due to this rate limitation. When called upon to do so, it does its best and moves its output at the maximum rate it is capable of. The maximum rate at which an amplifier output voltage can change is termed as its *slew rate*. The *slew rate* may be different for the two directions of change.

We conclude this section by reiterating the major points.

- DC Power Supplies are needed to fix the Quiescent Operating Point of the devices in an electronic amplifier. The Q-point (along with loading details) will decide the gain of the amplifier, maximum peak-to-peak swing at output and maximum symmetrical swing at the output before clipping takes place at any one end. Maximum peak-to-peak swing can not exceed the value of power supply voltage.
- Maximum current available at the output of an amplifier is limited and the positive and negative limits are also set by DC supplies through bias point details.
- Maximum rate of change that the output voltage of an amplifier can exhibit is also limited. The limits are again set by DC supplies through bias point of devices.
- DC power supplies are needed in amplifiers to function as the source of power delivered to the output.
- Linear models using dependent sources can be used to model electronic amplifiers only if the operating point of various devices in the amplifier undergo only *small* perturbations (typically < 15%) around their Q-points.
- The output waveshape will suffer non-linear distortion when the input to an amplifier is a large signal. There may be *clipping distortion* too if the input signal is large enough. Distortion can also occur due to the amplifier getting into *current-limited* or *rate-limited* modes of operation. Linear models using dependent sources *can not predict* these phenomena. Linear models *will not be valid* if the amplifier is in *large-signal mode* or *voltage-limited mode* or *current-limited mode* or *slope-limited (rate-limited) mode*. These modes of operation will be collectively termed as *non-linear range of operation*.

6.3 The Operational Amplifier

Ideal amplifiers are physically unrealizable. Operational Amplifiers try to approach the ideal.

Operational Amplifier is a muti-stage high gain voltage-to-voltage amplifier with differential input and single-ended output. It is an integrated circuit package. We use the short name '*Opamp*' for Operational Amplifier in this book.

It is a *differential amplifier* and has two signal input terminals. It amplifies the difference between the voltages applied at input terminals. These two input voltages as well as the output voltage are referred to a common *ground* terminal.

Ground in an Opamp is not a terminal or pin of the Opamp. It is a node outside the Opamp. In Opamps working from a single DC power supply, the *ground* is commonly assigned to the negative of the dc source. In Opamps working *from a balanced dual DC power supply*, the *ground* is commonly taken as the midpoint of the dual supply. The output voltage is measured between a single output terminal from the Opamp and the *ground* terminal that is outside the Opamp package.

Various integrated circuit design techniques are employed to minimise the non-linear distortion in output signal arising out of non-linear transfer characteristics of transistors. However, even an Opamp can not do away with voltage, current and rate limits. The non-linear distortion arising out of *clipping* due to one or more of these limits takes place in Opamp circuits when they are overdriven or overloaded. Thus, linear models are applicable to Opamps as long as they are not operating in one of the *limited modes*. That is, *small-signal* approximation is not needed for analysing Opamp circuits using linear models. But *voltage saturation or current saturation* or *slope saturation* should not take place in the circuit if linear models are to yield correct solution.

An ideal voltage amplifier is expected to have infinite input resistance, zero output resistance and infinite bandwidth, *i.e.,* it does not differentiate between two

> The previous section showed that an amplifier can not escape from limits on its output voltage, limits on its output current and limits on rate of change of output voltage. Neither can it escape from non-linear distortion under large-signal conditions.
>
> An Opamp design aims at the following:
>
> (i) Minimise the non-linear distortion till it is forced into one or more of limited modes – voltage-limited mode, current-limited mode or slope-limited mode.
>
> (ii) Make the voltage limits (called *saturation voltages*) symmetrical about the middle level of DC power supply.
>
> (iii) Make the peak-to-peak voltage swing at the output terminal approach the total DC supply voltage employed.
>
> (iv) Make the current limits symmetrical, and
>
> (v) Make the slope-limits (*slew rate*) more or less equal for increasing output and decreasing output.

sinusoidal signals of same amplitude and different frequencies and provides same gain to both. *Bandwidth is a measure of variation of gain with frequency of an applied sinusoid.* A practical Opamp has very large input resistance (in MΩ's) and small output resistance (in Ω's) and it has finite bandwidth. Therefore if the input applied to it is a mixture of sinusoids, it will offer different gains for different sinusoidal components at different frequencies. It will also add a phase shift to the output that will also depend on the frequency. These two kinds of differential treatment to sinusoids of different frequencies lead to a difference in waveshape of output compared to that of input. That is *distortion*. But it is not due to non-linearity in transistors. Therefore, it is not *non-linear* distortion. It is due to the gain of Opamp becoming a function of frequency and that happens because of capacitance of transistors. This distortion takes place even when the Opamp is in the *linear range* of operation. Therefore, it is called *linear distortion*.

