capacitively coupled ideal voltage amplifier

\[ T(s) = \frac{V_o(s)}{V_i(s)} = A_{v0} \frac{s}{s + \frac{1}{RC}} \]

High frequency gain:
\[ K = A_{v0} = 100 \]

Low frequency rolloff:
\[ \omega_0 = \frac{1}{\tau} = \frac{1}{RC} = 15.9 \text{Hz} \]

Ref. Sedra and Smith, Microelectronic Circuits, p. 33.
Application: Piezoresistive Microphone

- Capacitively coupled amplifier used to reject DC offset

Operational Amplifiers

- Basic building block for analog signal processing circuits
  - First integrated circuit operational amplifier, μ709, made by Fairchild Semiconductor in 1960s followed by the μ741.
  - Consists of active transistors, resistors, and limited number of capacitors
  - Approximated by single-pole frequency response
- Three stages
  - Differential amplifier stage
    - Amplifies difference between two inputs
  - High-gain amplifier stage
  - Output amplifier stage

Operational Amplifiers

- u741 Opamp
Operational Amplifiers

Wide variety of operational amplifiers:
• High power
• Low power
• Precision
• Low noise

National Semiconductor

LM741
Operational Amplifier

General Description
The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications. The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

Connection Diagrams

Metal Can Package

Dual-In-Line or S.O. Package

Order Number LM741J, LM741J/L883, LM741CN
See NS Package Number J08A, M08A or N08E

Order Number LM741H, LM741H/L883 (Note 1)

Note 1: LM741H is available per JM38510/10101

EEL5225: Principles of MEMS Transducers (Fall 2003)
### Operational Amplifiers

#### Absolute Maximum Ratings

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<th>LM741A</th>
<th>LM741</th>
<th>LM741C</th>
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<tbody>
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<td><strong>Supply Voltage</strong></td>
<td>±22V</td>
<td>±22V</td>
<td>±18V</td>
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<td><strong>Power Dissipation</strong></td>
<td>500 mW</td>
<td>500 mW</td>
<td>500 mW</td>
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<td><strong>Differential Input Voltage</strong></td>
<td>±30V</td>
<td>±30V</td>
<td>±30V</td>
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<tr>
<td><strong>Input Voltage</strong></td>
<td>±15V</td>
<td>±15V</td>
<td>±15V</td>
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<td><strong>Output Short Circuit Duration</strong></td>
<td>Continuous</td>
<td>Continuous</td>
<td>Continuous</td>
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<td><strong>Operating Temperature Range</strong></td>
<td>−55°C to +125°C</td>
<td>−55°C to +125°C</td>
<td>0°C to +70°C</td>
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<td><strong>Storage Temperature Range</strong></td>
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<td>−65°C to +150°C</td>
<td>−65°C to +150°C</td>
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<td><strong>Junction Temperature</strong></td>
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<td>150°C</td>
<td>100°C</td>
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<td><strong>Soldering Information</strong></td>
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<td>N-Package (10 seconds)</td>
<td>260°C</td>
<td>260°C</td>
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<td>J- or H-Package (10 seconds)</td>
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<td>300°C</td>
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<td>M-Package</td>
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<td>Vapor Phase (60 seconds)</td>
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<td>215°C</td>
<td>215°C</td>
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<td>Infrared (15 seconds)</td>
<td>215°C</td>
<td>215°C</td>
<td>215°C</td>
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</table>

See AN-450 “Surface Mounting Methods and Their Effect on Product Reliability” for other methods of soldering surface mount devices.

**ESD Tolerance (Note 8)**

<table>
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<th>LM741A</th>
<th>LM741</th>
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<td>400V</td>
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#### Electrical Characteristics

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<th>LM741C</th>
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<td>Typ</td>
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<td>Input Offset Voltage</td>
<td>$T_A = 25^\circ C$</td>
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### Operational Amplifiers

#### Electrical Characteristics (Note 5)

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<td>Max</td>
<td>Min</td>
<td>Typ</td>
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<td>Average Input Offset</td>
<td>Voltage Drift</td>
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<td>$\mu V/^\circ C$</td>
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<td>$V_S = \pm 20 V$</td>
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<td></td>
<td>V</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
</tbody>
</table>
Operational Amplifiers

