Lecture 5

Michael Brodskiy
Professor: M. Onabajo

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- Finite Open-Loop Gain and Bandwidth
  - Assumptions during most previous examples
    * Infinite A_{0OL} (subscript "0" indicates DC gain)
    * Gain independence with respect to frequency ("flat gain")
  - Open-loop gain of a typical (real) op-amp:
    * Single-pole approximation (F_{BOL} = break frequency)
    * High-frequency roll-off with -20dB/dec (single-pole approximation — for first order filters, can approximate $f_t = A_{0OL}f_{BOL}$)
    * f_t = transition frequency (unity-gain)
- Mathematical Representation of Finite Gain/Bandwidth
  - A_{0OL} = DC gain, $\omega_=$ break frequency, ω_t = unity-gain frequency
  - Op-amp model with a transfer function of a single-pole low-pass filter:

$$A(\omega) = \frac{A_{0OL}}{1 + (j\omega/\omega_B)},\ |A(\omega)| = \frac{A_{0OL}}{\sqrt{1 + \left(\dfrac{\omega}{\omega_B}\right)^2}}$$

- Inverting Amplifier Analysis
  - High closed-loop gain (high R_2/R_1 ratio) reduces the closed-loop break frequency
- Closed-Loop Gain versus Break Frequency Trade-off
  - Fundamental gain-bandwidth (GBW) product limitation:

$$f_t = A_{0OL}f_{BOL} = A_{0CL}f_{BCL}$$

- When $f >> f_B$:

$$|A(f)| \approx A_{0OL} \cdot \frac{f_B}{f} = \frac{f_t}{f}$$

- Closed-Loop: Gain Bandwidth $\propto f_{\text{3dB}}$
  - When an op-amp is connected in a feedback configuration, the gain-bandwidth product (f_t) remains unchanged
  - The 3dB frequency (break frequency) depends on feedback network components
  - Gain-bandwidth product ($f_t = A_{0OL} f_{BOL}$)
- Large-Signal Operation: Voltage Swing
  - Output voltage swing limitation
    * The output voltage can only be in the following range:

$$V_{S-} + x < V_o < V_{S+} - x$$

    * The output limits should be specified in the manufacturers datasheet
  - Clipping (saturation) occurs if the above condition is not met
- Linear Operating Range
  - The input/output transfer characteristic of an op-amp (with a specified supply) voltage provide valuable information about large-signal operation
- Large-Signal Operation: Current Restrictions
  - Op-amps have specified output current limits
  - The op-amp must source/sink the current to/from load impedance (and feedback network elements)
  - Careful: Small load or feedback resistors $\rightarrow$ high I_o
  - Clipping occurs when $I_o > I_{\text{limit}}$ would be required, but $I_o = I_{\text{limit}}$
- Finite Open-Loop Gain and Bandwidth

$$A(f) = \frac{A_{0OL}}{1 + j(f/f_{BOL})}$$

  - Closed-Loop Impact of Finite Gain/Bandwidth
    * Inverting amplifier: $G = -\frac{R_2}{R_1}$
    * Non-inverting amplifier: $G = 1 + \frac{R_2}{R_1}$
    * For both cases: $f_{\text{3dB}} \approx \frac{f_t}{1+(R_2/R_1)}$

- Output Slew-Rate Limitation

$$\left|\frac{dv_o(t)}{dt}\right| \leq SR$$

  - The magnitude of the output voltage's rate of change can not exceed the slew-rate (SR) specification of the op-amp
  - Typical 10^5[V/s] $< SR <$ 10^8[V/s]
  - Usually the SR is specified with load resistance conditions

- DC Imperfections of Op-Amps

  - Bias Current (I_B)
    - Required for proper operation of internal circuitry (or resulting from unwanted leakage currents)
    - Typical range: 0.1[nA] − 1[µA]
    - $I_B = (I_{B+} - I_{B-})/2$
    - I_{B+} and I_{B-} flow at the respective terminals
  - Offset Current (I_{off})
    - $|\pm I_{off}| = |I_{B+} - I_{B-}| < 200$[nA] normally
    - Results from internal device mismatches (transistors, resistors, etc.)
  - Offset Voltage (V_{off})
    - Due to internal device mismatches
    - $|\pm V_{off}| <$ a few millivolts

- Analysis Procedure with DC Imperfections

  - Draw a schematic diagram in which the source for a single DC imperfection is included (modeled)
  - Replace all other sources
    - Voltage source → short circuit
    - Current source → open circuit
  - Follow standard circuit analysis laws and ideal op-amp assumptions