Ngee Ann Polytechnic
Electronic and Computer Engineering Department
Diploma In Quality Assurance Engineering

Electronic Devices and Circuits

Topic 5:
OPERATIONAL AMPLIFIERS

Table of Contents

Table of Contents 1

Reference Readings 3

Objectives 4

1. Introduction 5

2. Operational Amplifier Basics 6

   2.1 Op-Amp Symbol 6
   2.2 Equivalent Circuit Schematic 7
   2.3 Standard Packages & Pin Configuration 7
   2.4 Power Supply Connections 8
   2.5 Main Features of Practical Op-Amps 9
   2.6 Output Voltage Swing 9

3. Fundamentals of Negative Feedback 10

   3.1 What is Negative Feedback? 10
   3.2 Why Use Negative Feedback in Op-Amp Circuits? 10
   3.3 Simplifying Assumptions for Analysis of Op-Amp Circuits with Negative Feedback 11

4. Inverting Amplifier 12

   4.1 Closed-Loop Gain 12
   4.2 Input Resistance 13
   4.3 Transfer Characteristic Curve 14

5. Non-inverting Amplifier 16

   5.1 Closed-Loop Gain 16
   5.2 Input Resistance 16

5.3 Transfer Characteristic Curve 17

6. Summing Amplifier Circuit 18

7. Voltage Follower...19

8. Differential and Instrumentation Amplifier (Optional) 21

8.1 Differential Amplifier (Optional) 22
8.2 Improving The Basic Differential Amplifier (Optional)......... 25
8.3 Instrumentation Amplifier (Optional).................................. 27

9. Op-Amp Parameters 28

9.1 Input Bias Current (I_B), Input Offset Current (I_{IO}) 29
9.2 Input Offset Voltage (V_{IO}) 32
9.3 Common Mode Rejection Ratio (CMRR) 35

10. AC Performance...37

10.1 Frequency Response 37
10.2 Slew Rate... 41

11. The Ideal Op-amp 45

12. Comparators...46

12.1 Zero-Level Detection.. 46
12.2 Non-Zero Level Detection 47
12.3 Noise Susceptibility of Comparator 49

13. Schmitt Triggers (Optional)...50

13.1 Operation of Schmitt Trigger 51
13.2 Transfer Characteristic of Schmitt Trigger.......................... 53

Reference Readings

Electronic Devices (Thomas L. Floyd)
4th Edition

Chapter 12
12-1 Introduction to Operational Amplifier
12-2 Differential Amplifier (Pg 649-654) (Optional)
12-3 Op-Amp Parameters
12-4 Negative Feedback
12-5 Op-Amp Configurations with Negative Feedback (For Info)
12-6 Effects of Negative Feedback on Op-Amp Impedances (For Info)
12-7 Bias Current and Offset Voltage Compensation

Chapter 13
13-1 Basic Concepts
13-2 Open-Loop Response
13-3 Closed-Loop Response

Chapter 14
14-1 Comparators
14-2 Summing Amplifiers

Chapter 15 (Optional)
15-1 Instrumentation Amplifiers

Objectives

1. Op-Amp Basics
   a) State the main features of practical op-amps
   b) Describe the effects of supply voltages on the op-amp maximum output voltage swing.

2. Op-amp Circuit with Negative Feedback
   a) Describe what is meant by negative feedback.
   b) State and explain the simplifying assumptions for analyzing op-amp circuits with negative feedback.
   c) Apply the assumptions for analyzing inverting, non-inverting op-amp amplifier circuits.

3. Op-amp Parameters
   a) Describe the effects of op-amp dc parameters on op-amp circuits
   b) Explain what is meant by slew rate, unity gain bandwidth and their effect on performance of op-amp circuits at high frequencies.
   c) List the characteristics of an ideal op-amp

4. Comparators/Schmitt Triggers
   a) Describe the operation of op-amp comparators and their limitations.
   b) Describe the operation of a Schmitt trigger circuit.

1. Introduction

An operational amplifier is a versatile integrated-circuit (IC) that is capable of performing a wide range of linear and non-linear signal processing functions.

Op-amps got their name from their early use in performing mathematical operations like addition, subtraction, integration and differentiation.

2. Operational Amplifier Basics

2.1 Op-Amp Symbol

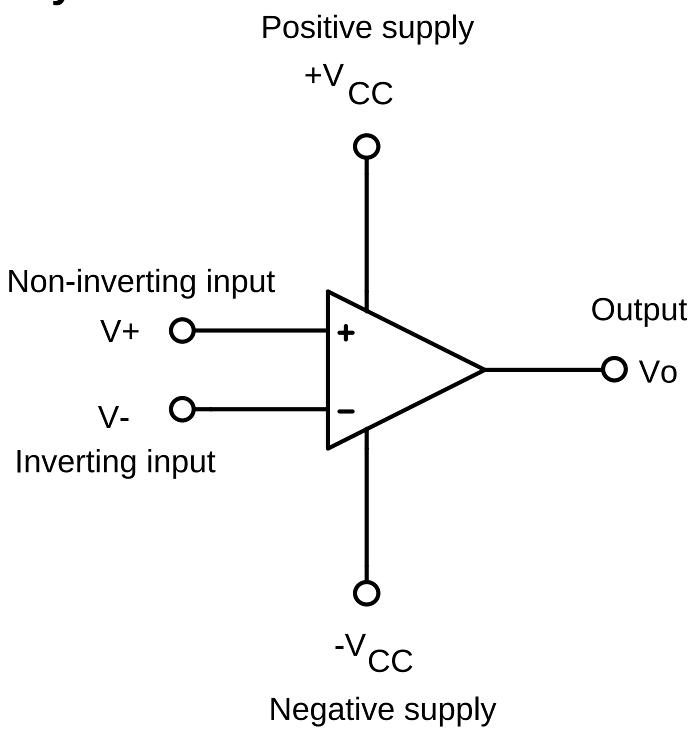


Figure 2.1

☑ Two signal input terminals, denoted as the inverting (V_-) and non-inverting terminals (V_+), respectively. The signal voltage at either pin may be positive or negative with respect to ground.

☑ One signal output terminal (V_O).

☑ In open-loop configuration (as shown),

$$V_O = A_{OL}(V_+ - V_-)$$

2.2 Equivalent Circuit Schematic

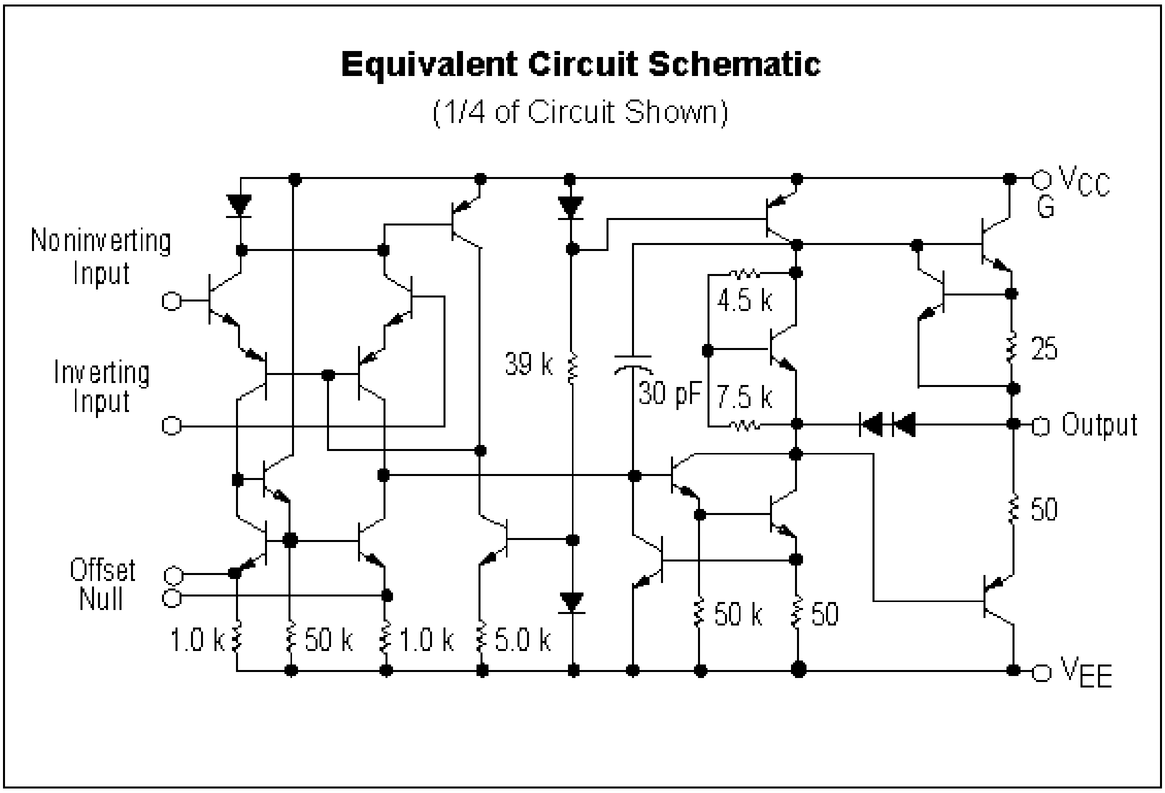
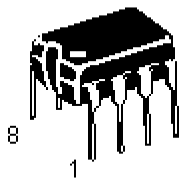
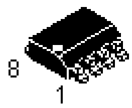


Figure 2.2

2.3 Standard Packages & Pin Configuration



DIP-8 Package



SO-8 Package

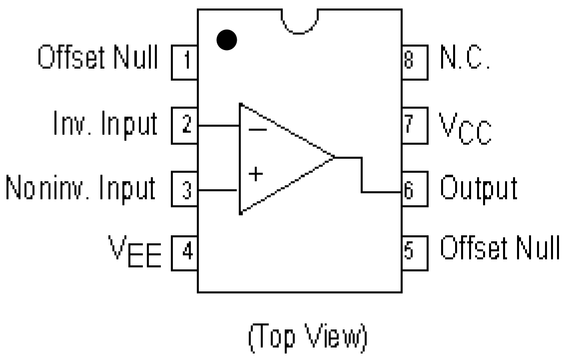


Figure 2.3

2.4 Power Supply Connections

(very useful for Lab)

- ☑ Most op-amps are powered from dual power supplies of opposite polarities. However single supply version is also available (e.g. LM324). Common supply voltage values are ±15V.
- ☑ Power supply terminals are designated as $+V_{CC}$ and $-V_{CC}$ on many pin connection diagram.
- ☑ The common ground point is not connected to op-amp itself.
- ☑ All input signals to the op-amp have their common grounds connected to this point.
- ☑ All output loads are connected between the op-amp signal output terminal and this common ground point.

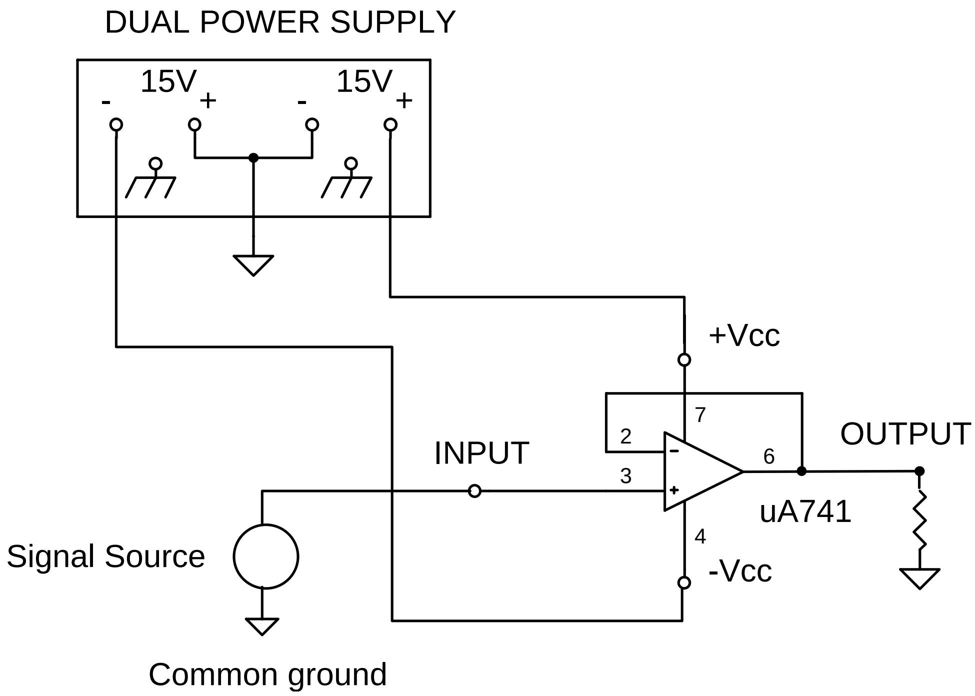


Figure 2.4

2.5 Main Features of Practical Op-Amps

☑ Very high open-loop gain (A_{OL}), typical 100,000 to 1,000,000.