- General input signals
  - Differential signal from transducer
  - Common mode signal
    - For example, 60 Hz electromagnetic interference appearing on both inputs

\[
v_+ = \frac{v_d}{2} + v_{cm}
\]

\[
v_- = -\frac{v_d}{2} + v_{cm}
\]

- Differential gain

\[
A_d = \frac{v_o}{v_d} = \frac{v_o}{(v_+ - v_-)}
\]

- Common-mode gain

\[
A_{cm} = \frac{v_o}{v_{cm}} = \frac{v_o}{(v_+ + v_-) / 2}
\]

Common Mode Rejection Ratio (CMRR)

\[
CMRR = \frac{A_d}{A_{cm}} \text{ or } 20 \log \left| \frac{A_d}{A_{cm}} \right|
\]

Actual opamps, CMRR range from 1000 to 100,000 (60dB to 100dB)

Operational Amplifiers

- Voltage Follower
  - Output follows input
  - $V_o = V_i$
- Serves as buffer
- Very high input impedance
- Low output impedance

![Operational Amplifier Diagram]

$V_{out} = V_{in}$
Operational Amplifiers

- **Non-inverting Amplifier**

  Short op-amp analysis method:
  
  Assume that the input current is zero (infinite input impedance) and $e=0$ ($v_+ \approx v_-$).

  Using this method, we can analyze the transfer function for the non-inverting amplifier:

  \[
  \frac{v_o}{v_s} = 1 + \frac{R_1}{R_2}
  \]

  If $R_2 = \infty$, $\frac{v_o}{v_s} = 1$

  [Unity-gain buffer or voltage follower.]

Operational Amplifiers

- **Inverting Amplifier**

Open-loop gain is $A$.

Equating currents:

$$\frac{V_s - \varepsilon}{R_1} = \frac{\varepsilon + A\varepsilon}{R_2}$$

Closed-loop gain:

$$\frac{V_o}{V_s} = -\frac{R_2}{R_1} \left[ \frac{1}{1 + \frac{1}{A} \left( 1 + \frac{R_2}{R_1} \right)} \right] \longrightarrow -\frac{R_2}{R_1}$$

∴ $\varepsilon \rightarrow 0$ when $A \rightarrow \infty$.

Inverting Amplifier

What is the frequency response of this configuration?

Replace \( A \) with the STC single-pole response, \( A(s) = \frac{A_0}{1 + \frac{s}{s_0}} \).

Substituting the single-pole response for \( A \) gives:

\[
\frac{V_o}{V_s} = -\frac{R_2}{R_1} \left[ \frac{A_0s_0}{A_0s_0 + \left( 1 + \frac{R_2}{R_1} \right)(s + s_0)} \right]
\]

with a DC gain of \( \frac{R_2}{R_1} \) and 3dB frequency determined by the pole at \( s_0 = -\frac{A_0 + 1 + \frac{R_2}{R_1}}{1 + \frac{R_2}{R_1}} \).

Note that the gain-bandwith product is preserved: \( A_0s_0 \).

Operational Amplifiers

- **Transimpedance Amplifier**

Since the input current is negligible,

\[ v_o = -R_1 I_s \]

The transimpedance amplifier (voltage at output proportional to current at input) is used as a current-to-voltage converter.

Operational Amplifiers

**Integrator**

Since the input current is negligible and the voltage at $v_-$ is approximately the same as $v_+$ at ground,

$$\frac{v_s - 0}{R_1} = i_c = C \frac{dv_c}{dt}$$

$$v_c = \frac{1}{R_1 C} \int V_s(t) dt$$

Note that the output voltage, $v_o = -v_c$.

Therefore,

$$v_o = -\frac{1}{R_1 C} \int V_s(t) dt \quad \text{[Output is integral of input!]}$$

Note: The integrator circuit is extremely sensitive to parasitic DC leakage currents.

**Differentiator**

Similarly, we find that for the differentiator circuit,

\[ v_o = -R_1 C \frac{dv_s}{dt} \quad \text{[Output is derivative of input!]} \]

Note: The output of the differentiator is limited by how fast the output of the op-amp can change, defined by the slew rate = \( \frac{\text{change in output voltage}}{\text{time}} \). Typical slew rates are on the order of 1V/\( \mu \text{sec} \).