1. CHARACTERISTICS AND PARAMETERS OF OPERATIONAL AMPLIFIERS

The characteristics of an ideal operational amplifier are described first, and the characteristics and performance limitations of a practical operational amplifier are described next. There is a section on classification of operational amplifiers and some notes on how to select an operational amplifier for an application.

1.1 IDEAL OPERATIONAL AMPLIFIER

1.1.1 Properties of An Ideal Operational Amplifier

The characteristics or the properties of an ideal operational amplifier are:

i. Infinite Open Loop Gain,
ii. Infinite Input Impedance,
iii. Zero Output Impedance,
iv. Infinite Bandwidth,
v. Zero Output Offset, and
vi. Zero Noise Contribution.

The opamp, an abbreviation for the operational amplifier, is the most important linear IC. The circuit symbol of an opamp shown in Fig. 1.1. The three terminals are: the non-inverting input terminal, the inverting input terminal and the output terminal. The details of power supply are not shown in a circuit symbol.

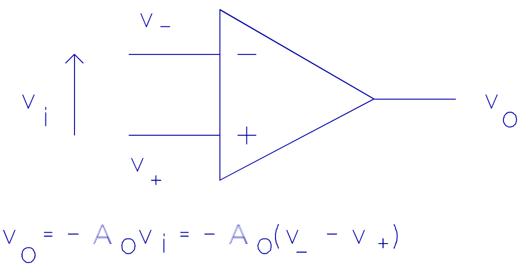

Fig.1.1: Circuit symbol of an opamp

1.1.2 Infinite Open Loop Gain

From Fig.1.1, it is found that $v_o = -A_o \times v_i$, where `A_o' is known as the open-loop gain of the opamp. Let v_o be -10 Volts, and A_o be 10^5. Then v_i is 100 :V. Here the input voltage is very small compared to the output voltage. If A_o is very large, v_i is negligibly small for a finite v_o. For the ideal opamp, A_o is taken to be infinite in value. That means, for an ideal opamp $v_i = 0$ for a finite v_o. Typical values of A_o range from 20,000 in low-grade consumer audio-range opamps to more than 2,000,000 in premium grade opamps (typically 200,000 to 300,000).

The first property of an ideal opamp: Open Loop Gain A_o = infinity.

1.1.3 Infinite Input Impedance and Zero Output Impedance

An ideal opamp has an infinite input impedance and zero output impedance. The sketch in Fig. 1.2 is used to illustrate these properties. From Fig. 1.2, it can be seen that i_{in} is zero if R_{in} is equal to infinity.

The second property of an ideal opamp: R_{in} = infinity or i_{in} =0.

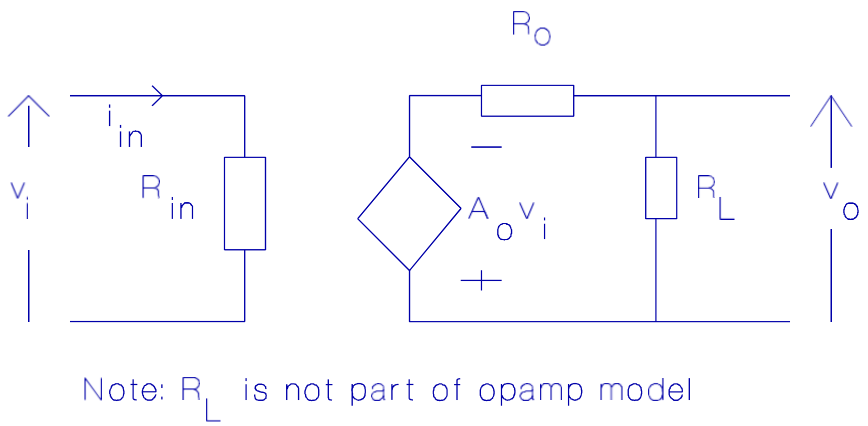

Fig. 1.2: Model of an Opamp

From Fig. 1.2, we get that

$$v_o = -A_o v_i * \frac{R_L}{R_o + R_L}$$

If the output resistance R_o is very small, there is no drop in output voltage due to the output resistance of an opamp.