☑ Can be used to amplify ac as well as dc input signal

☑ High input resistance, typically 250 kΩ to 2 MΩ

☑ Low output resistance, 75 ohms for 741 op amp.

☑ Output may swing through most of the supply range.

☑ Low drift

2.6 Output Voltage Swing

☑ Output voltage level is limited by supply voltages.

☑ Minimum output voltage, denoted as $-V_{SAT}$, is determined by $-V_{CC}$ supply. Maximum output voltage denoted as $+V_{SAT}$, determined by $+V_{CC}$ supply.

☑ Typical values:

Supply Voltage $\pm V_{CC}$	Positive Saturation Voltage $+V_{SAT}$	Negative Saturation Voltage $-V_{SAT}$
±9V	+8V	-7V
±15V	+14V	-13V

☑ Implications *(to be discussed in lecture)*

3. Fundamentals of Negative Feedback

3.1 What is Negative Feedback?

☑ Process whereby a fraction of the output voltage of an amplifier is returned to the input in a way to subtract from the input signal.

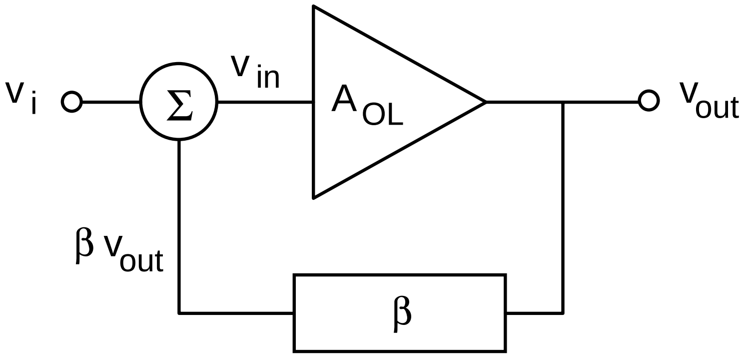


Figure 3.1

☑ The closed-loop gain is

$$A_{CL} = \frac{v_{out}}{v_i} = \frac{A_{OL}}{1 + \beta A_{OL}}$$

3.2 Why Use Negative Feedback in Op-Amp Circuits?

☑ Large open-loop gain, A_{OL} means that output of op-amp easily becomes saturated. Therefore not practical to use op-amp in open-loop configuration for linear amplifier applications.

3.3 Simplifying Assumptions for Analysis of Op-Amp Circuits with Negative Feedback

☑ The **input impedance** of the op amp as viewed from the input terminals (V_+ and V_-) is **infinite**.

In other words, there is NO current flowing into the input terminals.

☑ The **output impedance** of the op-amp viewed from the output terminals with respect to ground is **zero**.

In other words, the output voltage does not depend on the value of the load impedance.

☑ The **open-loop gain** A_{OL} approaches an **infinite** value in the ideal case.

The implication of the this assumption is the most significant and is best seen by considering following equations.

$$v_{OUT} = A_{OL}(v_+ - v_-)$$
$$= A_{OL} v_d$$
$$v_d = \frac{v_{OUT}}{A_{OL}}$$

As A_{OL} approaches infinity, and assuming v_{OUT} is finite, vd approaches ZERO. This means that **the voltages at the two input terminals (v_+ and v_-) are forced to be EQUAL**.

The two input terminals are said to be virtually shorted (i.e from the voltage point of view, they appear shorted but physically they are not shorted).

4. Inverting Amplifier

4.1 Closed-Loop Gain

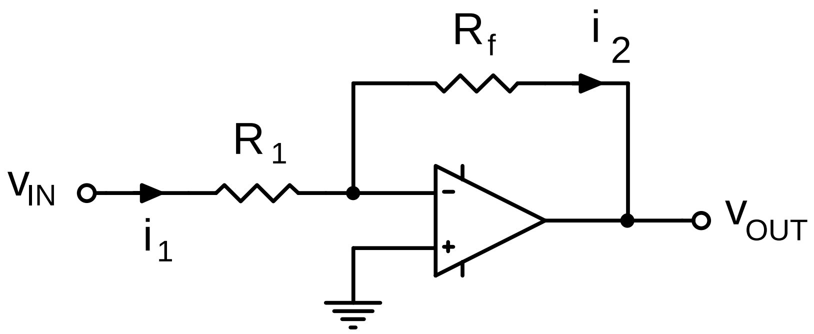


Figure 4.1: Inverting amplifier circuit

☑ The closed-loop gain A_{CL} can be shown to be

$$A_{CL} = \frac{v_{OUT}}{v_{IN}}$$
$$= -\frac{R_f}{R_1}$$

☑ Derivation of A_{CL} (for Info)

From circuit shown, $v_+ = 0$ since it is grounded. Since v_- is virtually shorted to v_+,

$$v_- = v_+ = 0$$

v_- is said to be at virtual ground.

Since there is no current flowing into the op-amp input terminals,

$$i_1 = i_2$$

But i_1 is the current flowing through R_1 and i_2 is the current flowing through R_f. By Ohm's law,

$$i_1 = \frac{\text{voltage drop across } R_1}{R_1}$$

$$= \frac{v_{IN} - v_-}{R_1}$$

$$= \frac{v_{IN} - 0}{R_1}$$

$$i_2 = \frac{\text{voltage drop across } R_f}{R_f}$$

$$= \frac{v_- - v_{OUT}}{R_f}$$

$$= \frac{0 - v_{OUT}}{R_f}$$

Setting $i_1 = i_2$, we can get the expression for A_{CL} (Show it!)

☑ The negative sign in the ACL means that the output voltage is always 180^o out of phase with the input voltage e.g. whenever the input voltage is positive, the output voltage will be negative and vice versa.

4.2 Input Resistance

☑ This is equivalent to the ratio v_{IN} / i_1 and evaluates to R_1 itself.

Do not confuse the input resistance of the op amp itself, which has been assumed to be infinite, with the input impedance of the inverting amplifier circuit.

4.3 Transfer Characteristic Curve

☑ The transfer characteristic curve of an amplifier is a plot of the output voltage versus the input voltage.

☑ The transfer characteristic curve of the inverting amplifier is as follows:

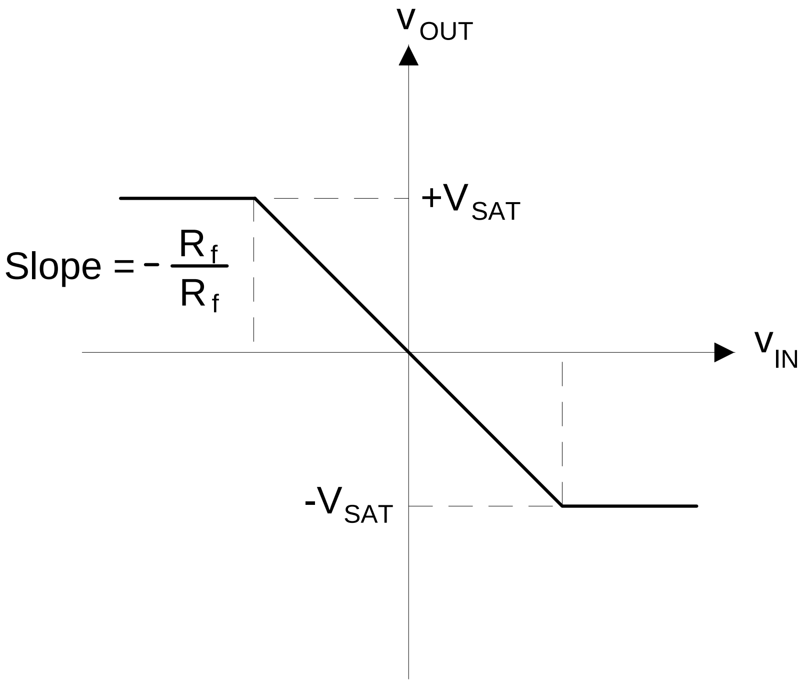


Figure 4.2: Transfer Characteristics of Inverting Amplifier

Example

Given that R_f = 100 kΩ, R_1= 10 kΩ, and v_{IN} is a sine wave of amplitude 1 $V_{p\text{-}p}$ and frequency 10 kHz.

a) Calculate the voltage gain.

b) On the same time axis, sketch the input and output signal voltages.

c) Sketch the transfer characteristic of the inverting amplifier given that $\pm V_{SAT} = \pm 13V$

Solution

Example

In the previous example, if v_{IN} is a sine wave of amplitude 0.2 volt and dc offset of 5 volts, sketch v_{OUT}. (Assume the frequency is 10 kHz).

Solution

5. Non-inverting Amplifier

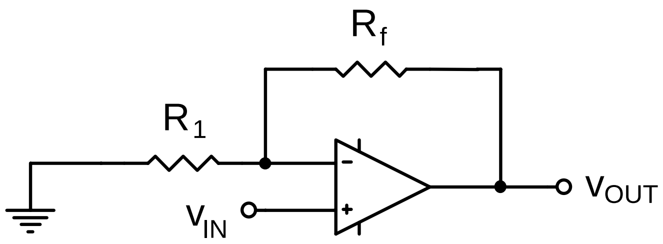


Figure 5.1: Non-inverting Amplifier

5.1 Closed-Loop Gain

☑ The closed-loop gain A_{CL} can be shown to be

$$A_{CL} = \frac{v_{OUT}}{v_{IN}} = \frac{R_f + R_1}{R_1} = 1 + \frac{R_f}{R_1}$$

☑ Since ACL is positive, the output is always in phase with the input.

