CHAPTER 1

BASIC PRINCIPLES AND APPLICATIONS

Op-amps were originally designed to perform the mathematical operations of addition, subtraction, integration, etc., in analogue computers. The devices have many other uses, however, and can readily be used as the basis of a host of a.c. and d.c. amplifiers, instrumentation circuits, oscillators, tone generators, and sensing circuits, etc. In this present volume we show 110 different projects that can be built around these versatile devices.

Basic characteristics and circuits

Most operational amplifiers are of the differential-input type, and are represented by the symbol shown in *Figure 1.1a. Figure 1.1b* shows the basic supply connections that are used with an op-amp. Note that the device is operated via a dual power supply with a common ground, thus enabling the op-amp output to swing either positive or negative with respect to ground.

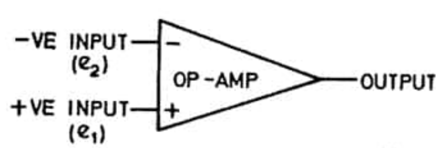

Figure 1.1a. Basic op-amp symbol.

The op-amp has two input terminals, and uses direct coupling between input and output. Typically, the device gives a basic low-frequency voltage gain of about 100 000 between input and output, has an input impedance of about 1 MΩ at each input terminal, and has an output impedance of a few hundred ohms.

One input terminal of the device is denoted negative, and gives an inverted output, and the other is denoted positive, and gives a non-inverted output. If a positive input voltage is applied to the negative

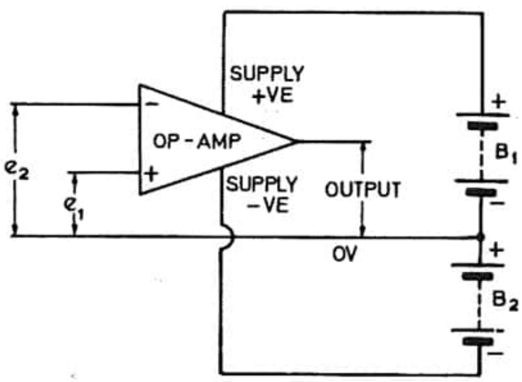

Figure 1.1b. Basic supply connections of an op-amp.

terminal while the other input is grounded the output is inverted, and swings negative. Alternatively, if a positive input is applied to the positive terminal while the other terminal is grounded the output is non-inverted, and swings positive. If identical signals are simultaneously applied to both inputs the output will ideally be zero, since the two signals are cancelled out by the differential action of the amplifier. Note that the output of the circuit is proportional to the *differential* signal between the two inputs, and is given by:

$$e_{out} = A_0(e_1 - e_2)$$

where A_0 = the open-loop voltage gain of the op-amp (typically 100 000).
e_1 = signal voltage at the positive input.
e_2 = signal voltage at the negative input.

Figure 1.2a shows a very simple application of the op-amp. This particular circuit is known as a differential voltage comparator, and has a fixed reference voltage applied to the negative input terminal, and a

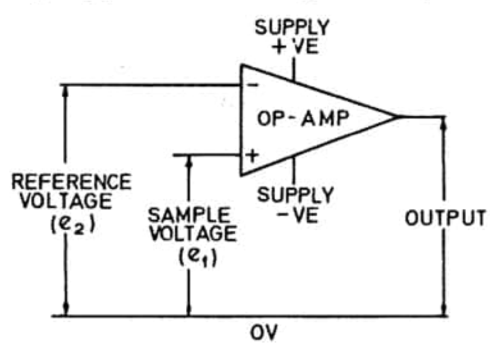

Figure 1.2a. Simple differential voltage comparator circuit.

variable test or sample voltage applied to the positive terminal. When the sample voltage is greater than that of the reference by more than a few hundred microvolts the output is driven to saturation in the positive direction, and when the sample is greater than a few hundred microvolts less than the reference voltage, the output is driven to saturation in the negative direction.

Figure 1.2b shows the voltage transfer characteristics of the above circuit. Note that it is the magnitude of the differential input voltage that dictates the magnitude of the output voltage, and that the absolute values of input voltage are of little importance. Thus, if a 1 V reference is used and a differential voltage of only 200 μV is needed to switch the output from a negative to a positive saturation level, this change can be caused by a shift of only 0.02 % on a 1 V signal applied to the sample input. The circuit thus functions as a precision voltage comparator or balance detector.

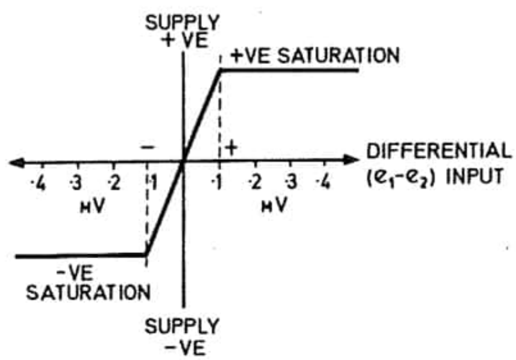

Figure 1.2b. Transfer characteristics of the differential voltage comparator circuit of Figure 1.2a.