The third property of an ideal opamp: R_o = 0.

1.1.4 Infinite Bandwidth

An ideal opamp has an infinite bandwidth. A practical opamp has a limited bandwidth, which falls far short of the ideal value. The variation of gain with frequency has been shown in Fig. 1.3, which is obtained by modelling the opamp with a single dominant pole, whereas the practical opamp may have more than a single pole.

The asymptotic log-magnitude plot in Fig. 1.3 can be expressed by a first-order equation shown below.

$$A(jw) = \frac{A_o}{1 + \frac{jw}{w_H}}.$$

It is seen that two frequencies, w_H and w_T, have been marked in the frequency response plot in Fig. 1.3.. Here w_T is the frequency at which the gain A(jw) is equal to unity. If $A(jw_T)$ is to be equal to unity,

$$A(jw_T) = 1 = \left| \frac{A_o}{1 + \frac{jw_T}{w_H}} \right|.$$

Since A_o is very large, it means that $w_T = A_o * w_H$.

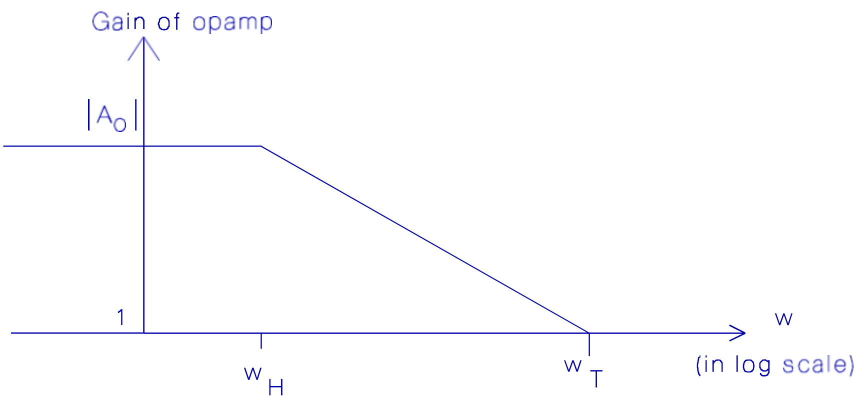

Fig. 1.3: Change in gain of Opamp with Frequency

1.1.5 Zero Noise Contribution and Zero Output Offset

A practical opamp generates noise signals, like any other device, whereas an ideal opamp produces no noise. Premium opamps are available which contribute very low noise to the rest of circuits. These devices are usually called as premium low-noise types.

The output offset voltage of any amplifier is the output voltage that exists when it should be zero. In an ideal opamp, this offset voltage is zero.

1.2 PRACTICAL OPERATIONAL AMPLIFIERS

This section describes the properties of practical opamps and relates these characteristics to design of analog electronic circuits. A practical operational amplifier has limitations to its performance. It is necessary to understand these limitations in order to select the correct opamp for an application and design the circuit properly.

Like any other semiconductor device, a practical opamp also has a code number. For example, let us take the code LM 741CP. The first two letters, LM here, denote the manufacturer. The next three digits, 741 here, is the type number. 741 is a general-purpose opamp. The letter following the type number, C here, indicates the temperature range. The temperature range codes are:

C commercial 0^o C to 70^o C,
I industrial -25^o C to 85^o C and
M military -55^o C to 125^o C.

The last letter indicates the package. Package codes are:

D Plastic dual-in-line for surface mounting on a pc board J
Ceramic dual-in-line
N,P Plastic dual-in-line for insertion into sockets.

1.2.1 Standard Operational Amplifier Parameters

Understanding operational amplifier circuits requires knowledge of the parameters given in specification sheets. The list below represents the most commonly needed parameters. Methods of measuring some of these parameters are described later in this lesson.