5.2 Input Resistance

☑ The input resistance can be shown to be

$$(1 + \beta A_{OL})\, R_{IN}$$

where R_{IN} is the input of the op-amp (assumed to be infinite in ideal case)

5.3 Transfer Characteristic Curve

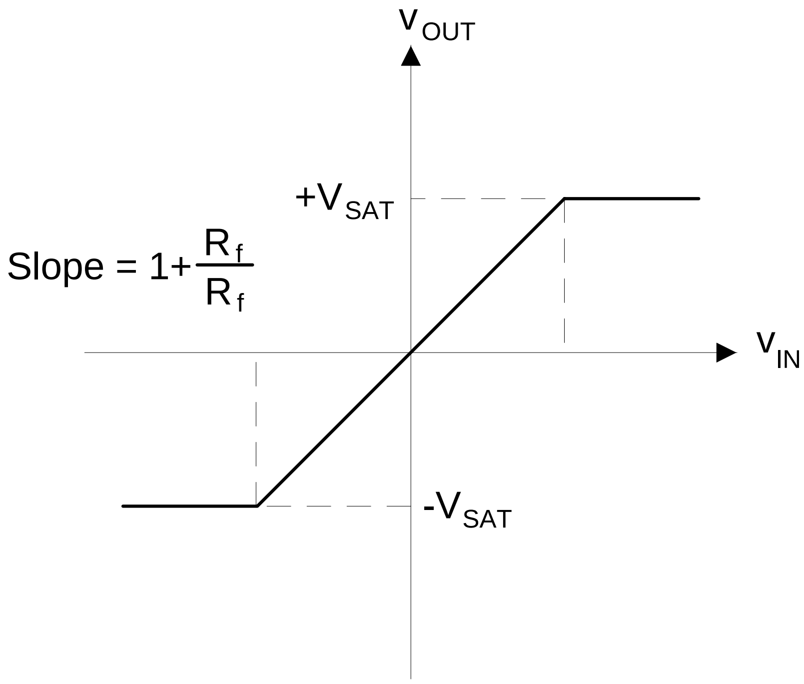


Figure 5.2: Transfer Characteristic of Non-inverting Amplifier

Example

Given that R_f = 20 kΩ, R_1= 10 kΩ, and v_{IN} is a sine wave of amplitude 1 $V_{p\text{-}p}$ and frequency 1 kHz.

a) Calculate the voltage gain.

b) On the same time axis, sketch the input and output signal voltages.

c) Sketch the transfer characteristic of the inverting amplifier given that $\pm V_{SAT} = \pm 13$V

6. Summing Amplifier Circuit

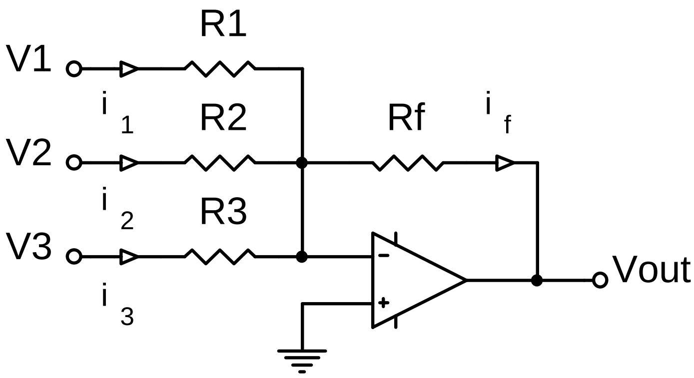


Figure 6.1: Summing Circuit

☑ Output of the summing amplifier is the weighted sum of the inputs.

$$i_1 + i_2 + i_3 = i_f$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = \frac{0 - V_o}{R_f}$$

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

Example

Design a summing amplifier whose output v_{OUT} in terms of its inputs V_1, V_2, V_3, V_4 is:

$v_{OUT} = -v_1 - 0.5v_2 - 2v_3 - 5v_4$

Choose $R_f = 10\ k\Omega$ for your answer.

Example

Using not more than two op-amps, design a circuit such that the output v_{OUT} in terms of the inputs v_1, v_2, v_3, v_4, v_5 is:

$$v_{OUT} = v_1 + 3v_2 - 2v_3 + 0.5v_4 - 6v_5$$

7. Voltage Follower

☑ For a non-inverting amplifier, where $A_{CL} = 1 + R_f / R_1$, setting $R_1 = \infty$ (open circuit) and/or setting $R_f = 0$ (short circuit), causes $A_{CL} = 1$ i.e unity gain.

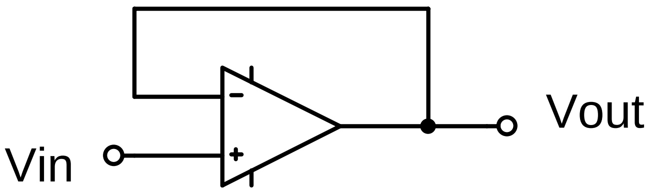


Figure 7.1: Voltage Follower

☑ This circuit senses the input voltage and drives external loads with a voltage that follows the input.

☑ The usefulness of this circuit lies in its ability to isolate a high resistance source from a low resistance load. To provide isolation, it must have a very high input resistance and a very low output resistance.

☑ The input resistance of a voltage follower,

$$R_I = A_{OL} * R_{IN}$$

where R_{IN} is the input resistance of the op-amp.

☑ The output resistance of a voltage follower,

$$R_O = R_{OUT}/A_{OL}$$

where R_{OUT} is the output resistance of the op-amp.

Example

For a 741 op amp, the typical value of R_{IN} and R_{OUT} is 2 MΩ and 75Ω respectively, and A_{OL} is about 10^5.

Solution

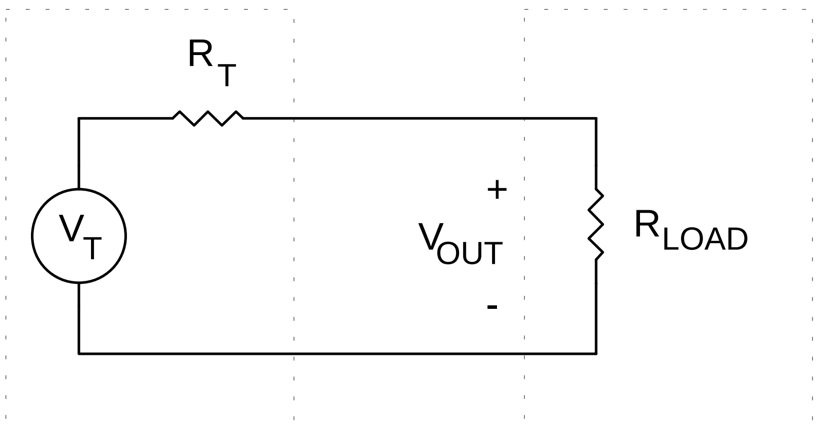
Input resistance of voltage follower = $10^5 * 2M\Omega = 200{,}000\ M\Omega$

Output resistance = $75 / 10^5 = 750\ \mu\Omega$

Therefore a voltage follower built by a op-amp would present an extremely high input resistance of 200,000 MΩ and extremely small output resistance of 750 μΩ

Example

An instrumentation transducer is characterized by a voltage V_T = 5V in series with a resistance R_T = 2000Ω. It operates an indicator characterized by an input resistance of 100Ω . Predict the voltage and power delivered to the indicator with and without the use of a voltage follower



Transducer Indicator

8. Differential and Instrumentation Amplifier (Optional)

☑ The most useful amplifier for measurement, instrumentation, or control is the instrumentation amplifier.

☑ It is a high-gain dc-coupled differential amplifier with single-end output, high input impedance, and high CMRR.

☑ It is commonly used to amplify small differential signals coming from transducers in which there may be a large common-mode signal or level.

☑ There are now many instrumentation ICs available in single packages but these packages are relatively expensive (from S$10 to S$200). These ICs are used when high performance and precision are required.

☑ An inexpensive first cousin to the instrumentation amplifier is the basic differential amplifier.

8.1 Differential Amplifier (Optional)

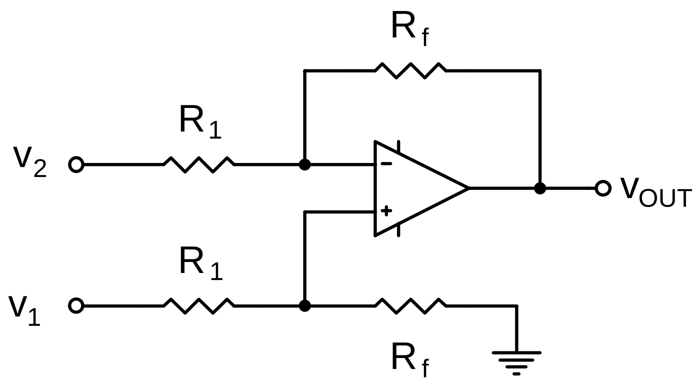
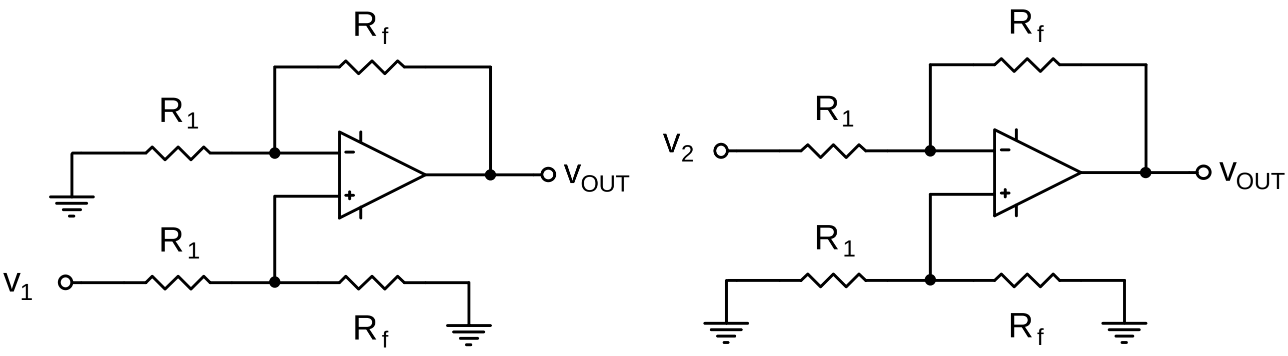


Figure 8.1: Differential Amplifier

There are two methods for determining the gain of the differential amplifier, namely, by method of **superposition** and by **nodal analysis**.

8.1.1 Method 1 - Superposition



Set $V_2 = 0$ (See figure on left),

$$V_{OUT1} = V_+ \; * \; \text{Non-inverting gain}$$

$$= \frac{R_f V_1}{R_1 + R_f} \text{x} \left(1 + \frac{R_f}{R_1}\right)$$

$$= \frac{R_f V_1}{R_1 + R_f} \text{x} \left(\frac{R_1 + R_f}{R_1}\right)$$

$$= \frac{R_f}{R_1} V_1$$

Set $V_1 = 0$ (See figure on right),

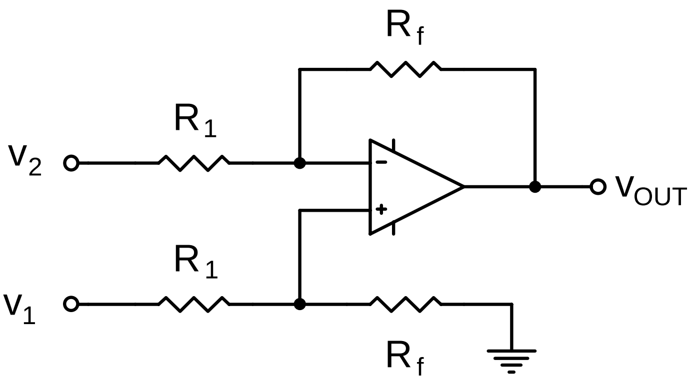
$$V_+ = 0$$

$$V_{OUT2} = -\frac{R_f}{R_1} V_2$$

$$V_o = V_{o1} + V_{o2}$$

$$= \frac{R_f}{R_1} V_1 - \frac{R_f}{R_1} V_2$$

8.1.2 Method 2 - Nodal Analysis



$$V_+ = \frac{R_f}{R_1 + R_f} V_1 \text{ (Voltage - divider rule)}$$

$$V_+ = V_-$$

$$\frac{v_2 - V_-}{R_1} = \frac{V_- - v_{OUT}}{R_f}$$

$$v_{OUT} = V_- - \frac{R_f}{R_1}(V_2 - V_-)$$

$$= \frac{R_1 + R_f}{R_1} V_- - \frac{R_f}{R_1} V_2$$

$$= \left(\frac{R_1 + R_f}{R_1}\right)\left(\frac{R_f}{R_1 + R_f}\right) V_1 - \frac{R_f}{R_1} V_2$$

Then

$$\boxed{V_o = \frac{R_f}{R_1}(V_1 - V_2)}$$

8.2 Improving The Basic Differential Amplifier (Optional)

There are two disadvantages to the basic differential amplifier :

1) low input resistance

2) changing gain is difficult

The first disadvantage can be eliminated by buffering or isolating the inputs with voltage followers.

