Chapter 13 Operational Amplifiers

1. Characteristics of ideal op amps.
2. Negative feedback in op-amp circuits.
3. Summing-point constraint.
4. Analysis of various op-amp circuits.
5. Practical op-amp limitations.
6. Active filters.

Ideal operational amplifiers

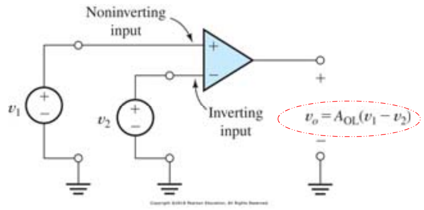


Figure 13.1 Circuit symbol for the op amp.

Characteristics of Ideal Op Amps

- Infinite gain for the differential input signal
- Infinite input impedance
- Zero output impedance
- Infinite bandwidth

Equivalent Circuit or Model of Ideal Op Amps

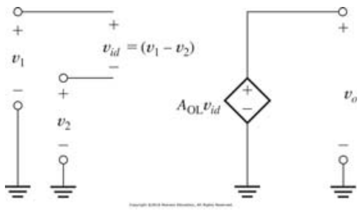


Figure 13.2 Equivalent circuit for the ideal op amp. The open-loop gain A_{OL} is very large (approaching infinity).

Op Amps showing dc power supplies

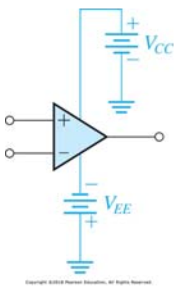


Figure 13.3 Op-amp symbol showing the dc power supplies, V_{CC} and V_{EE} .

How to use operational amplifiers?

Negative Feedback

Negative Feedback

Operational amplifiers are almost always used with negative feedback, in which part of the output signal is returned to the input in opposition to the source signal.

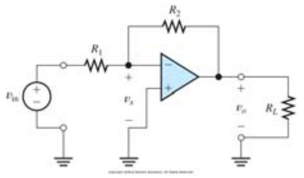


Figure 13.4 The inverting amplifier.

Summing-point constraint

In a *negative feedback* system, the ideal op-amp output voltage attains the value needed to force the differential input voltage and input current to zero. We call this fact the **summing-point constraint.**

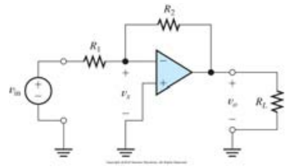


Figure 13.4 The inverting amplifier.

How to analyze ideal op-amp circuits?

Analysis procedure of ideal op-amp circuits:

1. Verify that *negative* feedback is present.
2. Assume that the differential input voltage and the input current of the op amp are forced to zero. (This is the summing-point constraint).
3. Apply standard circuit-analysis principles, such as Kirchhoff's laws and Ohm's law, to solve for the quantities of interest.

Case study: Inverting amplifier

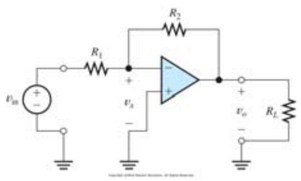


Figure 13.4 The inverting amplifier.

$$A_v = \frac{v_o}{v_{in}} = ?$$

Analysis of inverting amplifier

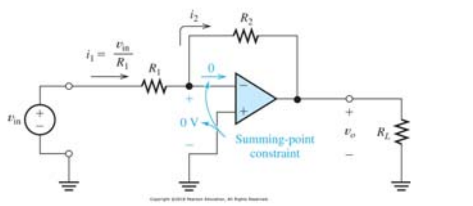
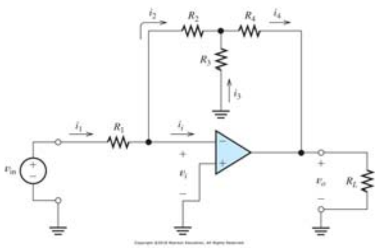


Figure 13.5 We make use of the summing-point constraint in the analysis of the inverting amplifier.

Case Study: Example 13.1



$A_v = ?$

$R_{in} = ?$

$R_o = ?$

Figure 13.6 An inverting amplifier that achieves high gain magnitude with a smaller range of resistance values than required for the basic inverter. See Example 13.1.

$$i_i = 0, \quad v_i = 0 \quad \Longrightarrow \quad i_1 = i_2 = \frac{v_{in}}{R_1}$$

$$R_2 i_2 = R_3 i_3$$

$$i_4 = i_2 + i_3$$

$$v_o = -R_4 i_4 - R_3 i_3$$

$$v_o = -v_{in}\left(\frac{R_2}{R_1} + \frac{R_4}{R_1} + \frac{R_2 R_4}{R_1 R_3}\right)$$

$$A_v = \frac{v_o}{v_{in}} = -\left(\frac{R_2}{R_1} + \frac{R_4}{R_1} + \frac{R_2 R_4}{R_1 R_3}\right)$$

Exercise 13.1

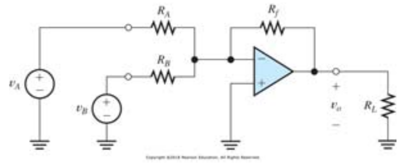


Figure 13.7 Summing amplifier. See Exercise 13.1.