Non-linear distortion changes the waveshape of output even when the input is a single frequency sinusoid. But linear distortion does not do that. Linear distortion changes the waveshape of output only when the input is *not* a single frequency sine wave, but is a mixture of sine waves of different frequencies. An ideal Opamp does not produce any linear distortion.

The voltage gain of a practical Opamp is very large – typically hundreds of thousands. We hardly ever need that kind of gain in any practical application. Thus, we hardly ever find an Opamp being used as an amplifier without some other components (usually resistors) limiting the gain of the overall amplifier circuit to the required value that is likely to be in the range 1-100. But, then, why make a circuit with a huge gain and kill its gain when it is used for amplification purposes? The short answer is that the huge gain of Opamp is the currency that we pay for improvements in other performance measures of the overall amplifier circuit. We gain on other performance parameters by paying out gain.

For instance, the input resistance of overall amplifier can be increased and its output resistance decreased by sacrificing the gain. Its bandwidth can be increased and non-linear distortion can be decreased by sacrificing the Opamp gain.

The circuit technique that we use in order to bring about this trade-off between gain of Opamp and performance of overall amplifier circuit in which the Opamp is embedded is called *negative feedback*. We will take it up in a later section. But we note here that higher the Opamp gain, better the advantages that accrue from employing negative feedback around it.

An Opamp is expected to produce zero output when both its input terminals are connected to same voltage with respect to ground. However, practical Opamps do produce a small output under this condition. The corresponding gain is called the *common-mode gain*. The gain registered by the Opamp when it is driven by two equal but opposite sources at its input terminals is called the *differential gain*. The ratio of differential mode gain to common mode gain is defined as its '*Common Mode Rejection Ratio*' and is usually quoted in decibels (dB). Decibel value of a quantity is obtained by calculating 20 times the logarithm of the quantity with 10 as the base of logarithm.

An Opamp is expected to produce zero output when both its input terminals are connected to ground. However, practical Opamps do produce non-zero output under this condition. Thus practical Opamps exhibit *output offset*.

The need for establishing proper bias points for transistors in an amplifier was already discussed. Biasing of transistors has to take place within an Opamp too. As a result some dc currents will flow out of (or into) the signal input terminals in certain Opamp designs. These currents are called *input bias currents*.

Features of an Ideal Operational Amplifier (IOA)

Ideal Opamp, obviously, can not be made. But it provides a benchmark for evaluating a practical Opamp.

An Ideal Operational Amplifier is a voltage-to-voltage differential amplifier with infinite input resistance, infinite gain, infinite bandwidth and zero output resistance. An IOA has the following features.

1. **Input Resistance, $R_{in} \rightarrow \infty$**
2. **Output Resistance, $R_o \rightarrow 0$**
3. **Voltage Gain, $A_v \rightarrow \infty$**
4. **Bandwidth, bw $\rightarrow \infty$**
5. **Common Mode Rejection Ratio (CMRR) $\rightarrow \infty$**
6. **No voltage, current and slope limits.**
7. **Zero offsets and zero input bias currents.**

The Practical Operational Amplifier

The most popular general purpose Opamp, the μA 741, is available as a DIP (Dual-in-Line) package of $\frac{1}{4}\text{inch} \times \frac{3}{8}\text{inch}$ size. It has 8 pins. The pin details and circuit symbol of Opamp are shown in Fig. 6.3-1. It is a dual supply Opamp and the midpoint of the supply connection is taken as ground usually.

This Opamp has a differential gain of 250,000 and CMRR of 80dB. This implies that its common mode gain is indeed negligible. Its input resistance is about 2MΩ and output resistance is about 75Ω.

With a supply voltage of ±12 volts, its output saturation limits are 10.6 volts and –11 volts. It has a bandwidth of ≈ 4 Hz (very small) and a slew rate of 0.5 volts/μs. Its output current is limited at ± 20mA with a supply voltage of ±12 V.

Its input bias currents, called I_{B+} and $I_{B\_}$, are ≈ 100 nA and the difference (I_{B+}-$I_{B\_}$) between them can be ± 20nA. This difference is called *input bias offset current*.