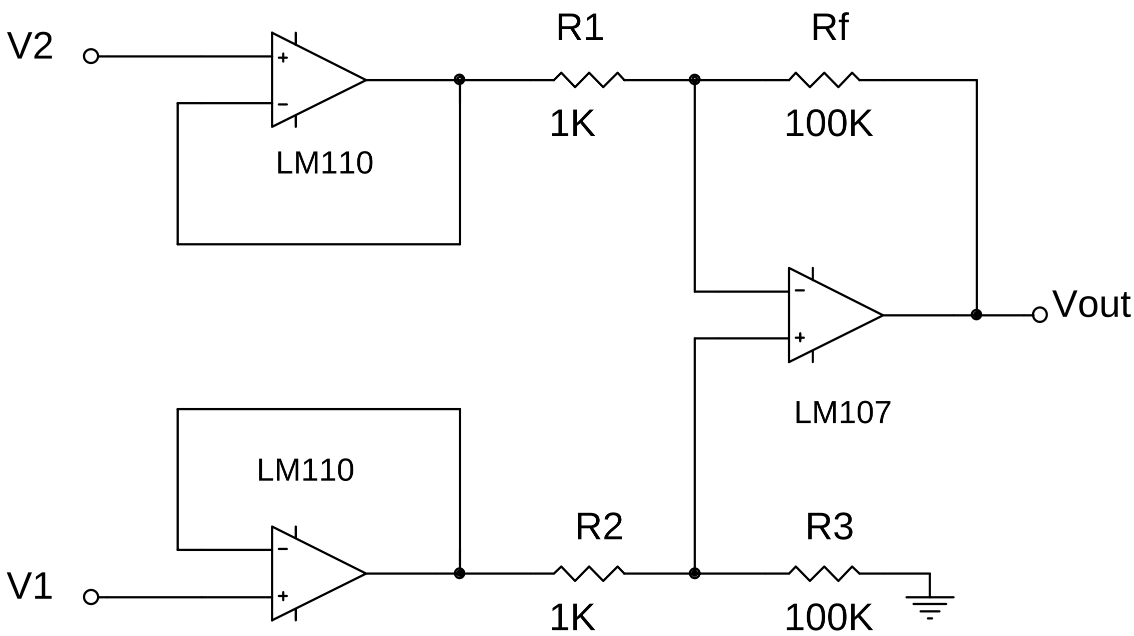


Figure 8.2

LM110 is a high speed buffer and LM107 is general purpose op amp which features low noise and good accuracy in high impedance circuit.

The voltage gain = l00 kΩ / l kΩ = 100

The second disadvantage of the basic differential amplifier is the lack of adjustable gain. This problem can be eliminated by adding three more resistors as shown below

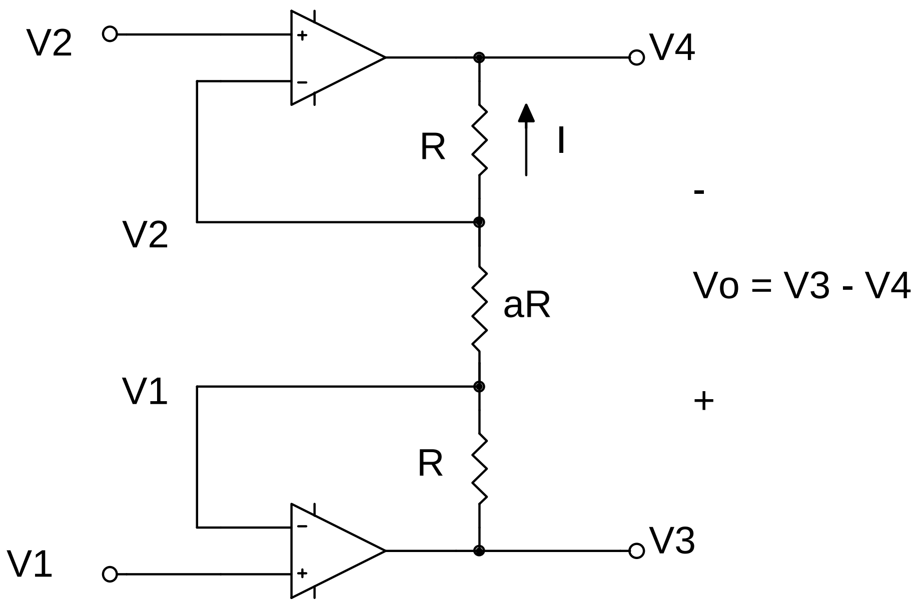


Figure 8.3

Assuming $V_1 > V_2$

$$\text{Current through aR} = I = \frac{(V_1 - V_2)}{aR}$$

$$\text{Voltage across R} = IR = \frac{(V_1 - V_2)}{a}$$

$$V_4 = V_2 - \frac{(V_1 - V_2)}{a}$$

$$V_3 = V_1 + \frac{(V_1 - V_2)}{a}$$

$$V_o = V_3 - V_4 = (V_1 - V_2)\left(1 + \frac{2}{a}\right)$$

Output can be adjusted by varying aR. The equation is also valid when $V_2 > V_1$.

8.3 Instrumentation Amplifier (Optional)

An instrumentation amplifier is made by connecting a buffer to a basic differential amplifier.

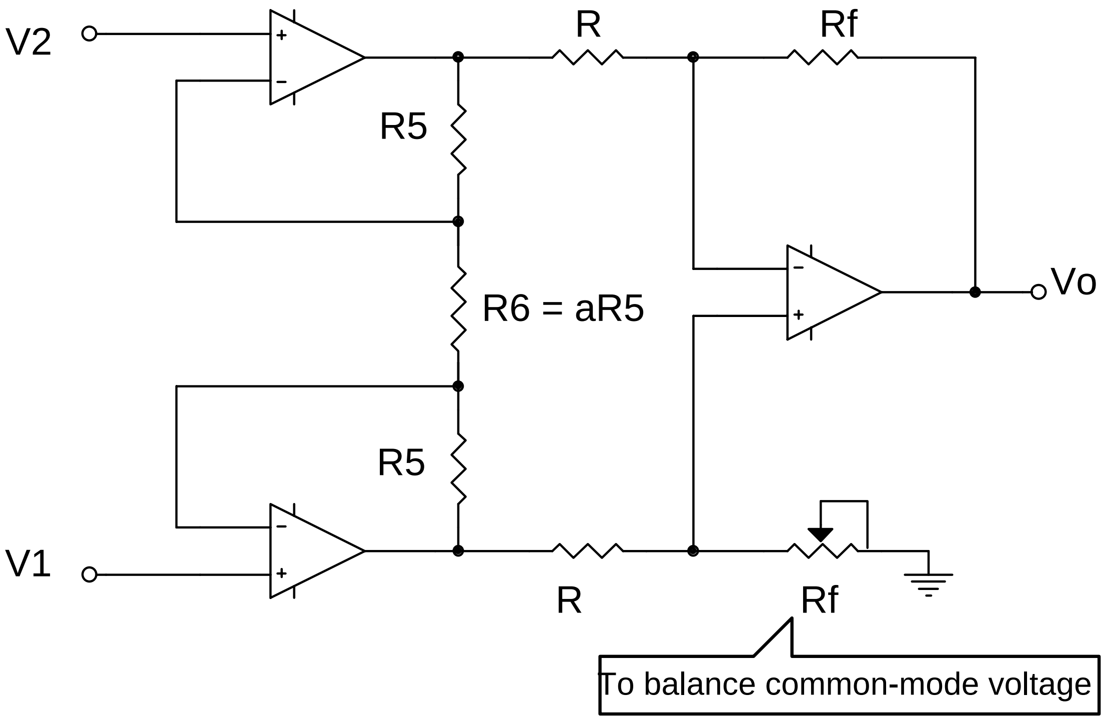


Figure 8.4: Instrumentation Amplifier

$$V_o = (V_1 - V_2)\left(1 + \frac{2R_5}{R_6}\right)\left(\frac{R_f}{R}\right)$$
$$= (V_1 - V_2)\left(1 + \frac{2}{a}\right)\left(\frac{R_f}{R}\right)$$

The voltage gain is contributed by the first stage of the amplifier as the differential amplifier only gives unity gain. Modification may be made to the differential amplifier to provide extra gain.

9. Op-Amp Parameters

☑ Op-amp is widely used in amplifier circuit to amplify DC or AC signals or combinations of them.

☑ In DC amplifier applications, certain electrical characteristics of the op-amp can cause errors in the output voltage.

If these the value of the output voltage is large compared with the error components, then we can usually ignore the op-amp characteristic that causes it.

However, if the error component is comparable to or even larger than value of the output voltage, we must try to minimize the error.

☑ Op-amp characteristics that add error components to the DC output voltage are:

1) Input Bias Current, I_B
2) Input Offset Current, I_{IO}
3) Input Offset Voltage, V_{IO}

☑ When the op-amp is used in an ac amplifier, coupling capacitors eliminate DC output voltage error. However, there are new problems for ac amplifiers. They are :

1) Finite Bandwidth
2) Slew Rate

9.1 Input Bias Current (I_B), Input Offset Current (I_{IO})

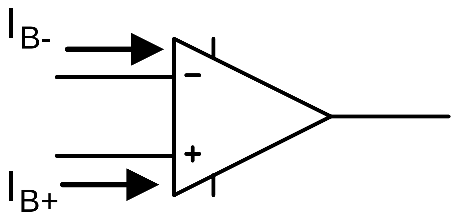


Figure 9.1

☑ The input terminals draws a small current called the input bias current, I_B to bias the op amp's transistors.

☑ The (-) input's bias current, I_{B-} is usually not exactly equal to the (+) input's bias current, I_{B+}. Manufacturers specify an average input bias current (I_B):

$$I_B = \frac{I_{B+} + I_{B-}}{2}$$

☑ Op amps are available with input bias currents down to a nA or less for bipolar transistor-input circuit types or down to a few pA for FET-input circuit types.

☑ Input offset current I_{IO} is the ***difference*** in magnitudes between I_{B+} and I_{B-}.

$$I_B = \left| I_{B+} - I_{B-} \right|$$

The typical value of I_{IO} is less than 25% of I_B. I_{IO} for the 741C is 200 nA max.

☑ The significance of input bias current is that it causes a **voltage drop** across the resistors of the feedback network, bias network, or source impedance.

9.1.1 Effect of I_{B-}

V_o should ideally be 0 V when input $E_i = 0$, however, due to I_{B-},

$$V_o = R_f * I_{B-}$$

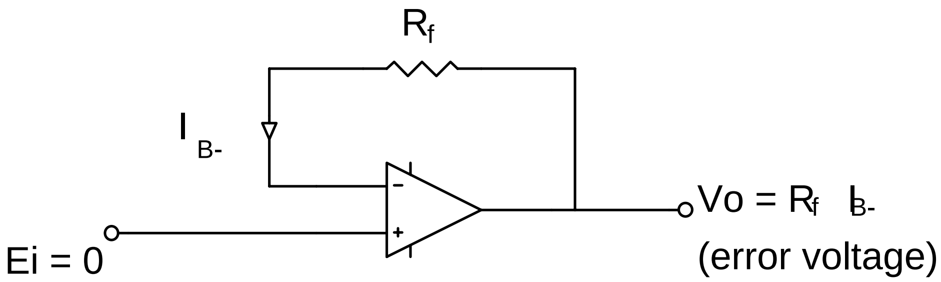


Figure 9.2

9.1.2 Effect of I_{B+}

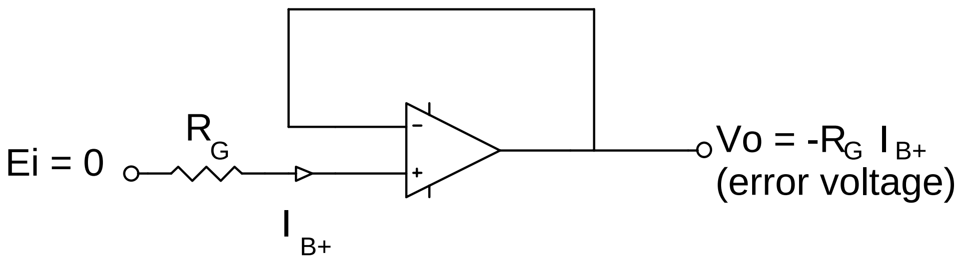


Figure 9.3

$V_+ = -R_G * I_{B+}$ and $V_+ = V_-$

$$V_o = -R_G * I_{B+}$$

9.1.3 Minimizing Errors Caused By Bias Currents

☑ To minimize errors in output due to bias currents for either inverting or non-inverting amplifiers, a **current-compensating resistor, R_{om}** must be added in series with the non-inverting input terminal.

