Lecture 3: Opamp Review

- Inverting amplifier
- Generalized impedances
  - Inverting integrator
  - Inverting differentiator
- Weighted summer
- Non-inverting amplifier
- Voltage buffer
- Non-linear amplifiers

First, assume ideal op amp.

Basic Opamp

- Op amp is a circuit that has two inputs and one output.
- It amplifies the difference between the two inputs.
Inverting Amplifier

- **Note:**
  - Negative feedback
  - Find close loop gain

- **Analysis**

  **Virtual short circuit:** Due to infinite gain of op amp, the circuit forces $V_2$ to be close to $V_1$, thus creating a virtual short.

  
  Closed loop gain

  \[ \frac{V_o}{V_i} = -\frac{R_2}{R_1} \]

Inverting Amplifier

- **Note** that the virtual ground is not actually shorted to ground; otherwise this would force all the current flowing through R2 to ground and Vout would be zero.

- The behavior of the virtual ground is similar to a seesaw, where the point between the two arms is pinned (does not move), allowing the displacement at point A to be “amplified” (and “inverted”) at point B.
Non-inverting amplifier

- A noninverting amplifier returns a fraction of output signal thru a resistor divider to the negative input.
- With a high $A_0$, $V_{out}/V_{in}$ depends only on ratio of resistors, which is very precise.

\[
\frac{V_{out}}{V_{in}} = \frac{R_2 + R_1}{R_2} = 1 + \frac{R_1}{R_2}
\]

Extreme Cases of $R_2$ (Infinite $A_0$)

- If $R_2$ is zero, the loop is open and $V_{out}/V_{in}$ is equal to the intrinsic gain of the op amp.
- If $R_2$ is infinite, the circuit becomes a unity-gain amplifier and $V_{out}/V_{in}$ becomes equal to one.
Unity Gain Amplifier

- Why use this if $V_{out} = V_{in}$?

$$A_0 = 1000$$

Another View of Inverting Amplifier

- For large $R_1/R_2$, magnitude of closed loop gain is roughly the same. Why use one over the other?
Voltage Adder or Weighted Summer

- Replace R1 and R2 with impedances, Z1 and Z2.
- The closed-loop gain is still equal to the ratio of two impedances.
- Transfer function:
  - Magnitude
  - Phase

Ref. Sedra and Smith, Fig. 2.10.

Current summation at inverting node:

Output voltage:

Complex Impedances Around the Op Amp

- Replace R1 and R2 with impedances, Z1 and Z2.
- The closed-loop gain is still equal to the ratio of two impedances.
- Transfer function:
  - Magnitude
  - Phase
Example: Inverting Integrator

\[ V_{in} = \frac{1}{R_1} \int V_{in}(t) dt \]

\[ V_{out} = \frac{1}{R_1 C_1} \int V_{in}(t) dt \]

\[ \omega_{int} = \frac{1}{R_1 C_1} \]

Is the integrator frequency

Note that at \( \omega = 0 \), the impedance of \( C_1 \) is infinite and the opamp operates open loop (i.e. no negative feedback). That is, the gain at DC is infinite, as the open loop gain is infinite. This should also be obvious from the transfer function:

\[ \frac{V_{out}}{V_{in}} = -\frac{1}{R_1 C_1 s} \]

where the root of the denominator, or pole of the transfer function, is at zero (i.e. DC). In practice, since at DC the opamp is in open loop configuration, any DC offsets will saturate the output. How do you fix this?
Integrator with Pulse Input

\[ V_{out} = -\frac{1}{RC_1} \int V_{in} dt = -\frac{V_1}{R_1 C_1} t \quad 0 < t < T_b \]

Comparison of Integrator and RC Lowpass Filter
Lossy Integrator

Consider the case when $A_0$ is finite.

$$\frac{V_{out}}{V_{in}} = \frac{-1}{\frac{1}{A_0} + \frac{1}{A_0} R C s}$$

- When finite op amp gain is considered, the integrator becomes lossy as the pole moves from the origin to $-1/[(1+A_0)R_1C_1]$.
- It can be approximated as an RC circuit with $C$ boosted by a factor of $A_0+1$.

Note: pole frequencies are obtained by setting the denominator of the transfer function to zero.

Differentiator

Time domain:

$$i(t) = C \frac{dV(t)}{dt}, \quad v_0(0) = -RC \frac{dV(t)}{dt}$$

$$V_{out} = -RC_1 \frac{dV_{in}}{dt}$$

$$\frac{V_{out}}{V_{in}} = -\frac{R}{C_1 s} = -R C_1 s$$

Frequency domain:

$$V_s(s)/V_t(s) = -\frac{R}{s RC}$$

$$\mid V_s(j\omega)/V_t(j\omega) \mid = \omega RC = \frac{\omega}{\omega_{max}}$$

$$\angle V_s(j\omega)/V_t(j\omega) = -90 \degree$$

$$\frac{V_s(j\omega)}{V_t(j\omega)} = -j\omega RC \quad \omega_{max} = \frac{1}{RC}$$
Differentiator with Pulse Input

\[ V_{out} = \mp R_1 C_1 V_1 \delta(t) \]

Comparison of Differentiator and High-Pass Filter
Lossy Differentiator

Consider the case when $A_0$ is finite

$$
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{-R_1C_1s}{1 + \frac{1}{A_0} + \frac{R_1C_1s}{A_0}}
$$

- When finite op amp gain is considered, the differentiator becomes lossy as the zero moves from the origin to $-(A_0+1)/R_1C_1$.

- It can be approximated as an RC circuit with $R$ reduced by a factor of $(A_0+1)$.

Precision Rectifier

Suppose we want to eliminate the diode voltage drop (i.e. dead zone) associated with a simple rectifier circuit.

Assume a unity-gain buffer tied to the resistive load. High gain of opamp ensures $X$ tracks $V_{\text{in}}$.

Insert a diode to "break" connection and hold $X$ at zero during negative cycles. Assume $V_{\text{in}}=0$; the opamp raises $V_y$ to $V_{\text{don}}$ to hold $X$ at roughly zero. If $V_{\text{in}}$ becomes positive, $X$ tracks. If $V_{\text{in}}$ becomes negative, $V_y$ goes negative. Since $D_1$ cannot carry current (reversed biased), the opamp produces a very large negative output (near the negative rail).
Inverting Precision Rectifier

- When $V_{\text{in}}$ is positive, the diode is on, $V_y$ is pinned around $V_{D\text{,on}}$ and $V_x$ at virtual ground.
- When $V_{\text{in}}$ is negative, the diode is off, $V_y$ goes extremely negative, and $V_x$ becomes equal to $V_{\text{in}}$.

Logarithmic Amplifier

- By inserting a bipolar transistor in the loop, an amplifier with logarithmic characteristic can be constructed.
- This is because the current to voltage conversion of a bipolar transistor is a natural logarithm.
- Logamps are useful in applications where the input signal may vary by a large factor. In such cases, weak signals are amplified and strong signals are attenuated (compressed), hence the log dependence.
- Logamps implement the inverse function of the exponential characteristic

\[ V_{\text{out}} = -V_T \ln \frac{V_{\text{in}}}{R_1 I_S} \]
Square-Root Amplifier

- By replacing the bipolar transistor with a MOSFET, an amplifier with a square-root characteristic can be built.
- This is because the current to voltage conversion of a MOSFET is square-root.
- Similar to the logamp using a bipolar transistor in the feedback path, the square root amp implements the inverse function of the MOS quadratic current dependence on VGS.

\[ V_{out} = - \sqrt{\frac{2V_{ds}}{\mu_c W L R_i}} - V_{th} \]