Open-Loop Voltage Gain. Voltage gain is defined as the ratio of output voltage to an input signal voltage, as shown in Fig. 1.1. The voltage gain is a dimensionless quantity.

Large Signal Voltage Gain. This is the ratio of the maximum allowable output voltage swing (usually one to several volts less than V- and V++) to the input signal required to produce a swing of ± 10 volts (or some other standard).

Slew rate. The slew rate is the maximum rate at which the output voltage of an opamp can change and is measured in terms of voltage change per unit of time. It varies from 0.5 V/:s to 35 V/:s. Slew rate is usually measured in the unity gain noninverting amplifier configuration.

Common Mode Rejection Ratio. A common mode voltage is one that is presented simultaneously to both inverting and noninverting inputs. In an ideal opamp, the output signal due to the common mode input voltage is zero, but it is nonzero in a practical device. The common mode rejection ratio (CMRR) is the measure of the device's ability to reject common mode signals, and is expressed as the ratio of the differential gain to the common mode gain. The CMRR is usually expressed in decibels, with common devices having ratings between 60 dB to 120 dB. The higher the CMRR is, the better the device is deemed to be.

Input Offset Voltage. The dc voltage that must be applied at the input terminal to force the quiescent dc output voltage to zero or other level, if specified, given that the input signal voltage is zero. The output of an ideal opamp is zero when there is no input signal applied to it.

Power-supply rejection ratio. The power-supply rejection ratio PSRR is the ratio of the change in input offset voltage to the corresponding change in one power-supply, with all remaining power voltages held constant. The PSRR is also called "power supply insensitivity". Typical values are in :V / V or mV/V.

Input Bias Current. The average of the currents into the two input terminals with the output at zero volts.

Input Offset Current. The difference between the currents into the two input terminals with the output held at zero.

Differential Input Impedance. The resistance between the inverting and the noninverting inputs. This value is typically very high: 1 MS in low-cost bipolar opamps and over 10^{12} Ohms in premium BiMOS devices.

Common-mode Input Impedance
The impedance between the ground and the input terminals, with the input terminals tied together. This is a large value, of the order of several tens of MS or more.

Output Impedance. The output resistance is typically less than 100 Ohms.

Average Temperature Coefficient of Input Offset Current. The ratio of the change in input offset current to the change in free-air or ambient temperature. This is an average value for the specified range.

Average Temperature Coefficient of Input Offset Voltage. The ratio of the change in input offset voltage to the change in free-air or ambient temperature. This is an average value for the specified range.

Output offset voltage. The output offset voltage is the voltage at the output terminal with respect to ground when both the input terminals are grounded.

Output Short-Circuit Current. The current that flows in the output terminal when the output load resistance external to the amplifier is zero ohms (a short to the common terminal).

Channel Separation. This parameter is used on multiple opamp ICs (device in which two or more opamps sharing the same package with common supply terminals). The separation specification describes part of the isolation between the opamps inside the same package. It is measured in decibels. The 747 dual opamp, for example, offers 120 dB of channel separation. From this specification, we may state that a 1 :V change will occur in the output of one of the amplifiers, when the other amplifier output changes by 1 volt.

1.2.2 Minimum and Maximum Parameter Ratings

Operational amplifiers, like all electronic components, are subject to maximum ratings. If these ratings are exceeded, the device failure is the normal consequent result. The ratings described below are commonly used.

Maximum Supply Voltage. This is the maximum voltage that can be applied to the opamp without damaging it. The opamp uses a positive and a negative DC power supply, which are typically ± 18 V.

Maximum Differential Supply Voltage. This is the maximum difference signal that can be applied safely to the opamp power supply terminals. Often this is not the same as the sum of the maximum supply voltage ratings. For example, 741 has ± 18 V as the maximum power supply voltage, whereas the maximum differential supply voltage is only 30 V. It means that if the positive supply is 18 V, the negative supply can be only -12 V.