What is the output in terms of inputs? What is the input impedance? What is the output impedance?

Exercise 13.3

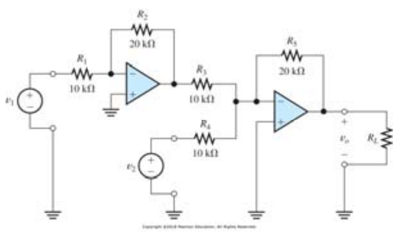


Figure 13.9 Circuit for Exercise 13.3.

Positive Feedback

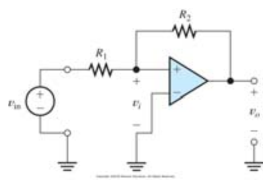


Figure 13.10 Circuit with positive feedback.

With positive feedback, the op amp's input and output voltages increase in magnitude until the output voltage reaches one of its extremes.

Noninverting amplifiers

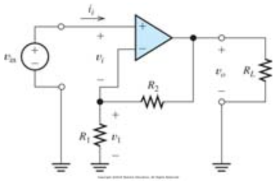


Figure 13.11 Noninverting amplifier.

Under the ideal-op-amp assumption, the non-inverting amplifier is an ideal voltage amplifier having infinite input resistance and zero output resistance.

Voltage Follower

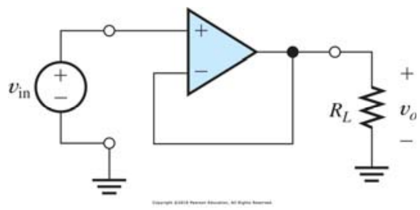


Figure 13.12 The voltage follower which has $A_v = 1$.

Case Study: Exercise 13.4

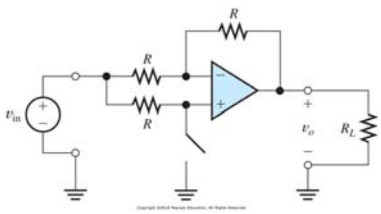
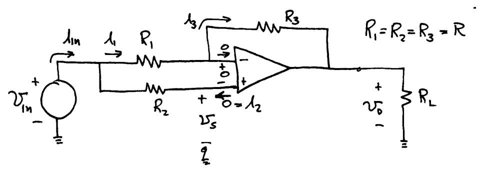


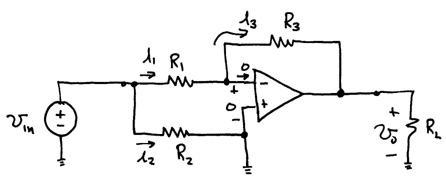
Figure 13.13 Inverting or noninverting amplifier. See Exercise 13.4.

$$Find \quad v_o / v_i$$



$i_2 = 0 \qquad v_s = v_{in} + R_2 i_2 = v_{in} \qquad i_1 = \dfrac{v_{in} - v_s}{R_1} = 0$

$i_3 = i_1 = 0 \qquad i_{in} = i_1 - i_2 = 0 \qquad v_o = R_3 i_3 + v_s = v_{in}$



$i_1 = \dfrac{v_{in}}{R_1} = \dfrac{v_{in}}{R} \qquad i_2 = \dfrac{v_{in}}{R_2} = \dfrac{v_{in}}{R} \qquad i_{in} = i_1 + i_2 = \dfrac{2v_{in}}{R}$

$\boxed{R_{in} = \dfrac{R}{2}} \qquad i_3 = i_1 = \dfrac{v_{in}}{R_1}$

How to design simple amplifiers

- selecting a suitable circuit configuration
- selecting values for the feedback resistors

Case Study: Example 13.2: gain of 10

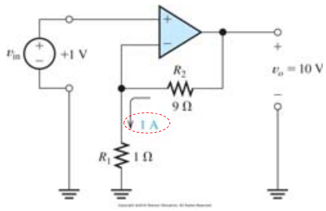


Figure 13.16 If low resistances are used, an excessively large current is required.

If the resistances are too small, an impractical amount of current and power will be needed to operate the amplifier.

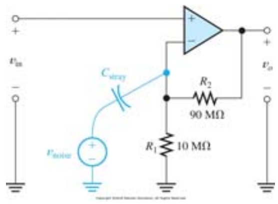


Figure 13.17 If very high resistances are used, stray capacitance can couple unwanted signals into the circuit.

