Lecture 2 – Analog circuits

Seeing the light…..

IR detection

Noise sources:
• Electrical (60Hz, 120Hz, 180Hz….)
• Other electrical
• IR from lights
• IR from cameras (autofocus)
• Visible light

Q1 OP805
Vout
+V
V1
9V
RL

What we want: 0 – 5 V DC signal representing the IR amplitude.

Analog circuits – filtering and detection

Amplify
Filter
Peak detect

IR detect
DC block

Analog circuits – discrete devices: BJT

Application: light detection

Phototransistor:
Acts like BJT except charge carriers generated by incident light add to the base current.

In other words, \( I_c = I_t \); Incident light

V1
Q1
OP805
RL

For the circuit below,

1) Smaller R increases the DC sensitivity to light
2) Larger R increases the DC sensitivity to light

Selecting \( R_L \)….

Vout = \( I_c \cdot R_L \)
Analog circuits – filtering and detection

What is the result of the following:

\[ \frac{Z_2}{Z_1} = 3 \]

\[ V_{out} = \frac{Z_2}{Z_1} V_{in} \]

1) 2) 3) 4)

DC block circuit

Capacitors:
- Open circuits for DC
- Short circuit at high frequencies

Analog circuits: Op-amps

Ideal op-amp:

\[ V_{out} = K (V_i - V_c) \]
\[ K = 10^6 \text{ (at DC!)} \]

With feedback to limit gain:

\[ V_{out} = K (V_i - V_{sat}) \]
\[ V_{sat} = V_i (1+K) = KV_i \]
\[ V_{sat} = V_i (K/(1+K)) \]
\[ V_{sat} = V_i \]

When negative feedback is applied to an op-amp, \( V_i = V_c \).

...if the amplifier is within its operating range.

The next few slides will show some bad design choices.
Analog circuits: Op-amps

Eg: Inverting amplifier.

\[ V_{in} - Z_1 I_1 = V_{out} \]

\[ V_{out} = 0 - Z_2 I_1 \]

\[ V_{out} = - (Z_2/Z_1) V_{in} \]

10x gain is a “reasonable” value

Eg 1: \( Z_2 = 100k\Omega \)
\( Z_1 = 10k\Omega \)
\( V_{out} = - 10 V_{in} \)

Eg 2: \( Z_2 = 100k\Omega \)
\( Z_1 = 1 \Omega \)
\( V_{out} = - 100,000 V_{in} \)

Not likely….

Analog circuits: Real Op-amps

Eg 2: \( Z_2 = 100k\Omega \)
\( Z_1 = 1 \Omega \)
\( V_{out} = - 100,000 V_{in} \)

Several problems:

- \( I_1 = 1A \) for \( V_{in} = 1 \) V !! (excessive load for upstream circuitry)
- Gain Bandwidth product \( \sim 3 \) MHz. This would limit the bandwidth of the amplifier from DC up to 30 Hz (i.e. not a very responsive system).

Analog circuits: Real Op-amps

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations

Since \( V_{in} \) is a virtual ground, input impedance seen by \( V_{in} \) is \( Z_1 \)

Analog circuits: Real Op-amps

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations

Since Op-amp inputs source or sink very little current (depends on type), input impedance in this case is very high. This is a commonly used buffer to separate your low impedance circuit from a sensitive source that you need to measure without drawing current.

Gain-Bandwidth limit (Hz) = Gain * Max. Frequency = CONSTANT
TL082: Gain*Bandwidth = 3 MHz

This means that at a gain of 100, Bandwidth is 30 kHz.

**Analog circuits: Real Op-amps**

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations

Op-amp terminals can act as small current sources. These Bias Currents can become large error or offset voltages if the resistors in the circuit are large.

Eg: 20 nA bias current * 10 MΩ = 200 mV!

**Analog circuits: Real Op-amps**

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current limitations

Op-amp input voltages ($V_+, V_p$) must be at least a few volts away from the power rails ($+Vcc, -Vcc$). Applying input voltages equal or near the power rails will cause the Op-amp to behave unexpectedly.

Rail-to-rail Op-amps are an expensive solution to this limitation.

**Analog circuits: Real Op-amps**

Things to consider:

- Input impedance
- Gain Bandwidth product
- Bias Currents
- Voltage limitations
- Output current / voltage limitations

Op-amp output terminals can only provide a few mA of current. Motors, lamps and similar high current devices cannot typically be driven by a normal OP-amp. High power OP-amps exist that can provide much higher current levels. Output voltage range is also limited within a few volts of the power rails.
Q: We wish to amplify a 100 kHz, 10mV p-p sine wave, as much as possible. Which is the best circuit?

