Electronics Engineering

Analog Circuits

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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Analog Circuits

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Analog Circuits

Introduction to Analog Circuits

After studying the basic electronic devices and their characteristics, now we shall deal with more complex analog circuits, of which amplifiers is a very significant category. We shall start our analysis with applications of diode, a very fundamental component, in various circuit configurations such as clipper, clamper, regulator etc. Further, we shall proceed to applications of BJT and FET, particularly as an amplifier.

The other complex analog circuits, including circuits that form operational amplifiers, are also part of this book. These circuits are composed of fundamental configurations, such as differential amplifier, constant-current source, active load, and output stage, all of which have been discussed in detail.

The major emphasis throughout the book is on developing the reader's understanding for analyzing and designing various fundamental circuits, which are always an integral part of various competitive examinations. Throughout the book, a very sequential and comprehensive approach has been used, so that a beginner can also utilize the book in very efficient manner.

Prelude to Analog Circuits

Electronics

Electronics is defined as the science of motion of charges in a gas, vacuum, or semiconductor. Note that the charge motion in a metal is excluded from this definition.

This definition was used early in the 20th century to separate the field of electrical engineering, which dealt with motors, generators, and wire communications, from the new field of electronic engineering, which at that time dealt with the vacuum tubes.

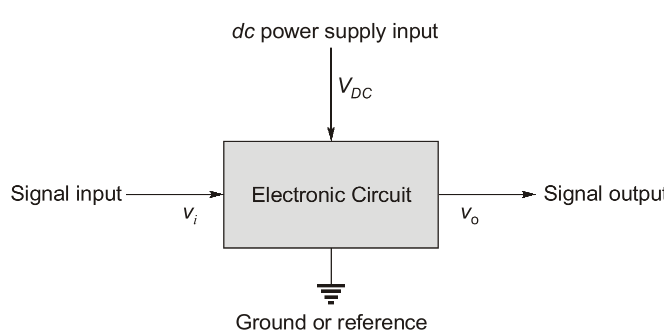
Microelectronics

Microelectronics refers to the integrated-circuit (IC) technology that is capable of producing circuits which contain millions of components in a small piece of silicon (known as a silicon chip) whose area is on the order of 100 mm^2.

Electronic Circuits

A circuit which consists of at least one electronic device (e.g. amplifier, rectifier, oscillator etc.) is known as an electronic circuit.

In most of the electronic circuits there are two inputs. One input is from power supply which provides dc voltages and currents to establish proper biasing for transistors. The second input is a signal that can be amplified by the circuit. Although the output signal can be larger than the input signal but the output power can never exceed the dc input power. Therefore, the magnitude of dc power supply is one limitation to the output signal response.



Discrete and Integrated Circuits

Discrete electronic circuits contain discrete components, such as resistors, capacitors and transistors whereas an integrated circuit consists of a single crystal chip of silicon containing both active and passive elements and their interconnections. Such circuits are produced by the same processes used to fabricate individual transistors and diodes.

Analog and Digital Signals

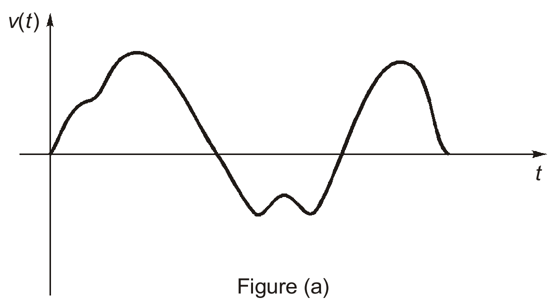


Figure (a)

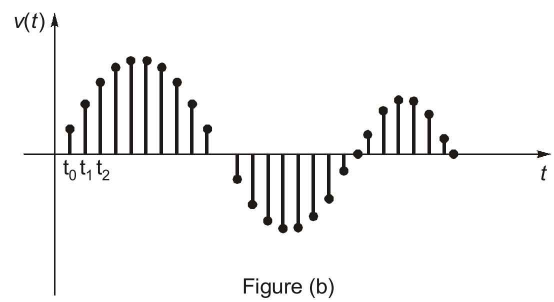


Figure (b)

The voltage signal shown graphically in Fig. (a) is called an ***analog signal***. The name derives from the fact that such a signal is analogous to the physical signal that it represents. The magnitude of an analog signal can take on any value; that is, the amplitude of an analog signal exhibits a continuous variation over its range of activity. Electronic circuits that process such signals are known as ***analog circuits***.