The value of R_{om} should equal the **parallel combination** of all resistance branches connected to the inverting terminal such that the errors caused by I_{B+} & I_{B-} respectively would be equal.

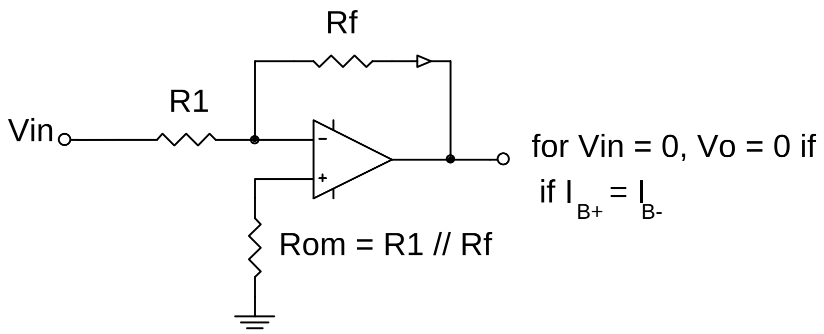
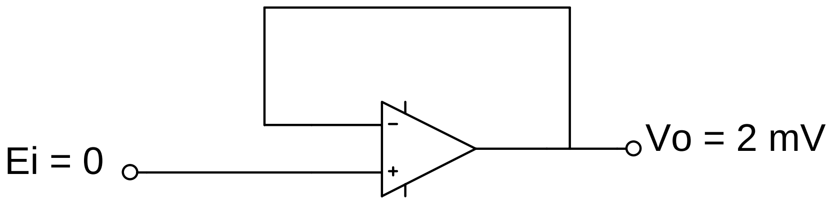


Figure 9.4: Inverting Amplifier

The use of R_{om} will minimize though not completely eliminate the error because I_{B+} & I_{B-} are not exactly equal.

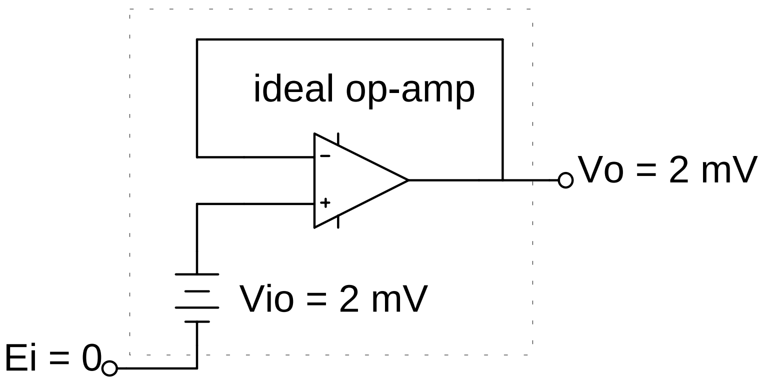
9.2 Input Offset Voltage (V_{IO})

☑ In the circuit below, V_o should be 0V since input is zero. However, op-amps don't have perfectly balanced input stages, owing to manufacturing variations, which results in a small error voltage present at the output.



real op-amp
Figure 9.5

☑ The effect of input offset voltage, V_{io} in the real op-amp can be modeled by an ideal op amp plus a voltage V_{io}.



real op-amp
Figure 9.6

☑ **Note:** It makes no difference whether V_{io} modeled in series with the (-) input or the (+) input. V_{io} could be positive or negative. Therefore its ***absolute*** value is listed on the data sheet.

☑ The smaller the value of V_{io}, the better the input terminals are matched.

For a 741C, the max value of V_{io} is 6 mV.

9.2.1 Effect of Input Offset Voltage

Given $R_f = R_1 = R_2 = R_3 = 10\ k\Omega$

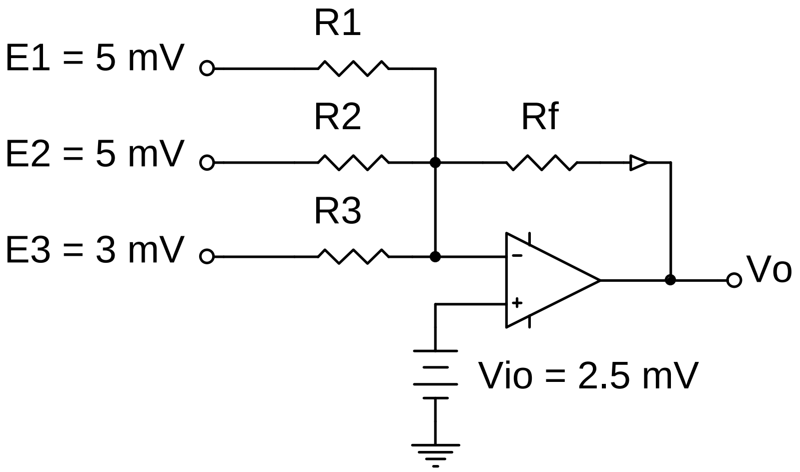


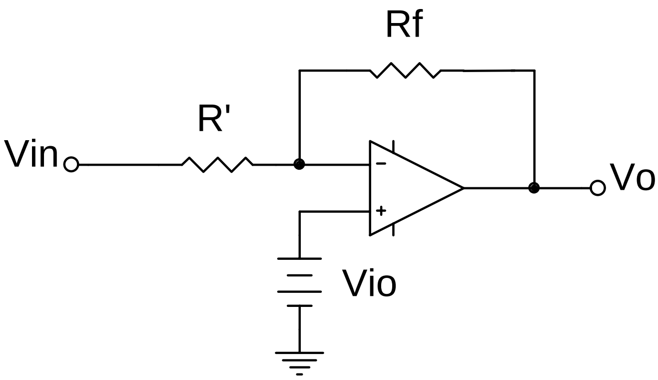
Figure 9.7

Ideally,

$$V_{o(ideal)} = -\left(\frac{R_f}{R_1}E_1 + \frac{R_f}{R_2}E_2 + \frac{R_f}{R_3}E_3\right)$$

$$= -\left(\frac{10K}{10K}5mV + \frac{10K}{10K}5mV + \frac{10K}{10K}3mV\right)$$

$$= -13mV$$



R' = R1//R2//R3 = 10K/3

Output due to V_{io}

$= V_{io}\ (R_f\ + R')\ /\ R'$

$= 2.5\ (10 + 10/3)\ /\ (10/3)$ mV

$= 10$ mV

Actual output V_o = - l3 mV + 10 mV = -3 mV

Due to the presence of V_{IO}, the actual output voltage becomes -3 mV instead of -l3 mV

9.2.2 Offset Voltage Nulling

Some op-amps have null terminals brought out for connection to external voltage offset null circuit.

Follow the null circuit designed by the manufacturer for minimizing effects of input offset voltage.

Some typical circuits are shown below.

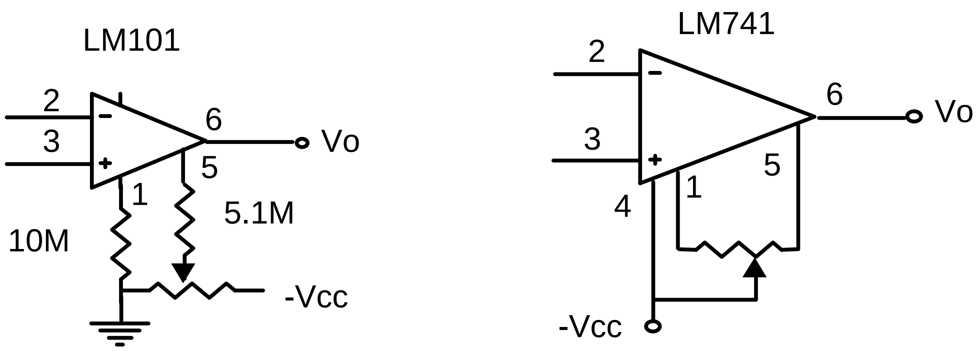


Figure 9.8

9.2.3 Input Offset Voltage Drift with Temperature

The input offset voltage drift is a parameter which specifies who much V_{IO} changes for each degree change in temperature. Typical values range from 5µV/^{o}C to 50µV/^{o}C.

9.3 Common Mode Rejection Ratio (CMRR)

Common Mode Rejection Ratio (CMRR) is an important parameter in all differential amplifiers (including op-amp). It measures the ability of a differential amplifier to reject "common-mode" signals.

☑ What is a common-mode signal?

A signal applied to (+) and (-) input is termed as a **common mode signal**. A common mode signal appearing in a op-amp may arise due to noise or temperature changes.

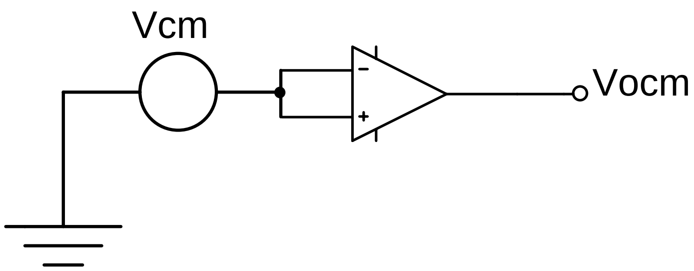


Figure 9.9

☑ The output voltage of a practical differential amplifier is given by:

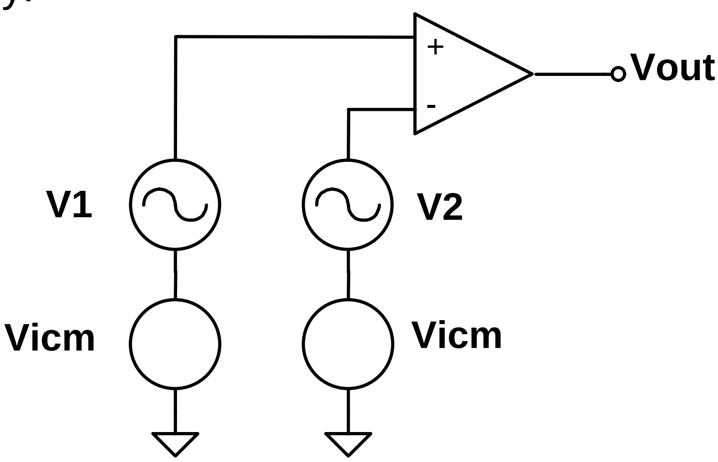


Figure 9.10

$$V_{out} = A_d (V_1 - V_2) + A_{cm}V_{icm}$$

where

A_d is the differential gain (equivalent to A_{OL} for the op-amp)
A_{cm} is the common mode gain

☑ In general, CMRR is given by:

$$CMRR = A_d / A_{cm}$$

$$CMRR \text{ (expressed in decibels)} = 20 \log_{10} [A_d / A_{cm}]$$

☑ A good op-amp should reject common mode signals and thus has high CMRR, that is to say A_{cm} should be as small as possible relative to A_d. Typical values of CMRR for 741 is 90 dB.

☑ Insufficient CMRR degrades circuit precision by introducing a error offset voltage as a function of DC level at the input. It is particularly critical in instrumentation amplifier application where a small differential signal rides on a large DC offset.

Example

An op-amp has a CMRR of 80 dB and an open loop gain, A_{OL} of 200,000. What is the common mode gain, A_{cm}? (Ans: 20)

10. AC Performance

10.1 Frequency Response

Many types of general purpose op-amps are internally compensated; there is a small capacitor, usually 30 pF installed within the op-amp to prevent oscillation by decreasing voltage gain as frequency increases.

10.1.1 Open-Loop Frequency Response

A typical frequency response of a 741 open-loop gain is shown below.