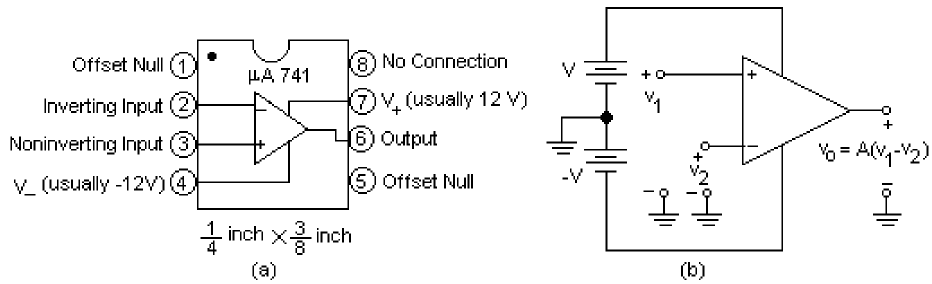

Fig. 6.3-1 (a) Top View of μA 741 IC (b) Circuit Symbol and Voltage Polarities for an Opamp

The output of this Opamp will be at one of the saturation limits when both inputs are grounded. There is so much of offset. Hence the offset voltage for Opamps is specified at input indirectly rather than at output directly. Applying a differential voltage across the inverting and non-inverting inputs of the Opamp can null the output offset. The differential voltage that has to be applied across the two input terminals in order to bring the output to zero with respect to ground is defined as the *input offset voltage* and denoted by v_{io}. The value for μA741 is about 2mV. The polarity of this voltage can be decided only by experiment on the particular piece of IC that is being used.

Input Offset Voltage of an Opamp

The circuit (b) of Fig. 6.3-1 show the power supply connections in detail. However these connections are usually suppressed in circuit diagrams involving Opamps. It is understood implicitly that the Opamps are powered properly in circuits. This is permissible since we hardly ever apply KCL at power supply nodes of Opamps in analysing a circuit containing Opamps. We do not apply KCL at ground node too. But that is because of the fact that we always assign the role of reference node to the ground node in Opamp circuits when we prepare the node equations of such circuits.

6.4 Negative Feedback in Operational Amplifier Circuits

Consider the circuit (a) in Fig. 6.4-1. We ignore the offsets in output in our analysis in this section. Therefore, the output in circuit (a) is given by $v_o = A(v_1 - v_2)$ where A is the differential mode voltage gain of the Opamp. The value of A for μA741 Opamp is around 250,000. Let us assume that the power supply used is ±12 V in all the three circuits. The voltage saturation levels will be taken approximately equal to supply voltage of 12V. Actually it is 10.6 V and –11 V; we ignore the difference.

Hence, the first circuit will saturate when the differential input voltage $v_d = v_1 - v_2$ goes out of the range (-48μV, +48μV). We usually do not need this much of gain. If $v_d = v_1 - v_2$ is in mV or Volts range, the output will spend most of the time in nonlinear range under saturated condition. For instance say $v_1 = 0.0048 \sin 2\pi t$ and v_2 = 0. Then the output will be an almost clean square wave of period 1 sec and amplitude of 12 V. The Opamp will be in the linear range of operation only for about 6.4 ms in 1 sec. It will be in saturated condition for the remaining duration. Thus, this mode of using Opamp, called the *open loop* mode, is not really useful for linear amplification purposes.

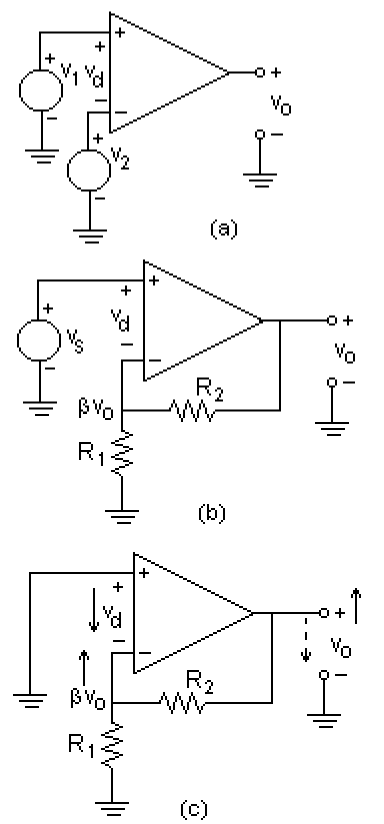

Fig. 6.4-1 (a) Opamp on Open Loop (b) Opamp Embedded in a Resistive Network (c) Opamp Circuit Illustrating Negative Feedback

Consider the circuit (b) in Fig. 6.4-1. Here the Opamp is embedded in a resistive network that generates interaction between the input side of Opamp with its own output side. This interaction takes place through the resistor chain R_1 and R_2. They loop back the output of Opamp to its own input. When there is such 'looping back' of output of an

Opamp to its input side in a circuit, we state that *the circuit employs feedback.* The *sense of feedback* can be negative or positive. We decide the *sense of feedback* in the circuit by analysing the circuit after assuming that its source is reduced to zero. The resulting circuit is shown in (c) of Fig. 6.4-1. We expect the output to be at zero since the Opamp was assumed to be free of offset.