An alternative form of signal representation is that of a sequence of numbers shown in Fig. (b), each number representing the signal magnitude at an instant of time. The resulting signal is called a ***discrete signal***. When discrete signal is quantized in magnitude it becomes a ***digital signal***. Electronic circuits that process digital signals are called ***digital circuits***.

Advantages of Analog Circuits

- Majority of signals in the “real world” are analog; so these signals can be directly processed in analog circuits whereas digital processing requires analog to digital and digital to analog conversion.
- Analog circuits can be designed to operate even at higher power levels.

Advantages of Digital Circuits

- In digital circuits effect of noise is less.
- Digital circuits are easier to design.
- Digital circuits can be programmed.
- Digital data can be stored.

CHAPTER 10

Operational Amplifier

10.1 Introduction

Linear integrated circuits are being used in a number of electronic applications such as in fields like audio and radio communication, medical electronics, instrumentation control, etc. An important linear IC is operational amplifier which will be discussed in this chapter.

The operational amplifier (commonly referred to as op-amp) is a multi-terminal device which internally is quite complex. Fortunately, for the ordinary user, it is not necessary to know about the op-amp's internal make-up. The manufacturers have done their job so well that op-amp's performance can be completely described by its terminal characteristics and those of external components that are connected to it. However, the electronics of op-amp is described where various stages of op-amp are discussed.

10.2 Block Diagram Representation of A Typical Op-Amp

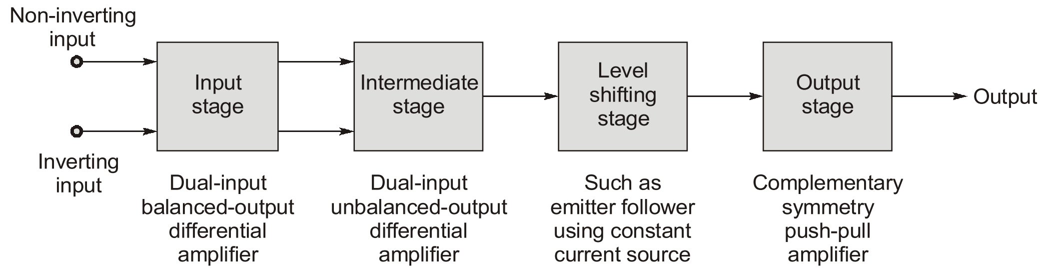


Figure-10.1 : *Block diagram of a typical op-amp*

- An operational-amplifier is a direct-coupled high gain amplifier usually consisting of one or more differential amplifiers and usually followed by a level translator and an output.
- The input stage is the dual-input, balanced-output differential amplifier. This stage generally provides most of the voltage gain and also establishes the input resistance of the op-amp.
- The intermediate stage is usually another differential amplifier, which is driven by the output of the first stage. In most amplifiers the intermediate stage is dual input, unbalanced (single-ended) output.

- As direct coupling is used, so the DC voltage at the output of the intermediate stage is well above ground potential. Therefore, generally, the level translator (shifting) circuit is used after intermediate stage to shift the DC level at the output of intermediate stage downward to zero volts with respect to ground.
- The final stage is usually a push-pull complementary amplifier output stage. The output stage increases the output voltage swing and raises the current supplying capability of the op-amp. A well-designed output stage also provides low output resistance.

NOTE

The operational amplifier is a versatile device that can be used to amplify DC as well as AC input signals and was originally designed for computing such mathematical functions as addition, subtraction, multiplication, and integration. Thus the name ***operational amplifier*** stems from its original use for these mathematical operations.

10.3 Schematic Symbol

Given an op-amp schematic diagram, we can save time by using a schematic symbol for the entire op-amp circuit. Fig. (10.2) shows the most widely used symbol for a circuit with two inputs and one output. For simplicity, power supply and other pin connections are omitted. Since the input differential stage of the op-amp is designed to be operated in the differential mode, the differential inputs are designated by the (+) and (–) notations. The (+) input is non-inverting input. An AC signal or DC voltage applied to this input produces an inphase (or same polarity) signal at the output. On the otherhand, the (–) input is inverting input because an AC signal or DC voltage applied to this input produces an 180° out-of-phase (or opposite polarity) signal at the output.