Very large resistance may be unstable in value and lead to stray coupling of undesired signals.

$$R_1 = 20k\Omega, \quad R_2 = 180k\Omega$$

Case Study: Example 13.3: gain of -10

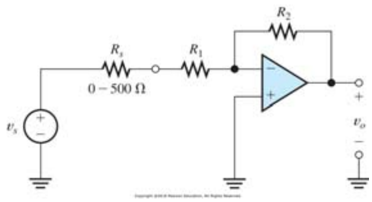


Figure 13.18 Circuit of Example 13.3.

$$R_1 \cong 100 R_{s\max} = 50k\Omega, \quad R_2 = 500k\Omega$$

Example 13.4: summing amplifier

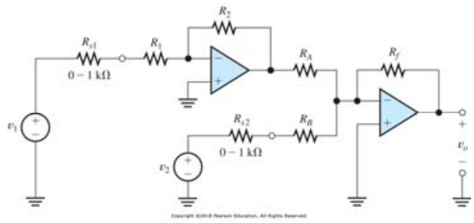


Figure 13.19 Amplifier designed in Example 13.4.

Example 13.4: summing amplifier

$$R_1 = R_B \cong 500k\Omega$$

$$A_1 = \frac{R_2}{R_s + R_1}\frac{R_f}{R_A}$$

$$A_2 = \frac{R_f}{R_B}$$

$$R_f = 1M\Omega$$

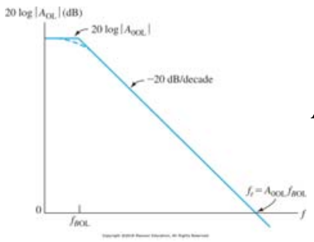
$$R_2 = 1M\Omega, \quad R_A = 400k\Omega$$

Op-amp imperfections in the linear range of operation

Real op amps have several categories of imperfections compared to ideal op amps.

- *finite input impedance*
- *nonzero output impedance*
- *gain and bandwidth limitations*
- *nonlinear limitations*
- *Dc-imperfections*, etc.

Gain and Bandwidth Limitations



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

Figure 13.20 Bode plot of open-loop gain for a typical op amp.

Nonlinear limitations

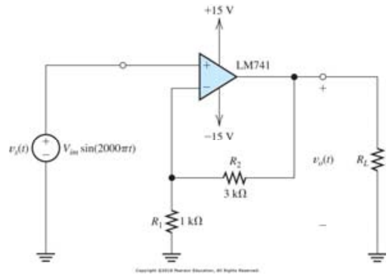


Figure 13.23 Noninverting amplifier used to demonstrate various nonlinear limitations of op amps.

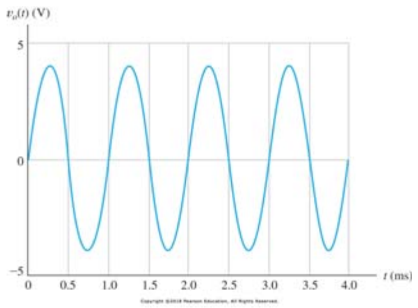


Figure 13.24 Output of the circuit of Figure 13.23 for R_L = 10 kΩ and V_{im} = 1 V. None of the limitations are exceeded, and $v_o(t) = 4v_s(t)$.

The output voltage of a real op amp is limited to the range that depend on the internal design of the op amp. When the output voltage tries to exceed these limits, clipping occurs.

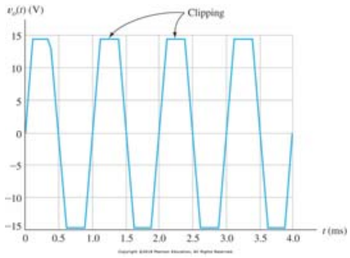


Figure 13.25 Output of the circuit of Figure 13.23 for R_L = 10 kΩ and V_{im} = 5 V. Clipping occurs because the maximum possible output voltage magnitude is reached.

The output current range of a real op amp is limited. If an input signal is sufficiently large that the output current would be driven beyond these limits, clipping occurs.

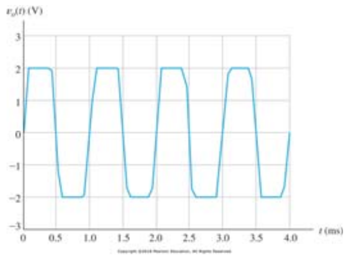
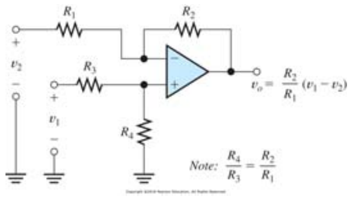


Figure 13.26 Output of the circuit of Figure 13.23 for R_L = 50 Ω and V_{im} = 1 V. Clipping occurs because the maximum output current limit is reached.