The feedback action, negative feedback, positive feedback

Now, let us analyse the process that takes place in the system when the output was momentarily disturbed by some kind of electromagnetic pickup from some neighboring circuit. Assume that the output voltage increased from zero level. This increase is felt at the inverting input of Opamp through the $R_1 - R_2$ chain. The current drawn by the inverting input of Opamp loads this potential divider. However, the Opamp has very large input resistance and hence the $R_1 - R_2$ potential divider may be considered unloaded. Therefore, the potential that appears at inverting input is βv_o where β is the feedback factor and is equal to $R_1/(R_1 + R_2)$. Therefore, when the output increases, the inverting input potential with respect to ground node also increases. This leads to a reduction in the differential voltage v_d that appears across the Opamp input terminals. A reduction of differential input of Opamp is followed by a reduction of its output voltage itself. Thus we see that an inadvertent increase in Opamp output goes through the feedback loop to generate a corrective action that tends to restore the output to its pre-disturbed condition. When feedback results in this kind of corrective action, we term it as *negative feedback* or *degenerative feedback*.

Those pins can't be mixed up!

A simple interchange of the roles of inverting input terminal and non-inverting input terminal of an Opamp in circuit changes the nature of feedback in the circuit and affects the function and operation of the circuit significantly.

One has to be very careful in drawing the circuit diagrams containing Opamp. The inverting and non-inverting terminals of Opamps have to be marked properly without fail.

Note that if we had connected the resistor chain at non-inverting input of Opamp and the input source to the inverting input terminal, a regenerative action instead of corrective action would have taken place. An increase in output would have resulted in an increase in differential input voltage and that would have resulted in further increase in Opamp output. All circuits are under constant disturbance from other circuits. Therefore, an Opamp circuit with this kind of feedback connection will find itself going to one of the saturation levels due to some initial pick up voltage at output getting encouragement from the feedback to grow further in the same direction that it started with. This kind of feedback is called *positive feedback* or *regenerative feedback.* Positive feedback usually takes the Opamp output to saturation condition as soon as it is switched on. Obviously positive feedback Opamp circuits can not function as linear amplifiers.

6.5 The Principles of 'Virtual Short' and 'Zero Input Current'

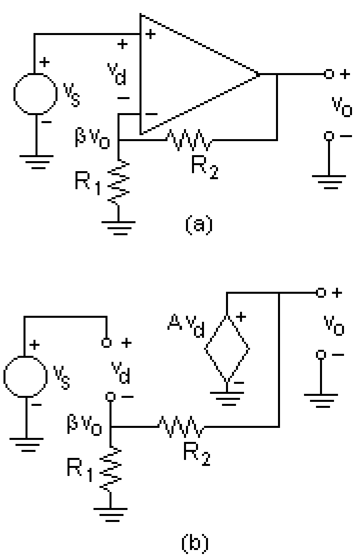

Fig. 6.5-1 (a) A Single Opamp Amplifier Circuit (b) Circuit with Opamp Replaced by its Equivalent Circuit

We continue with the analysis of circuit (b) in Fig. 6.4-1. We have ascertained that the feedback involved in this circuit is negative in sense. Hence we expect the output to be zero when input is zero. Now we set out to find the output in terms of input when the input is non-zero. Assume that the Opamp is ideal. Hence, its input resistance is an open-circuit, output resistance is a short-circuit and its gain is infinity. The gain is taken as A first and is sent to infinity at the end of circuit solution. The circuit is redrawn with the Opamp replaced by its ideal equivalent circuit as in circuit (b) of Fig. 6.5-1. We derive the equation for output as below.

$$v_d = v_s - \beta v_o \text{ where } \beta = \frac{R_1}{R_1 + R_2}$$

$$v_o = A v_d = A(v_s - \beta v_o)$$

$$\therefore v_o = \frac{A}{1 + A\beta} v_s \text{ and } v_d = \frac{1}{1 + A\beta} v_s$$

We observe that the differential input v_d is only $1/_{1+A\beta}$ times that of what it would have been had the source been applied directly to Opamp as in circuit (a) of Fig. 6.4-1. Since the Opamp gain is very large for a practical Opamp and is infinity for an ideal Opamp, we evaluate the limit of these expressions as $A \to \infty$. We get,

$$v_o = \lim_{A \to \infty} \frac{A}{1 + A\beta} v_s = \frac{1}{\beta} v_s = \left[1 + \frac{R_2}{R_1}\right] v_s$$

$$\text{and } v_d = \lim_{A \to \infty} \frac{1}{1 + A\beta} v_s = 0$$

Hence, the gain of overall amplifier goes to $1+R_2/R_1$. It is decided by external components entirely. And the differential input voltage goes to zero.