Power dissipation, P_d. This rating is the maximum power dissipation of the opamp in the normal ambient temperature range. A typical rating is 500 mW.

Maximum Power Consumption. The maximum power dissipation, usually under output short circuit conditions, that the device can survive. This rating includes both internal power dissipation as well as device output power requirements.

Maximum Input Voltage. This is the maximum voltage that can be applied simultaneously to both inputs. Thus, it is also the maximum common-mode voltage. In most bipolar opamps, the maximum input voltage is nearly equal to the power supply voltage. There is also a maximum input voltage that can be applied to either input when the other input is grounded.

Differential Input Voltage. This is the maximum differential-mode voltage that can be applied across the inverting and noninverting inputs.

Maximum Operating Temperature. The maximum temperature is the highest ambient temperature at which the device will operate according to specifications with a specified level of reliability.

Minimum Operating Temperature. The lowest temperature at which the device operates within specification.

Output Short-Circuit Duration. This is the length of time the opamp will safely sustain a short circuit of the output terminal. Many modern opamps can carry short circuit current indefinitely.

Maximum Output Voltage. The maximum output potential of the opamp is related to the DC power supply voltages. Typical for a bipolar opamp with ± 15 V power supply, the maximum output voltage is typically about 13 V and the minimum - 13 V.

Maximum Output Voltage Swing. This is the maximum output swing that can be obtained without significant distortion(at a given load resistance).

Full-power bandwidth. This is the maximum frequency at which a sinusoid whose size is the output voltage range is obtained.

1.2.3 Comparisons and Typical Values

Table 1.1 presents a summary of features of an ideal and a typical practical opamp.

Table 1.1: Comparison of an ideal and a typical practical opamp

Property	Ideal	Practical(Typical)
Open-loop gain	Infinite	Very high (>10000)
Open-loop bandwidth	Infinite	Dominant pole(-10 Hz)
CMRR	Infinite	High (> 60 dB)
Input Resistance	Infinite	High (>1 MS)
Output Resistance	Zero	Low(< 100 S)
Input Bias Currents	Zero	Low (< 50 nA)
Offset Voltages	Zero	Low (< 10 mV)
Offset Currents	Zero	Low (< 50 nA)
Slew Rate	Infinite	A few V/:s
Drift	Zero	Low

Table 1.2 shown below presents a summary of the effects of opamp characteristics on a circuit's performance. It is a simplified summary.

1.2.4 Effect of Feedback on Frequency Response

The effect of feedback on the frequency response of a system has already been described. Here the effect of feedback is described using the log-magnitude plot. Given that the transfer function of the forward path is specified as:

TABLE 1.2 EFFECTS OF CHARACTERISTICS ON OPAMP APPLICATIONS

Opamp Characteristic that may affect performance	OPAMP APPLICATION			
	DC amplifier		AC amplifier	
	Small output	Large output	Small output	Large output
1. Input bias current	Yes	Maybe	No	No
2. Offset current	Yes	Maybe	No	No
3. Input offset voltage	Yes	Maybe	No	No
4. Drift	Yes	Maybe	No	No
5. Frequency Response	No	No	Yes	Yes
6. Slew rate	No	Yes	No	Yes

$$A(s) = \frac{A_o}{1 + sT_1} \quad .(1.1)$$

If the closed-loop transfer function T(s) of the circuit is

$$T(s) = \frac{A(s)}{1 + \beta A(s)} \quad .(1.2)$$

On substituting for A(s) by its expression in equation (1.1), we get that

$$T(s) \simeq \frac{\frac{1}{\beta}}{1 + \frac{sT_1}{A_o\beta}}, \; if \; A_o\beta \gg 1 \quad .(1.3)$$

The plot of frequency response for open loop and closed-loop is shown in Fig. 1.4.