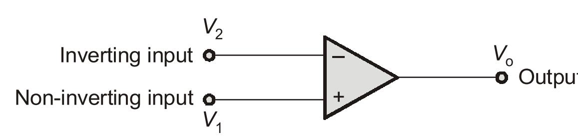


Figure-10.2: *Schematic symbol for the op-amp*

In figure

V_1 = Voltage at the non-inverting input (volts)
V_2 = Voltage at the inverting input (volts)
V_0 = Output voltage (volts)

Here $$\boxed{V_o = A(V_1 - V_2)} \quad ...(10.1)$$

All these voltages are measured with respect to ground.
where, A = Large-signal voltage gain, which is specified on the data sheet for an op-amp.

10.4 Operational Amplifier Characteristics

In an ideal op-amp it is assumed that the op-amp responds equally well to both DC and AC input voltages. However, a practical op-amp does not behave this way. A practical op-amp has some DC voltage at the output even if both the inputs are grounded. The factors responsible for this and the suitable compensating techniques are discussed here.

10.5 DC Characteristics

An ideal op-amp draws no current from the source and its response is also independent of temperature. However, a real op-amp does not work this way. Current is taken from the source into the op-amp inputs. Also the two inputs respond differently to current and voltage due to mismatch in transistors. A real op-amp also shifts its operation with temperature. These non-ideal DC characteristics that add error components to the DC output voltage are:

- Input bias current.
- Input offset current.
- Input offset voltage.
- Thermal drift.

10.5.1 Input Bias Current

Input bias current I_B is the average of the currents that flow into the inverting and non-inverting input terminals of the op-amp. In equation form,

$$I_B = \frac{I_{B_1} + I_{B_2}}{2} \quad \text{...(10.2)}$$

- I_B = 500 nA maximum for the IC 741.
- Note that the two input currents I_{B_1} and I_{B_2} are actually the base currents of the first differential amplifier stage.

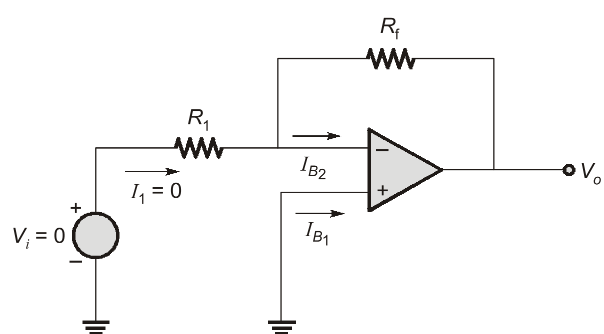


Figure-10.3: *Inverting amplifier with bias currents*

10.5.2 Input Offset Current

The algebraic difference between the currents into the inverting and non-inverting terminals is referred to as *input offset current* I_{io}.

$$I_{io} = \left| I_{B_1} - I_{B_2} \right| \quad \text{...(10.3)}$$

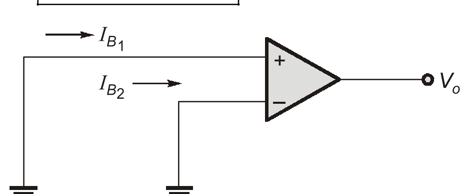


Figure-10.4: *Defining input offset current* I_{io}

- The maximum input offset current for the IC741 is 200 nA. As matching between the two input terminals is improved, the difference between I_{B_1} and I_{B_2} becomes smaller; that is, the I_{io} value decreases further.

10.5.3 Input Offset Voltage

Input offset voltage is the voltage that must be applied between two input terminals of an op-amp to null the output, as shown in ***Fig. 10.5 (a)***. The smaller the value of V_{ios}, the better the input terminals are matched.