Why does the differential input voltage go to zero? If the Opamp is in linear range, its differential input voltage has to be equal to its output divided by the gain. The negative feedback present in the circuit resists any change in the output. Consider the situation when a certain voltage is suddenly applied to the input. Then the differential voltage increases suddenly since the Opamp will take a little time to adjust its output. The large differential voltage causes the Opamp output to increase. Increasing Opamp output reduces the differential input voltage through the feedback mechanism. Finally a steady state comes up in the circuit when the output is such a value that the difference between source voltage and fed back voltage is exactly equal to the output divided by gain. The circuit attains equilibrium under that condition. Any deviation from this equilibrium condition will be corrected by negative feedback action. Since the gain is large, it requires only a small differential voltage to remain at this equilibrium. For instance, let v_s be 0.1 volt, A = 250,000 and β= 0.1. Then $v_d = 0.1\times1/(1+25000) = 4\mu V$ and $v_o = 0.1\times250000/(1+25000) = 999960\ \mu V \approx 1$ volt. It requires only $4\mu V$ of v_d to justify 1 volt of output since the gain is 250,000. Now if the gain is increased further the value of v_d goes down further and v_o approaches 1 volt more closely. And, in the limit when gain goes to infinity v_d goes to zero and v_o goes to 1 volt.

But will v_d be zero if v_s is 10 volts? No, since the amplifier will saturate and will be in the nonlinear range of operation. The large gain that is effective in linear range of operation is not available when the Opamp is operating in voltage-limited or current-limited or slope-limited modes of operation. Hence, we may conclude that the differential voltage across the non-inverting input terminal and inverting input terminal of an Opamp is arbitrarily close to zero if the Opamp is under negative feedback and is in its linear range of operation. Thus, the two input terminals, though are not connected together, are virtually at the same potential under these conditions and behave as if they are shorted together. Therefore, there is a *virtual short* across the input terminals of an Opamp working in its linear range of operation in a negative feedback circuit.

The input resistance of an ideal Opamp is infinite and hence the Opamp does not draw any current at its input terminals. The input resistance of a practical Opamp is large and the current drawn by the input terminals is usually negligible compared to currents elsewhere in the circuit. This remains true even when the Opamp is in its nonlinear range of operation. This principle is called 'the zero input current principle'.

Thus, from the point of view of input currents drawn by the ideal Opamp, its input terminals represent an open-circuit, and, from the point of view of differential input voltage the same two terminals represent a short-circuit. This model for an Opamp is called the *Ideal Opamp Model* (IOA Model). *It is emphasized again that IOA model will lead to correct analysis only if the Opamp is in a negative feedback circuit and is working in its linear range of operation.*

The virtual short principle

The input terminals of an ideal Opamp in a negative feedback circuit behave as if there is short-circuit across them.

The input terminals of a practical Opamp with large gain behave as if there is short-circuit across them provided the Opamp is in a negative feedback circuit and it is operating in its linear range.

The zero input current principle

"The input terminals of an ideal Opamp do not draw any current from the circuit in which the Opamp is embedded."

The input terminals of a practical Opamp with large input resistance draw negligible current from the circuit in which the Opamp is embedded.

The currents drawn by the input terminals are usually negligible in both linear and nonlinear ranges of operation.

6.6 Analysis of Operational Amplifier Circuits Using the IOA Model

The principles enunciated in the preceding section can be used to develop a much-simplified analysis procedure for circuits containing Opamps. The procedure is outlined below.

1. Ascertain whether the circuit has negative feedback or positive feedback. If it is a positive feedback circuit, the IOA Model can not be used for its analysis. Only the principle of zero input current will be applicable for such circuits. Other analysis procedures using nodal analysis or mesh analysis along with zero input current principle will be needed then.
2. Prepare node equations at all nodes except ground node. Ground node is taken as the reference node for nodal analysis. Use the principle of zero input current in writing the node equations.
3. Apply the principle of virtual short on all Opamps in the circuit to reduce the number of node equations and solve the reduced set of equations.

This procedure is illustrated in the case of various Opamp circuits in the remainder of this section. These circuits not only serve as illustrations for the technique