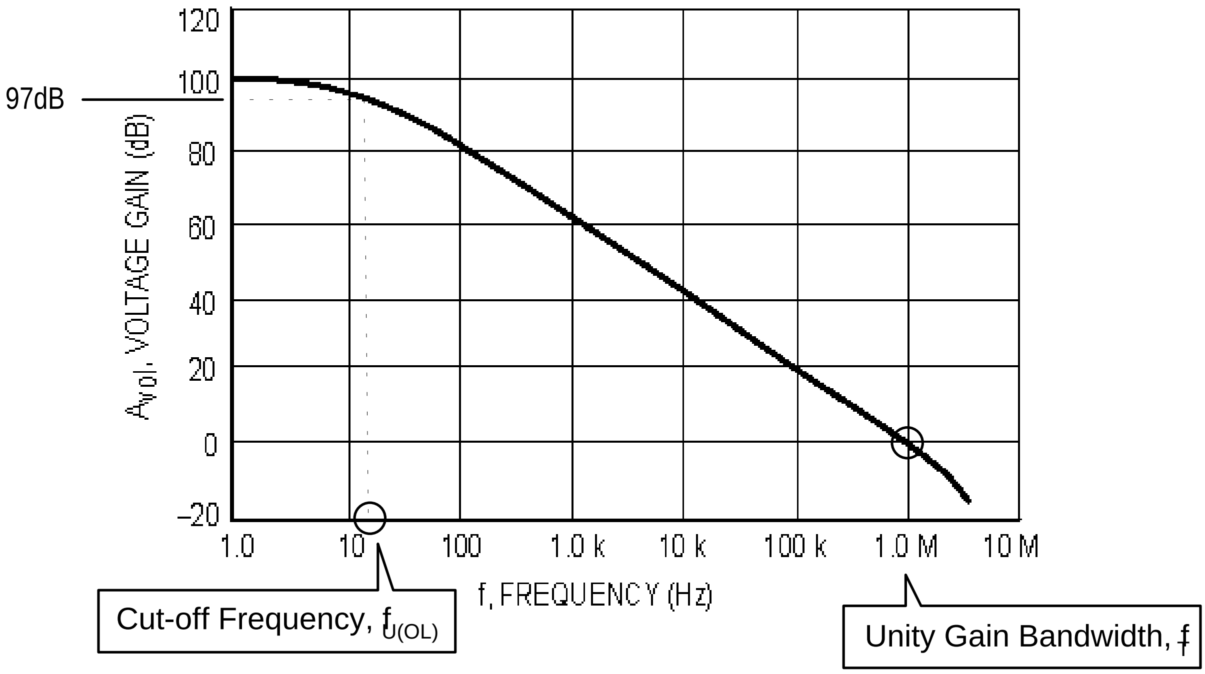


Figure 10.1: Frequency response of 741

☑ The **unity-gain bandwidth**, f_T is defined as that frequency where the op-amp's open loop gain equals **unity (0 dB)**. It is also called unity gain frequency or small gain bandwidth.

☑ The cut-off frequency, $f_{U(OL)}$ is the frequency where the open loop gain drops by 3 dB from its value at 0 Hz.

☑ It is possible to obtain unity gain bandwidth from the manufacturer's plot of open loop gain vs. frequency or from the specification (see figure 10.2) called **transient response rise time** (unit gain).

$$f_T = 0.35 / t_r$$

where t_r = 10% to 90% of the rise time.

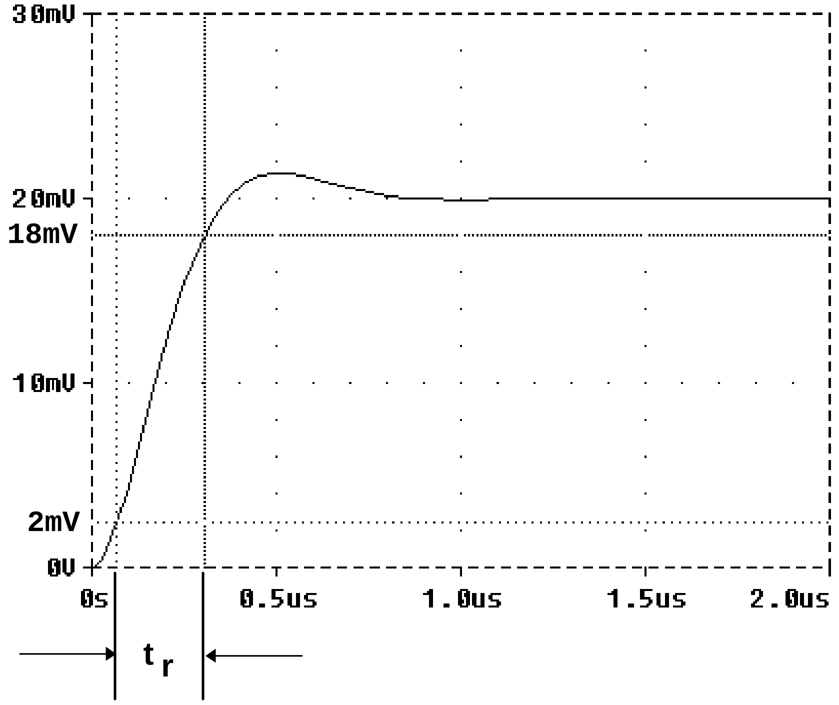


Figure 10.2 Transient response of 741

Example

Determine the unity gain bandwidth f_T from

a) Figure 10.1

b) Figure 10.2

10.1.2 Gain-Bandwidth Product

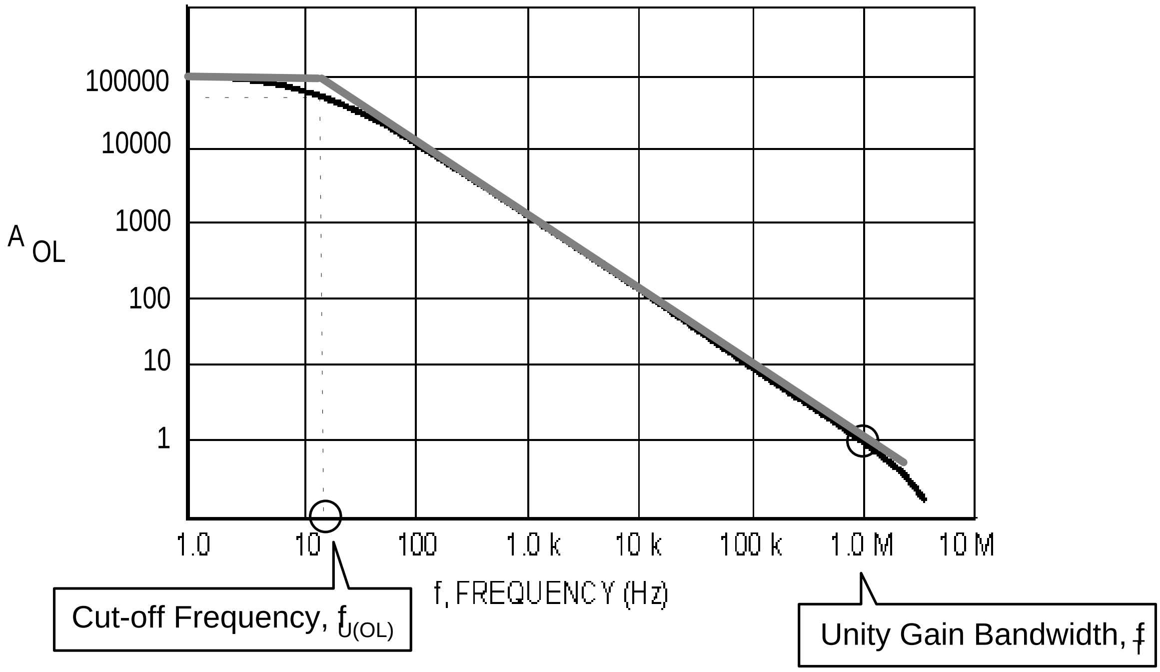


Figure 10.3

Assuming the slope of the open-loop response is a straight line, it can be observed that the open-loop gain at any frequency can be obtain from:

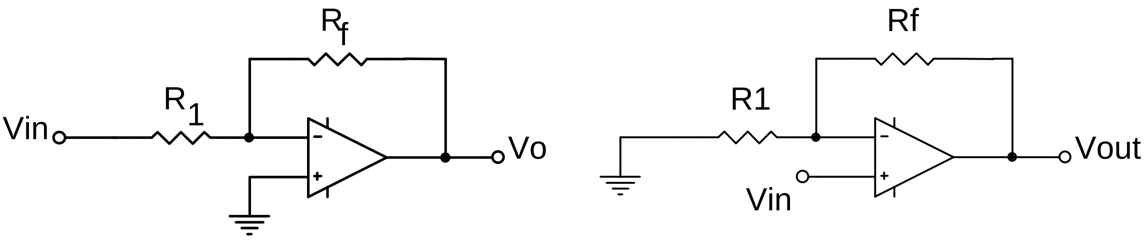
$$A = f_T/f$$

The product of the open-loop gain (at any frequency f) and the frequency f is always equal to f_T.

Assuming that the gain at $f_{U(OL)}$ is A_{OL} then,

$$f_{U(OL)} = f_T/A_{OL}$$

10.1.3 Closed-Loop Bandwidth



Inverting Amplifier Non-Inverting Amplifier

For the inverting and non-inverting amplifier, closed-loop bandwidth or cut-off frequency, $f_{U(CL)}$ is given by:

$$f_{U(CL)} = (1 + \beta A_{OL})\, f_{U(OL)}$$

where β is the negative feedback ratio given by:

$$\beta = \frac{R_1}{R_1 + R_f}$$

But from 10.1.2, $f_{U(OL)} = f_T / A_{OL}$

Therefore,

$$\begin{aligned} f_{U(CL)} &= (1 + \beta A_{OL})\, f_{U(OL)} \\ &= (1 + \beta A_{OL}) \frac{f_T}{A_{OL}} \\ &= \left(\frac{1}{A_{OL}} + \beta \right) f_T \\ &\cong \beta f_T \\ &= \left(\frac{R_1}{R_1 + R_f} \right) f_T \end{aligned}$$

Example

Given that unity-gain bandwidth f_T **=** 1 MHz, and $R_f = R_1 =$ l0 kΩ for both inverting amplifier and non-inverting amplifier, calculate bandwidth and plot the gain versus frequency response of

(a) the inverting amplifier
(b) the non-inverting amplifier

10.2 Slew Rate

☑ Together with the unity gain bandwidth, f_T, the slew rate is a key parameter characterizing the dynamic behavior of the op-amp.

☑ **The slew rate, SR is defined as the maximum rate at which the output can change**.

$$SR = dV_o(t) / dt \mid_{max}$$

For a general purpose op amp such as 741 the max slew rate is 0.5V / µs.

Newer op-amps have significantly improved slew rate. for example the AD518 has a slew rate of 80V / µs.

☑ A low slew rate of an op-amp limits its use in relatively high frequency applications, such as in oscillators, comparators and filters.

10.2.1 Full Power Bandwidth, f_M

☑ The effect of finite slew rate is to **distort** the output signal when it tries to exceed the slew rate capabilities of the op-amp. This is illustrated in the figure below for the case of sinusoidal and rectangular outputs.

