CHAPTER 02

Operational Amplifiers (Op-amp)

Surface mount: small-outline integrated circuit (SOIC) package

Dual-in-line package (DIP)
The Op-amp

**Figure 2.1** Circuit symbol for the op amp.

**Figure 2.2** The op amp shown connected to dc power supplies (dual or single supply).

Requires DC power to run, amplifies ac signal.
The Ideal Op-amp

1. Infinite input impedance
2. Zero output impedance
3. Zero common-mode gain (i.e., infinite common-mode rejection)
4. Infinite loop-gain $A (A=\infty)$
5. Infinite bandwidth
Differential and Common-mode signals

\[ v_{Id} = v_2 - v_1 \]

\[ v_{Icm} = \frac{1}{2}(v_1 + v_2) \]

**Figure 2.4** Representation of the signal sources \( v_1 \) and \( v_2 \) in terms of their differential and common-mode components.
Model of internal of an op-amp by circuit

\[ G_m v_1 \]

\[ G_m v_2 \]

\[ R \]

\[ \mu v_d \]
Inverting Configuration

Current at a node
($I_{in} = I_{out}$)

The inverting closed-loop configuration.
An analyzing an inverting amplifier

Figure 2.6 Analysis of the inverting configuration. The circled numbers indicate the order of the analysis steps.

- $R_{in} = R_1$
- $R_{out} = 0$

$v_i = 0$ (Virtual ground)

$v_o = \frac{-R_2}{R_1} v_i$

$Gain \equiv \frac{v_o}{v_i} = -\frac{R_2}{R_1}$
Figure 2.7 Analysis of the inverting configuration taking into account the finite open-loop gain of the op-amp.
Example 2.2. The circled numbers indicate the sequence of the steps in the analysis.

\[
\frac{v_O}{v_I} = -\frac{R_2}{R_1} \left(1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right)
\]
Figure 2.9 A current amplifier based on the circuit of Fig. 2.8. The amplifier delivers its output current to $R_4$. It has a current gain of $(1 + R_2/R_3)$, a zero input resistance, and an infinite output resistance. The load ($R_4$), however, must be floating (i.e., neither of its two terminals can be connected to ground).
A weighted summer (using superposition technique).

\[ v_o = -\left(\frac{R_f v_1}{R_1} + \frac{R_f v_2}{R_2} + \cdots + \frac{R_f v_n}{R_n}\right) \]

A weighted summer capable of implementing summing coefficients of both signs.
Figure 2.13 Analysis of the non-inverting circuit. The sequence of the steps in the analysis is indicated by the circled numbers.
Non-Inverting Configuration

1. Effect of finite loop gain

\[ G \equiv \frac{V_0}{V_i} = \frac{1 + \left(\frac{R_2}{R_1}\right)}{1 + \left(\frac{R_2}{R_1}\right) + \frac{R_2}{A}} \]

\[ \%\text{gain\_error} = -\frac{1 + \left(\frac{R_2}{R_1}\right)}{A + 1 + \left(\frac{R_2}{R_1}\right)} \times 100 \]

2. Input/output impedance
- Infinite input
- Zero output

3. Voltage follower

Microelectronic Circuits, Sixth Edition
Single Op-amp Difference Amplifiers

Given

\( v_{o2} = v_{i2} \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1}\right) = \frac{R_2}{R_1} v_{i2} \)

\( (R_4 / R_3) = (R_2 / R_1) \)
Figure 2.20 A popular circuit for an instrumentation amplifier. (a) Initial approach to the circuit
Instrumentation Amplifier
(buy, don’t build)

AD623ARZ

Figure 2.20 (c) Analysis of the circuit assuming ideal op amps.
Figure 2.22 The inverting configuration with general impedances in the feedback and the feed-in paths.
Integrators

\[ v_C(t) = V_C + \frac{1}{C} \int_0^\infty i_1(t) dt \]

\[ v_O(t) = -\frac{1}{CR} \int_0^t v_I(t) dt - V_C \]

\[ \frac{V_o}{V_i} = -\frac{1}{sCR} \]

\[ |\frac{V_o}{V_i}| \text{ (dB)} \]

\[ -6 \text{ dB/octave} \]
Differentiator

\[ i(t) = \frac{d}{dt} v_I(t) \]

\[ v_O(t) = -CR \frac{d}{dt} v_I(t) \]

\[ \frac{V_o}{V_i} = -sCR \]

\[ |\frac{V_o}{V_i}| \text{ (dB)} \]

\[ \omega = \frac{1}{CR} \]

+6 dB/octave
Figure 2.39 Open-loop gain of a typical general-purpose internally compensated op amp.
Figure 2.40 Frequency response of a closed-loop amplifier with a nominal gain of +10 V/V.
Figure 2.42 (a) A non-inverting amplifier with a nominal gain of 10 V/V designed using an op amp that saturates at ±13-V output voltage and has ±20-mA output current limits. (b) When the input sine wave has a peak of 1.5 V, the output is clipped off at ±13 V.
Figure 2.43 (a) Unity-gain follower. (b) Input step waveform. (c) Linearly rising output waveform obtained when the amplifier is slew-rate limited. (d) Exponentially rising output waveform obtained when $V$ is sufficiently small so that the initial slope ($\omega_i V$) is smaller than or equal to SR.
Figure 2.44 Effect of slew-rate limiting on output sinusoidal waveforms.
EE 221 Lab

(Check EE 221 class website)