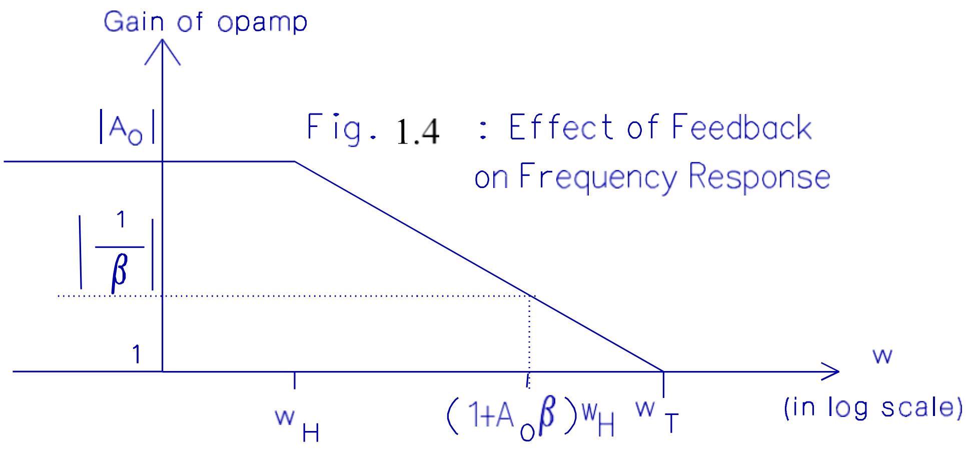

Fig. 1.4 : Effect of Feedback on Frequency Response

1.3 CLASSIFICATION OF OPAMPS

The classification of an opamp can be based on either its function or its family type. The classification based on function is described below.

i. **General-purpose amplifier**. These general purpose opamps are neither special purpose or premium devices. Most of them are internally compensate, so designers trade off bandwidth for inherent stability. A general purpose opamp is the default choice for an application unless a property of another class brings a unique advantage to this application.

ii. **Instrumentation amplifier**. Although an instrumentation amplifier is arguably a special purpose device, it is sufficiently universal to warrant a class of its own.

iii. **Voltage Comparators**. These devices are not true opamps, but are based on opamp circuitry. While all opamps can be used as voltage comparators, the reverse is not true. The special feature of a comparator is the speed at which its output level can change from one level to the other.

iv. **Low Input Current**. The quiescent current needed for these opamps is low. This class of opamps typical uses MOSFET , JFET or superbeta (Darlington) transistors for the input stage instead of npn/pnp bipolar devices.

v. **Low Noise.** These devices are usually optimized to reduce internally generated noise.

vi. **Low Power**. This category of opamp optimizes internal circuitry to reduce power consumption. Many of these devices also operate at very low DC power supply potentials.

vii. Low Drift. All DC amplifiers suffer from drift. Devices in this category are internally compensated to minimize drift due to temperature. These devices are typically used in instrumentation circuits where drift is an important concern, especially when handling low level input signals.

viii. Wide Bandwidth. The devices in this class are also called as video opamps and have a very high gain-bandwidth level, as high as 100 MHz. Note that 741 has a gain-bandwidth product of about 1 MHz .

ix Single DC Supply. These devices are designed to operate from a single DC power supply.

x. High Voltage. The power supply for these devices can be as high as ± 44 V.

xi. Multiple devices. Two or quad arrangement in one IC.

The classification based on family type:
i. Bipolar opamps, ii. BiFET opamps, iii. JET opamps, iv. CMOS opamps etc. The characteristics of opamps change with the internal architecture also. Some opamps have two-stage architecture, whereas some have three-stage architecture.

The purpose of this section is to highlight the facts that it is necessary to select a suitable opamp for the application in hand and that there is a wide choice available. Choosing the right opamp is not simple. Aspects to be considered are: technology,dc performance,ac performance,output drive requirements, supply requirements, quiescent current level, temperature range of operation, nature of input signal, costs etc. Table 1.3 presents a summary of characteristics of a few selected opamps. It is preferable to go through the databooks on linear ICs for selecting the right opamp.