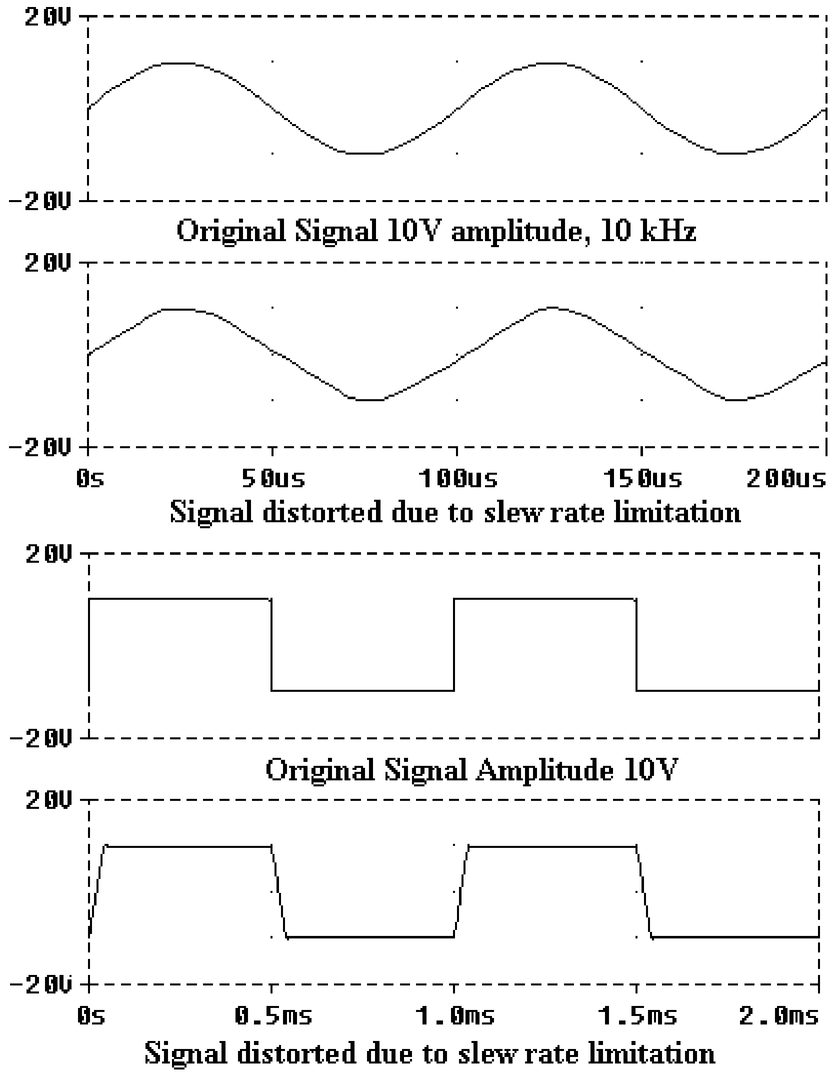


Figure 10.4

☑ **Full-power bandwidth** is defined as the maximum frequency which can be amplified by the op-amp without slew rate distortion at a specified **output amplitude**, **V**, for **sinusoidal** waveforms.

☑ To prevent distortion at the output, we must impose the condition:

$$2\,\pi\, f_M\, V \leq SR$$

where
V is the amplitude of the op-amp output signal
f_M is the frequency of the op-amp output signal

☑ Because of the limited slew rate, the max output swing drops above a certain frequency. The next diagram shows the curve for a 741, with its 0.5V/µs slew rate.

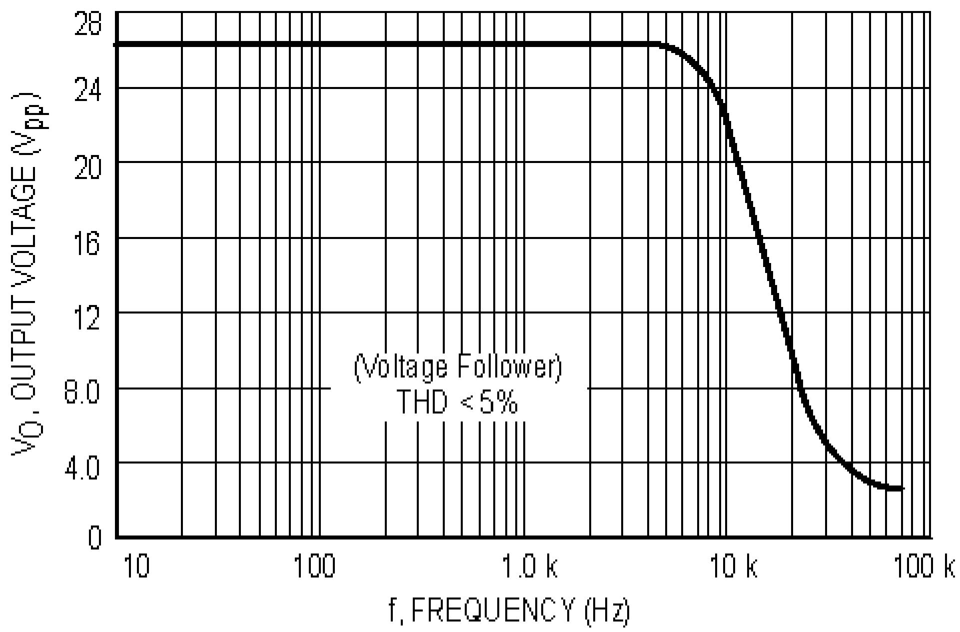


Figure 10.5

Example

If the output signal of a 741 op amp is a sine wave operating at 20 kHz and the slew rate = 0.5 V/μs, calculate the max output swing without distortion.

Example

An op-amp inverting amplifier has resistors R_f = 10 kΩ and R_1 = 2.2 kΩ, what is maximum signal frequency allowed for there to be no slew rate distortion if the slew rate of the op-amp is 0.2V/μs? (Assume V_{in} = 0.1V)

11. The Ideal Op-amp

A ideal op-amp would exhibit the following electrical characteristic :

1) Infinite open-loop voltage gain, A_{OL}

2) Infinite input resistance, R_i

3) Zero output resistance, R_o

4) Zero input offset voltage & zero input bias current

5) Infinite bandwidth, so that any frequency signal from 0 Hz to infinite frequency can be amplified without attenuation.

6) Infinite CMRR, so that the output common mode noise voltage is zero.

7) Infinite slew rate, so that the output voltage changes occur simultaneously with input voltage changes.

12. Comparators

In a comparator application, the op-amp performs **not** as an amplifier but as a device comparing a signal voltage (E_i) on one input with a reference voltage (V_{ref}) on the other input. There is ***no feedback*** involved in this case.

12.1 Zero-Level Detection

In this application, the comparator is used to determine if a signal is greater or less than zero volts.

12.1.1 Non-Inverting Zero-Level Detection

If $E_i > 0$ then $V_o = +V_{sat}$; If $E_i < 0$ then $V_o = -V_{sat}$

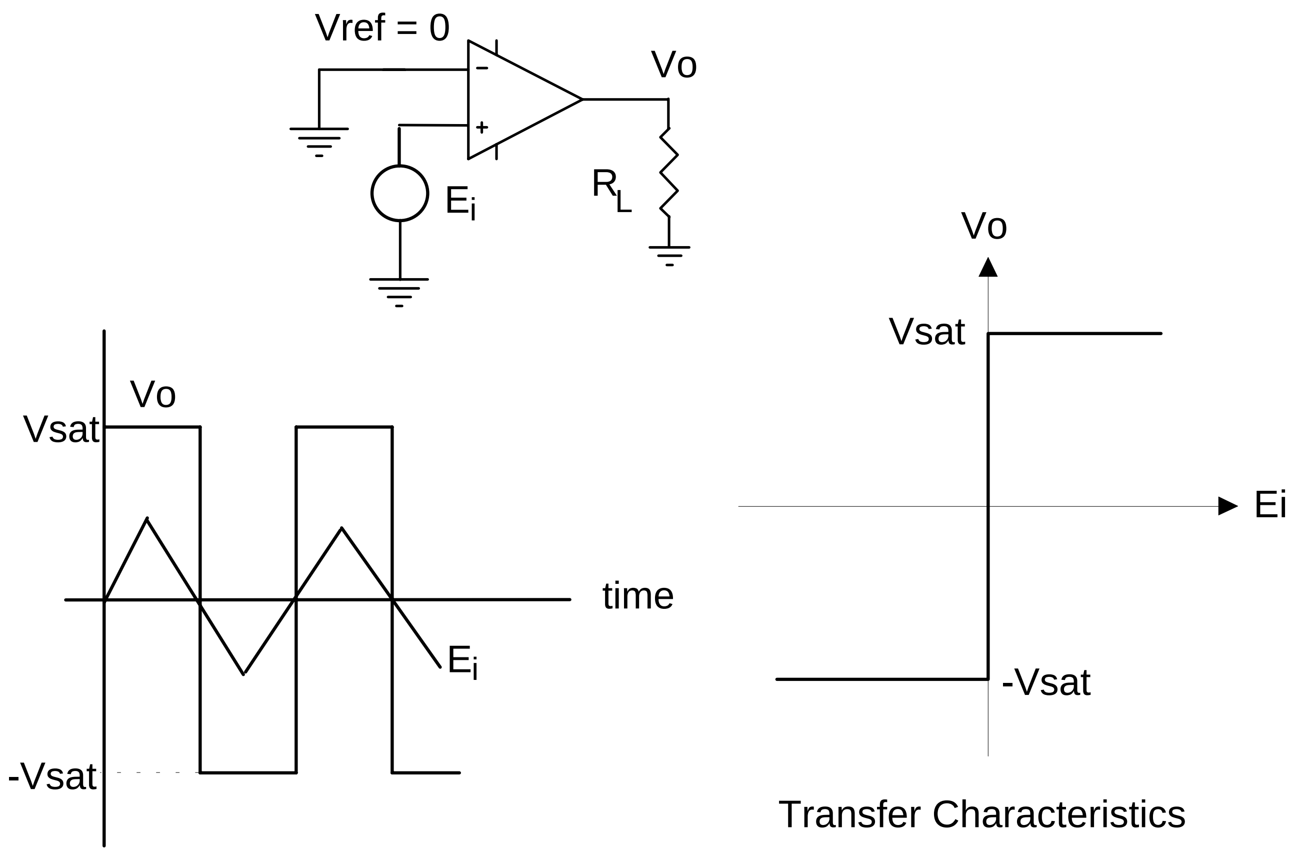


Figure 12.1: Non-inverting Zero-Level Detection

12.1.2 Inverting Zero-Level Detection

If $E_i > 0$ then $V_o = -V_{sat}$; If $E_i < 0$ then $V_o = +V_{sat}$

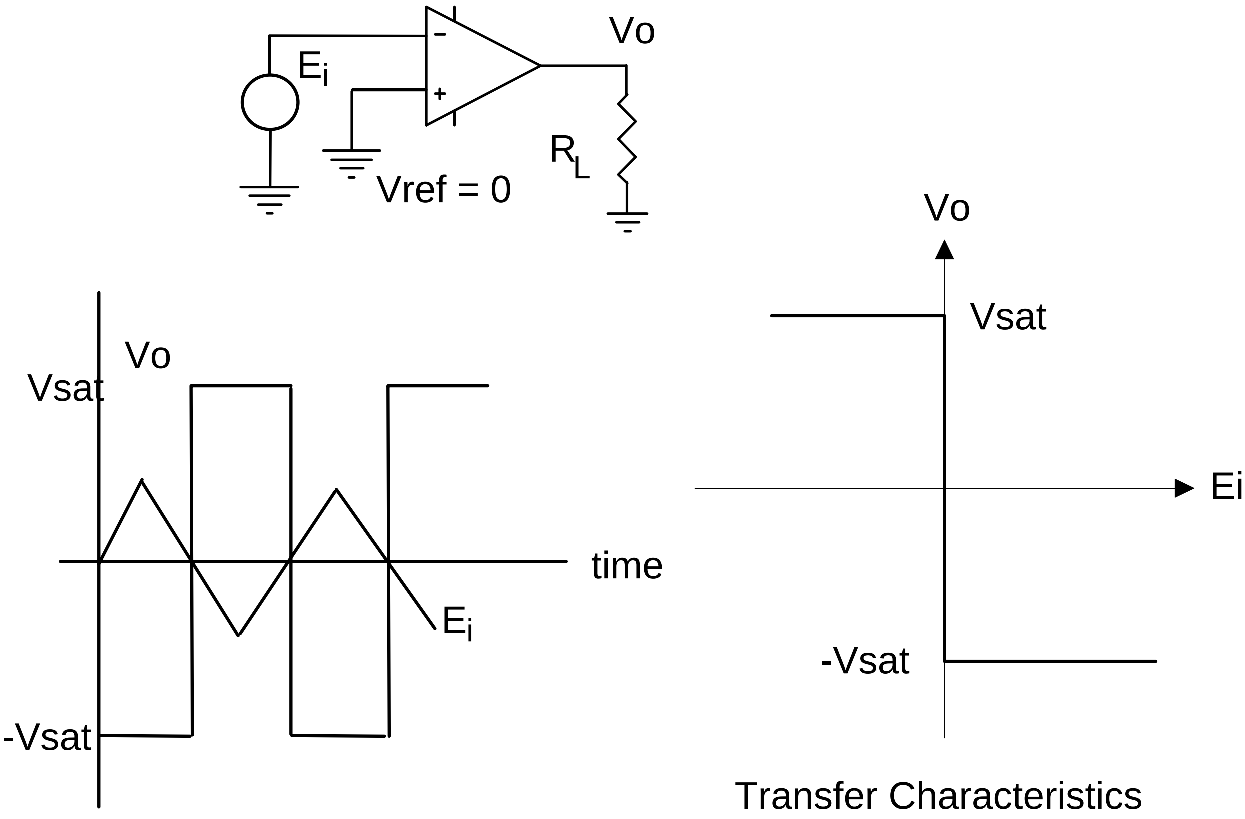


Figure 12.2: Inverting Zero-Level Detection

12.2 Non-Zero Level Detection

In this case, the operation is similar to zero voltage detection, except a non-zero reference voltage, V_{ref} is used.

