Practical Op-Amps

• Linear Imperfections:
  – Finite open-loop gain \( A_0 < \infty \)
  – Finite input resistance \( R_i < \infty \)
  – Non-zero output resistance \( R_o > 0 \)
  – Finite bandwidth / Gain-BW Trade-off

• Other (non-linear) imperfections:
  – Slew rate limitations
  – Finite swing
  – Offset voltage
  – Input bias and offset currents
  – Noise and distortion
Offset Voltage
Trimming of Offset Voltage

The output dc offset voltage of an op amp can be trimmed to zero by connecting a potentiometer to the two offset-nulling terminals. The wiper of the potentiometer is connected to the negative supply of the op amp.
Input Bias Currents and Offset Currents

- Some op-amps (bipolar) have input bias currents that need to flow for the op-amp to function properly.

- They are typically very small, ~ 100 nA, but may differ slightly (by 10 nA)

\[
I_B = \frac{I_{B1} + I_{B2}}{2}
\]

\[
I_{OS} = |I_{B1} - I_{B2}|
\]

MOS \( I_B = 0 \)

BJT

Bipolar \( I_B \neq 0 \)

Junction Transistor

off set
Effect of Input Bias Current in Amplifier Circuit

In the absence of input voltage, the output should be zero for ideal Op Amp. However, with non-zero $I_B$,

$$V_O = I_{B1}R_2 \approx I_B R_2$$

$$V^- = V^+ = 0$$

$$I_1 = 0$$

$$I_2 = I_{B1} \neq 0$$

$$V_O = V^- + I_2R_2 = I_{B1}R_2$$

$0\text{mA} \times 1\text{k} \Omega \Rightarrow 0.1V$
Reducing the Effect of Input Bias Currents

\[ V^+ = 0 - I_{B2} R_3 \]
\[ V^- = V^+ = -I_{B2} R_3 \]
\[ I_1 = \frac{V^-}{R_1} = \frac{I_{B2} R_3}{R_1} \]
\[ I_2 = I_{B1} - I_1 \]
\[ I_{B1} \approx I_{B2} \]
\[ U_0 = V^- + I_2 R_2 \]
\[ = -I_{B2} R_3 + \left(I_{B1} - I_{B2} R_3\right) \frac{R_2}{R_1} \]
\[ = I_B \left(R_2 - \frac{R_3 R_2}{R_1} - R_3\right) \]
\[ = I_B \left(R_2 - R_3 \left(\frac{R_2}{R_1} + 1\right)\right) \rightarrow 0 \]

\[ R_3 = \frac{R_2}{\frac{R_2}{R_1} + 1} = \frac{R_1 R_2}{R_1 + R_2} \]

\[ U_0 = I_{OS} R_2 \]
\[ I_{OS} \approx 10\% \cdot I_B \]
Output Saturation

• The output voltage swing is limited by
  1. Saturation voltage (usually a volt or two lower than power supply voltage)
  2. Maximum output current (in case of small load resistance)

• Output waveform appears to be “clipped” when either condition happens
Slew Rate

Amplifier output is limited by "slew rate": maximum rate of change possible at output

\[ SR = \left. \frac{dv_o}{dt} \right|_{max} = \text{Spec.} \quad SR = 1 \text{ V/μs} \]

\[ v_o = 10 \text{ V} \quad t = \frac{10 \text{ V}}{SR} = 10 \text{ μs} \]

SR is specified in datasheet in V/μs.

Note

SR limit is different from bandwidth limit:

- Limited bandwidth is a linear phenomenon, it does not change the shape of input sinusoid
- SR limitation can cause nonlinear distortion to input sinusoidal signal
Comparison of Slew Rate and Bandwidth Limits

For step function input waveform, both SR and bandwidth limits cause the output to rise with a finite slope, but there is an important difference:

Slew rate limited output: 
Slope = SR

Bandwidth limited output: 
Slope = \omega_t V < SR
(V is the steady state output voltage)
Full-Power Bandwidth

For sinusoidal input to unity-gain follower:

\[ v_i = V_i \sin{\omega t} \]

\[ v_c = V_c \sin{\omega t} \]

Rate of change:

\[ \frac{dv_c}{dt} = V_c \omega \cos{\omega t} \leq 1 \]

\[ \frac{dv_i}{dt} = V_i \omega \cos{\omega t} \leq \text{SR} \]

Max slope:

\[ = V_c \omega \leq \text{SR} \]

Full-power bandwidth:

The frequency at which SR-limited distortion starts to occur for an output sinusoid with maximum rated output voltage, \( V_{o \text{max}} \),

\[ \omega_M V_{o \text{max}} = \text{SR} \]

\[ f_M = \frac{SR}{2\pi V_{o \text{max}}} \]
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<th>Slew Rate (Typ) (V/µs)</th>
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<th>Vos (Offset Voltage @ 25C) (Max) (mV)</th>
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