1)  

2)  

3)  

Analog circuits: Real Op-amps  
Application: amplifier stages

Total gain: 30*30*11 = 9900  
Input impedance = high  
Max Bandwidth = 100 kHz

Analog circuits – filtering and detection

Which is the correct match between the following time-domain (left) signals and their Fourier Transforms (right)?

a)  

b)  

c)  

d)  

1) a-i, b-iv, c-ii, d-iii  
2) a-ii, b-iv, c-iii, d-i  
3) a-iii, b-iv, c-i, d-ii  
4) a-iv, b-ii, c-iii, d-i

Analog circuits: Filters  
To understand filters you should first understand the difference between the TIME DOMAIN and FREQUENCY DOMAIN
Analog circuits: Filters

Demo: Frequency generator and Spectrum analyzer

- Frequency Generator
- Spectrum Analyzer

“Transfer Function” = \[ \frac{V_{out}}{V_{in}} = H(\omega) \]

So: \[ V_{out}(\omega) = H(\omega)V_{in}(\omega) \]

This is all in terms of \( \omega \) since, in general, impedances are functions of \( \omega \).

Similar to voltage divider, except \( \omega \)-dependent.

\[ Z_{cap} = \frac{1}{j\omega C} \]
\[ Z_{ind} = j\omega L \]
\[ Z_{res} = R \]

Now plug in a resistor and a capacitor:

<table>
<thead>
<tr>
<th>Frequency Generator</th>
<th>[ V_{in} ]</th>
<th>[ Z_{1} ]</th>
<th>[ V_{out} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum Analyzer</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For low frequencies (small \( \omega \)), \( H = 1 \)
For high frequencies (large \( \omega \)), \( H = 0 \)

This is a LOW PASS FILTER

\[ f_0 = \frac{1}{2\pi RC} = 30 \text{ Hz} \]
Analog circuits: Transfer Functions

**Bode plots:** a graphical representation of frequency response on logarithmic axes.

**Vertical axis:**

\[ \text{dBV} = 20 \log_{10}(V) \]
-3 dB = 1/2 as much power as 0 dB
\[ V_{in} \] is 1/\sqrt{2} of \[ V_{out} \] at -3dB

**Horizontal axis:**

\[ \log_{10}(f) \]
Log of frequency is used to ensure linear plots from 1/f or 1/f^2 functions

**Pole:** \( \frac{1}{1+j\omega C} \)
-20 db/decade in amplitude after \( \omega_p \), -90 phase

**Zero:** \( \frac{1+j\omega}{C} \)
+20 db/decade in amplitude after \( \omega_p \), +90 phase

Analog circuits: Filters

**Transfer Functions**

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

**Bode Plot:**

-3dB, 1/RC
-20dB/decade / pole
-45 deg, 30 Hz
-90 deg / pole

**Simple Pole**

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

**Bode Plot:**

-3dB, 1/RC
-20dB/decade
-45 deg, 1/RC
-90 deg

**Simple Zero**

\[ H(\omega) = 1 + j\omega RC \]

**Bode Plot:**

+3dB, 1/RC
+20dB/decade
+45 deg, 1/RC
+90 deg

Analog circuits: Simple Pole

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

**Bode Plot:**

-3dB, 1/RC
-20dB/decade
-45 deg, 1/RC
-90 deg

**Filters**

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

**Bode Plot:**

-3dB, 1/RC
-20dB/decade
-45 deg, 30 Hz
-90 deg / pole
Analog circuits: **Filters**

How does this circuit affect the following waveform:

1)  
2)  
3)  
4)  

Analog circuits: **Active Filters**

Active Band Pass:

\[ Z_1 = \left( \frac{1}{R} + j\omega C_1 \right) \]

\[ Z_2 = R_2 + \frac{1}{j\omega C_2} \]

\[ H(\omega) = -\frac{Z_1}{Z_2} \]

Analog circuits: **Active Filters**

Idealized Bode Plot:

Zero at \( \omega = 0 \)

Pole at \( \omega = 1/(R_1C_1) \)

Pole at \( \omega = 1/(R_2C_2) \)

Analog circuits: **Active Filters**

Which best describes the amplitude response (Bode plot) of the following transfer function (\( R_1C_1 > R_2C_2 \)):

\[ H(\omega) = \frac{1}{1 + j\omega R_1C_1} \]

\[ H(\omega) = \frac{1}{1 + j\omega R_2C_2} \]

1)  
2)  
3)  
4)  

Analog circuits: **Active Filters**

Idealized Bode Plot:

Zero at \( \omega = 0 \)

Pole at \( \omega = 1/(R_1C_1) \)

Pole at \( \omega = 1/(R_2C_2) \)
**Analog circuits – filtering and detection**

- **IR detect**
- **DC block**
- **Amplify**
- **Filter**

**Use multiple stages to get steeper filter roll-offs…**

\[ H_{eq}(\omega) = H_1(\omega) \times H_2(\omega) \times H_3(\omega) \]

Remember –20dB/dec for each POLE

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**Debugging Circuits**

Learn to systematically check your circuits:

- **Power rails:**
  - Check that 15V is really 15V; if not, localize the component that is shorting the power rail.
- **Physical check:**
  - Check pinouts, missing/loose wires, etc.
- **Isolate stages** where possible
  - Check output of stage 1 – if ok plug into stage 2 and see if stage 1 output is degraded.
  - If ok check output of stage 2 etc
- **Keep wiring TIDY!**

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**DISCUSSION Q:** What is wrong with this circuit, when implemented with a TL082 OP-AMP?