Example

Design an inverting voltage-level comparator with V_{ref} = 0.5V and $E_i = 2 \sin 2\pi ft$ where f = 1 kHz. Sketch the output voltage for two cycles of E_i and the transfer characteristic of the comparator.

12.3 Noise Susceptibility of Comparator

☑ Once of the disadvantages of the basic comparator is its susceptibility to noise.

In the Figure B below, due to noise added to the input Ei, glitches can be observed at the output Vout.

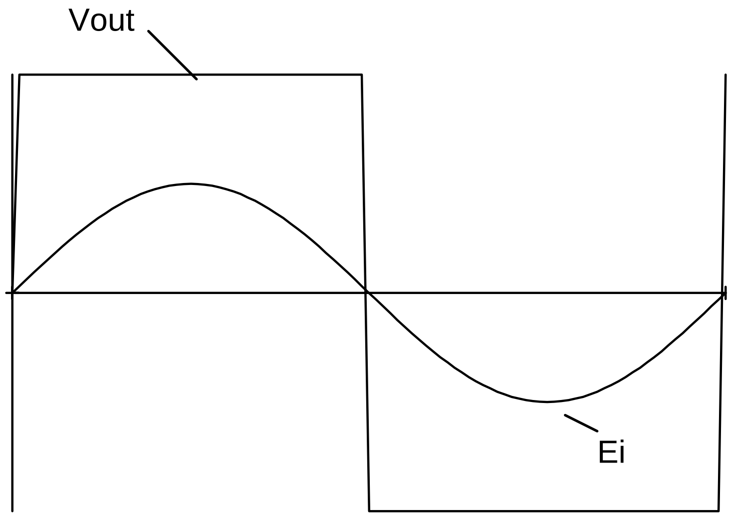


Figure A: "Clean" Input Ei

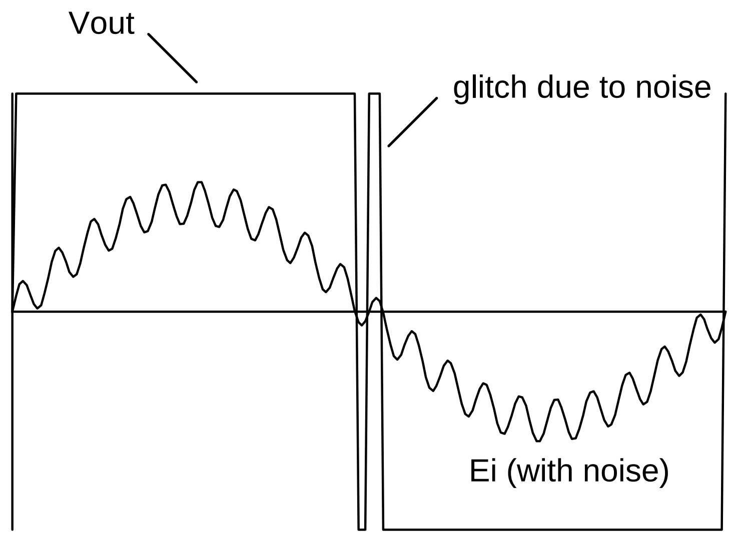


Figure B: "Noisy" Input Ei

Figure 12.3: Noise Susceptibility of Comparator

13. Schmitt Triggers (Optional)

☑ Schmitt Triggers are circuits which are less prone to the noise problems faced in comparator circuits.

☑ Noise effects is reduced by incorporating positive feedback in the basic comparator. The result is having two voltage reference levels used to determine the switching of the output voltage.

☑ These two voltage reference levels are known as V_{UTP} (upper triggering point voltage) and V_{LTP} (lower triggering point voltage).

☑ The difference between V_{UTP} and V_{LTP} is known as the hysteresis voltage, V_{HYS} i.e.

$$V_{HYS} = V_{UTP} - V_{LTP}$$

☑ Two types:

a) Inverting Schmitt Trigger
b) Non-Inverting Schmitt Trigger

We shall focus only on the inverting Schmitt Trigger in this course.

13.1 Operation of Schmitt Trigger

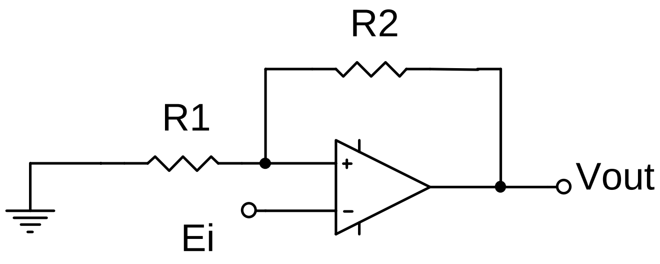


Figure 13.1: Inverting Schmitt Trigger Circuit

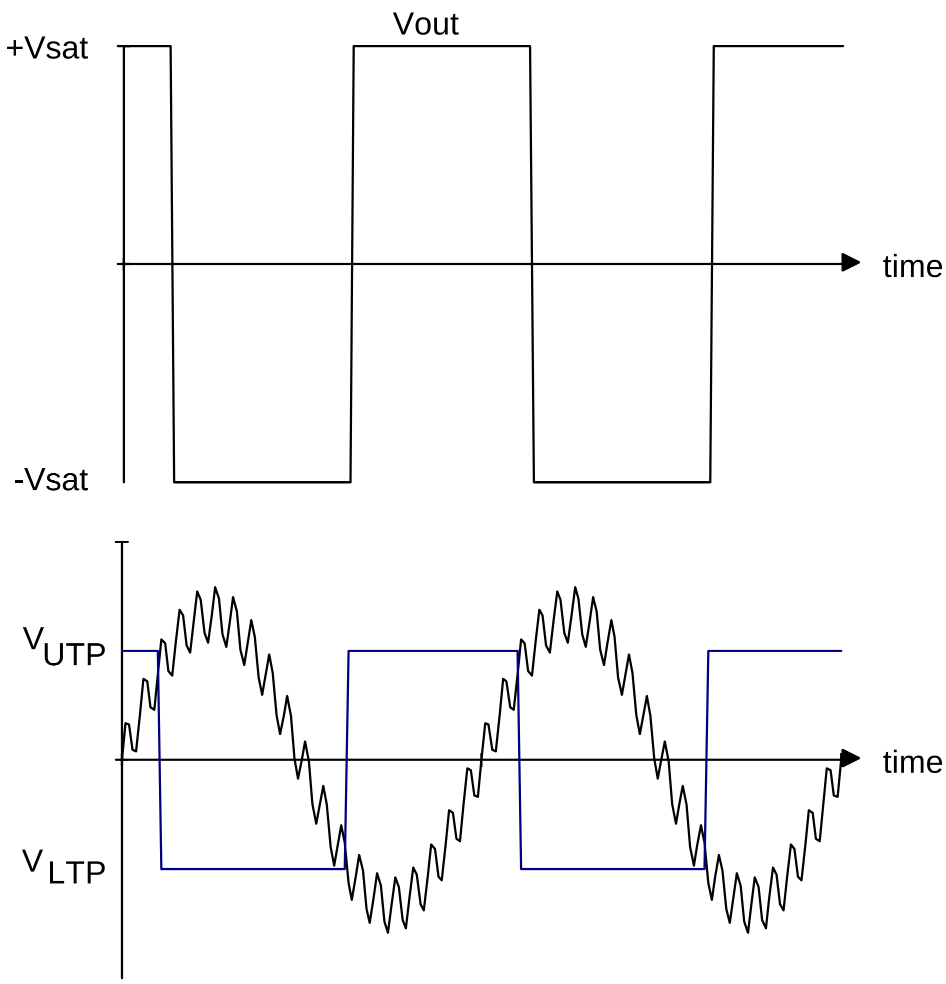


Figure 13.2

☑ Assuming V_{out} = +V_{sat} then

$$V_+ = \frac{R_1}{R_1 + R_2} V_{out}$$
$$= \frac{R_1}{R_1 + R_2} V_{sat}$$
$$= V_{UTP}$$

For V_{out} to swing to -V_{sat}, E_i must exceed V_+ i.e. V_{UTP}

☑ Once $E_i > V_{UTP}$, V_{out} swings to +V_{sat}

$$V_+ = \frac{R_1}{R_1 + R_2} V_{out}$$
$$= \frac{R_1}{R_1 + R_2} (-V_{sat})$$
$$= V_{LTP}$$

For V_{out} to swing to +V_{sat}, E_i must now drop below V_+ i.e. V_{LTP}.

13.2 Transfer Characteristic of Schmitt Trigger

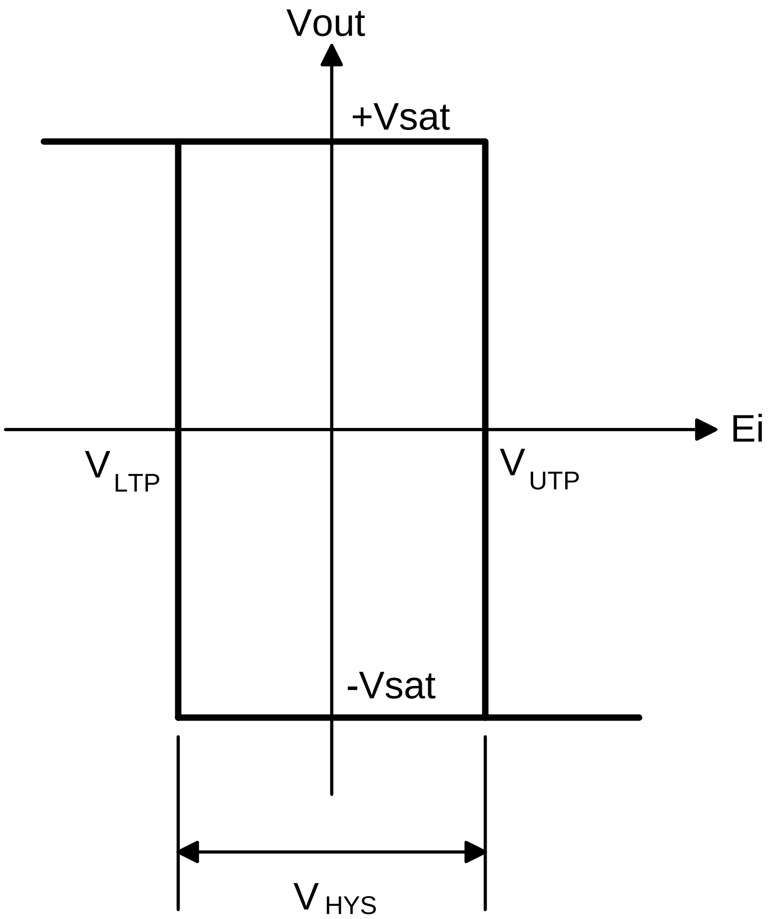


Figure 13.3