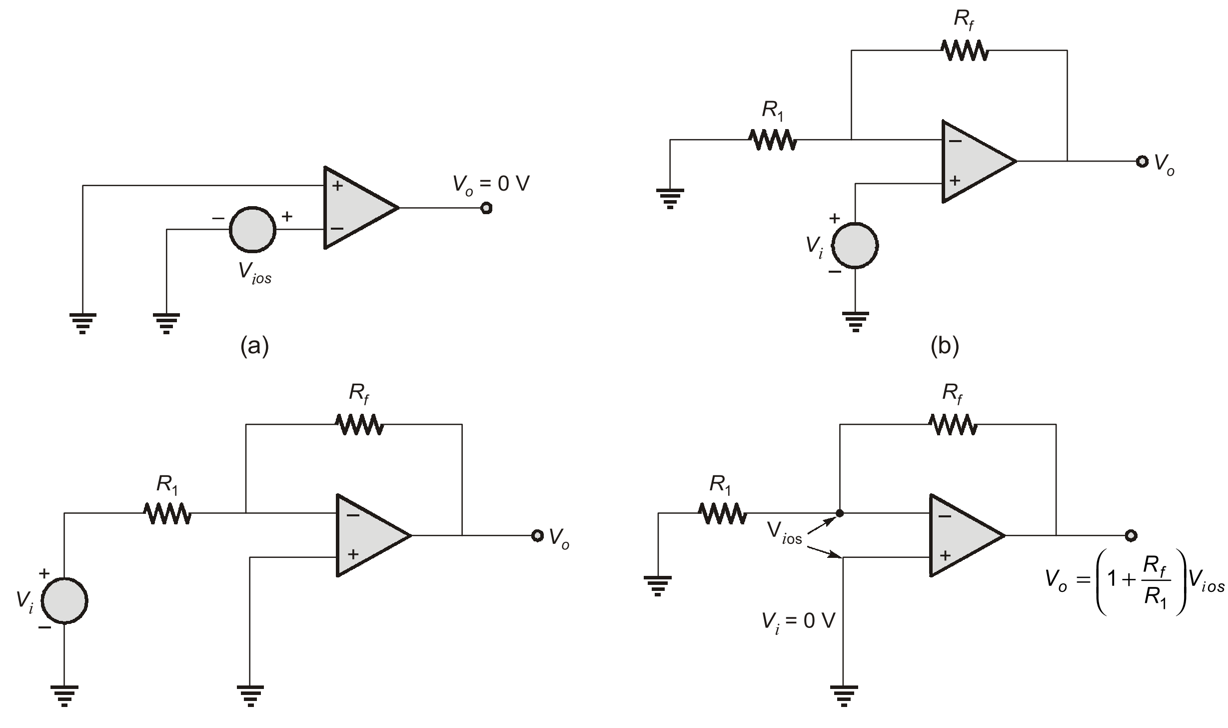


Figure-10.5 *(a) Op-amp showing input offset voltage (b) Non-inverting amplifier (c) Inverting amplifier (d) Equivalent circuit for* $V_i = 0$

Let us now examine the effect of V_{ios} on the output of non-inverting and inverting op-amp as shown in Fig. 10.5 (b) and 10.5 (c). If V_i is set to zero, the circuits of Fig. 10.5 (b, c) become the same as in Fig. 10.5 (d). The voltage V_2 at the (–) input terminal is given by

$$V_2 = \left(\frac{R_1}{R_1+R_f}\right)V_o \quad ...(10.4)$$

or

$$V_o = \left(\frac{R_1+R_f}{R_1}\right)V_2 = \left(1+\frac{R_f}{R_1}\right)V_2 \quad ...(10.5)$$

Since,

$$V_{ios} = |V_i - V_2| \text{ and } V_i = 0$$

$\Rightarrow$

$$V_{ios} = |0 - V_2| = V_2$$

or,

$$\boxed{V_o = \left(1+\frac{R_f}{R_1}\right)V_{ios}} \quad ...(10.6)$$

Thus, the output offset voltage of an op-amp in closed-loop configuration (inverting or non-inverting) is given by equation (10.6).

10.5.4 Thermal Drift

Bias current, offset current and offset voltage change with temperature. A circuit carefully nulled at 25°C may not remain so when temperature rises to 35°C. This is called drift. Often, offset current drift is expressed in nA/°C and offset voltage drift in mV/°C. This indicates the change in offset for each degree Celsius change in temperature.

10.6 AC Characteristics

We have discussed so far the DC characteristics such as bias current, offset current offset voltage and thermal drift. These will affect the steady state (DC) response of the op-amp only. For small signal sinusoidal (AC) applications, one has to know the AC characteristics such as frequency response and slew-rate which will be discussed in this section.