Applications: Differential amplifiers with higher quality



Differential amplifiers are widely used in engineering instrumentation

Figure 13.33 Differential amplifier.

Instrumentation amplifiers

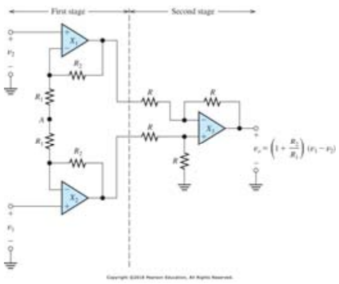


Figure 13.34 Instrumentation-quality differential amplifier.

Integrators

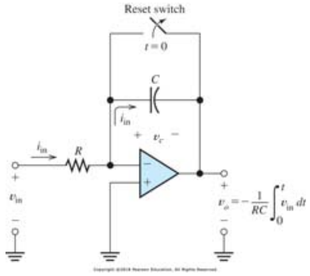


Figure 13.35 Integrator.

Chapter 13
Operational Amplifiers

Exercise 13.17

$$(a)\ R = 10k\Omega,\ C = 0.1\mu F,\ Output?$$
$$(b)\ R = 10k\Omega,\ V_{pp} = 2,\ C = ?(0.5\mu F)$$

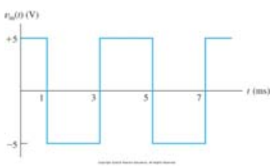


Figure 13.36 Square-wave input signal for Exercise 13.17.

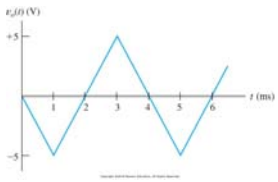


Figure 13.37 Answer for Exercise 13.17.

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Operational Amplifiers

Differentiator Circuit

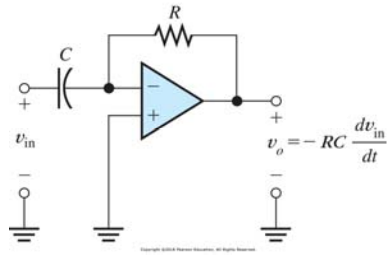

Figure 13.38 Differentiator.

Chapter 13
Operational Amplifiers

Active filters

Filters with Op amplifiers

Filters can be very useful in separating desired signals from noise.

Chapter 13
Operational Amplifiers

Active filters - Filters with Op amplifiers

Ideally, an active filter circuit should:

1. Contain few components
2. Have a transfer function that is insensitive to component tolerances
3. Place modest demands on the op amp's specifications
4. Be easily adjusted
5. Require a small spread of component values
6. Allow a wide range of useful transfer functions to be realized

Chapter 13
Operational Amplifiers

Butterworth Transfer Function

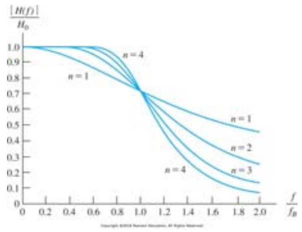

Figure 13.39 Transfer-function magnitude versus frequency for lowpass Butterworth filters.

$$|H(f)| = \frac{H_0}{\sqrt{1+(f/f_B)^{2n}}}$$

Sallen–Key Circuits (Second-order)

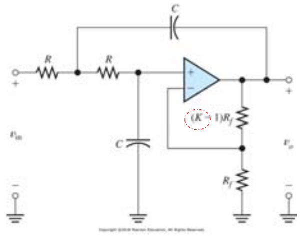

Figure 13.40 Equal-component Sallen–Key lowpass active-filter section.

$$|H(f)| = \frac{H_0}{\sqrt{1+(f/f_B)^{2n}}}$$

$$n=2$$

$$f_B = \frac{1}{2\pi RC}$$

$$H_0 = K$$

Table 13.1 *K* **Values for Lowpass or Highpass Butterworth Filters of Various Orders**

Order	K
2	1.586
4	1.152
	2.235
6	1.068
	1.586
	2.483
8	1.038
	1.337
	1.889
	2.610

Example 13.8
Design a fourth-order Butterworth filter with a cutoff frequency of 100 Hz

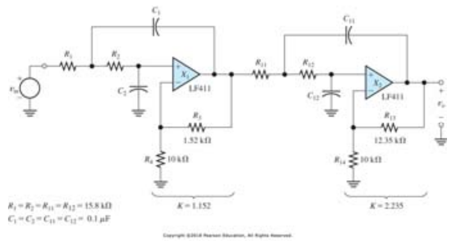

Figure 13.41 Fourth-order Butterworth lowpass filter designed in Example 13.8.

Table 13.1 *K* **Values for Lowpass or Highpass Butterworth Filters of Various Orders**

Order	K
2	1.586
4	1.152
	2.235
6	1.068
	1.586
	2.483
8	1.038
	1.337
	1.889
	2.610