10.6.1 Frequency Response

Since an op-amp is a direct coupled amplifier so ideally, it should have infinite bandwidth. But practically op-amp gain, however decreases (rolls-off) at higher frequencies. Actually, the op-amp acts as a low pass circuit i.e. its gain remains constant at low frequencies but it decreases at high frequencies.

The magnitude and the phase angle of the open loop voltage gain are function of frequency and can be written as

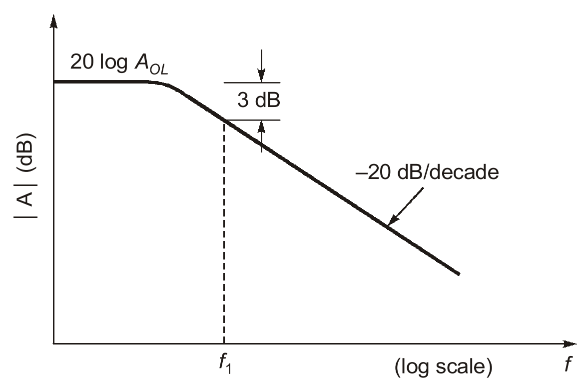


Figure-10.6 *Open loop magnitude characteristics*

$$|A| = \frac{A_{OL}}{\sqrt{1+\left(\frac{f}{f_1}\right)^2}} \qquad \text{...(10.7)}$$

$$\phi = -\tan^{-1}\left(\frac{f}{f_1}\right) \qquad \text{...(10.8)}$$

From ***Fig. (10.6)***, we can observe that

- For frequency of $f << f_1$, the magnitude of the gain is 20 log A_{OL} in dB.
- At frequency $f = f_1$, the gain is 3 dB down from the DC value of A_{OL} in dB. This frequency f_1 is called corner frequency.
- For $f >> f_1$, the gain rolls-off at the rate of –20 dB/decade or –6 dB/octave.

Remember

- Frequency at which open loop gain of an op-amp becomes equal to 1, is called unity gain frequency or unity gain bandwidth (UGB).
- UGB is the product of open loop gain and bandwidth. It is also called gain bandwidth product.

Example - 10.1 The first dominant pole encountered in the frequency response of a compensated op-amp is approximately at

(a) 5 Hz (b) 10 kHz
(c) 1 MHz (d) 100 MHz

Solution:(a)

Example - 10.2 A 741-type op-amp has a gain-bandwidth product of 1 MHz. An non-inverting amplifier using this op-amp and having a voltage gain of 20 dB will exhibit a –3 dB bandwidth of

(a) 50 kHz (b) 100 kHz
(c) $\frac{1000}{17}$ kHz (d) $\frac{1000}{7.07}$ kHz

Solution:(b)

To find gain

$$\therefore \quad 20 \log X = 20$$

$$X = 10$$

$$\because \quad \text{Gain} \times \text{BW} = 1 \times 10^6$$

$$\Rightarrow \quad \text{BW} = \frac{1 \times 10^6}{\text{Gain}} = \frac{10^6}{10} = 100 \text{ kHz}$$

10.6.2 Slew Rate

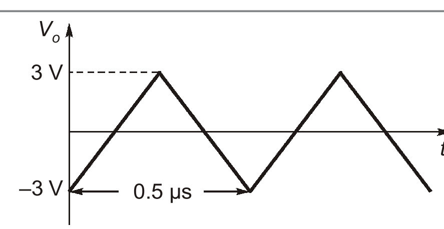
Slew rate (SR) is defined as the maximum rate of change in output voltage per unit of time and is expressed in volts per microseconds. In equation form,

$$SR = \left.\frac{dV_o}{dt}\right|_{\text{maximum}} \text{V/μsec}$$

Remember

- Slew rate indicates how rapidly the output of an op-amp can change in response to change in the input frequency.
- The slew rate of an op-amp is fixed ; therefore, if the slope requirements of the output signal are greater than slew rate, then distortion occurs.

Example - 10.3 The output of an op-amp voltage follower is a triangular wave as shown in figure for a square wave input of frequency 2 MHz and 8 V peak to peak amplitude. What is the slew rate of the op-amp?



Solution:

Since slew rate is defined as the maximum rate of change of the output, so from given figure it can be seen that,

$$\text{SR} = \frac{6 \text{ V}}{(0.5/2)\,\mu s} = 24 \text{ V/μsec}$$