The op-amp can be made to function as a low-level inverting d.c. amplifier by simply grounding the positive terminal and feeding the input signal to the negative terminal, as shown in *Figure 1.3a*. The op-amp is

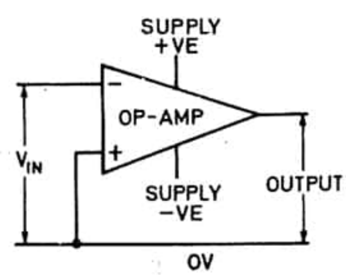

Figure 1.3a. Simple open-loop inverting d.c. amplifier.

used 'open-loop' (i.e., without feedback) in this configuration, and thus gives a voltage gain of about 100 000 and has an input impedance of about 1 MΩ. The disadvantage of this circuit is that its parameters are dictated by the actual op-amp, and are subject to considerable variation between individual devices.

A far more useful way of employing the op-amp is to use it in the closed-loop mode i.e., with negative feedback. *Figure 1.3b* shows the method of applying negative feedback to make a fixed-gain inverting d.c. amplifier. Here, the parameters of the circuit are controlled by feedback

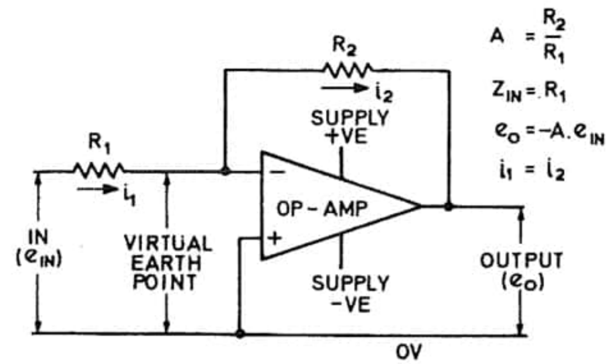

Figure 1.3b. Basic closed-loop inverting d.c. amplifier.

resistors R_1 and R_2. The gain, A, of the circuit is dictated by the ratios of R_1 and R_2, and equals R_2/R_1. The gain is virtually independent of the op-amp characteristics, provided that the open-loop gain (A_0) is large relative to the closed-loop gain (A). The input impedance of the circuit is equal to R_1, and again is virtually independent of the op-amp characteristics.

It should be noted at this point that although R_1 and R_2 control the the gain of the complete circuit, they have no effect on the parameters of the actual op-amp, and the full open-loop gain of the op-amp is still available between its negative input terminal and the output. Similarly, the negative terminal continues to have a very high input impedance, and negligible signal current flows into the negative terminal. Consequently, virtually all of the R_1 signal current also flows in R_2, and signal currents i_1 and i_2 can be regarded as being equal, as indicated in the diagram.

Since the signal voltage appearing at the output terminal end of R_2 is A times greater than that appearing at the negative terminal end, the current flowing in R_2 is A times greater than that caused by the negative terminal signal only. Consequently, R_2 has an apparent value of R_2/A when looked at from its negative end, and the $R_1 - R_2$ junction thus appears as a low-impedance *virtual earth* point.

It can be seen from the above description that the *Figure 1.3b* circuit is very versatile. Its gain and input impedance can be very precisely controlled by suitable choice of R_1 and R_2, and are unaffected by variations in the op-amp characteristics. A similar thing is true of the non-inverting d.c. amplifier circuit shown in *Figure 1.4a.* In this case the voltage gain is equal to $(R_1 + R_2)/R_2$, and the input impedance is approximately equal to $(A_0/A)Z_{in0}$, where Z_{in0} is the open-loop input impedance of the op-amp. A great advantage of this circuit is that it has a very high input impedance.

The op-amp can be made to function as a precision voltage follower by connecting it as a unity-gain non-inverting d.c.amplifier, as shown in *Figure 1.4b.* In this case the input and output voltages of the circuit are identical, but the input impedance of the circuit is very high and is approximately equal to $A_0 \times Z_{in0}$.

The basic op-amp circuits of *Figure 1.2a* to *1.4b* are shown as d.c. amplifiers, but can readily be adapted for a.c. use. Op-amps also have many applications other than as simple amplifiers. They can easily be made to function as precision phase splitters, as adders or subtractors, as active filters or selective amplifiers, as precision half-wave or full-wave rectifiers, and as oscillators or multivibrators, etc. A whole range of useful applications are described in following chapters of this volume.

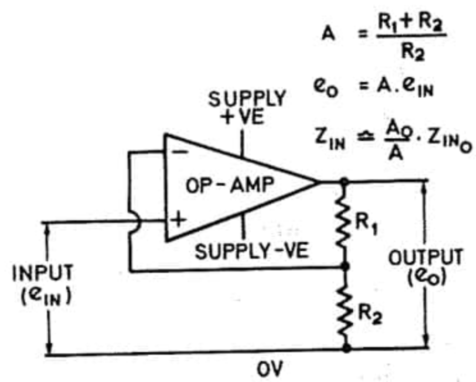

Figure 1.4a. Basic non-inverting d.c. amplifier.

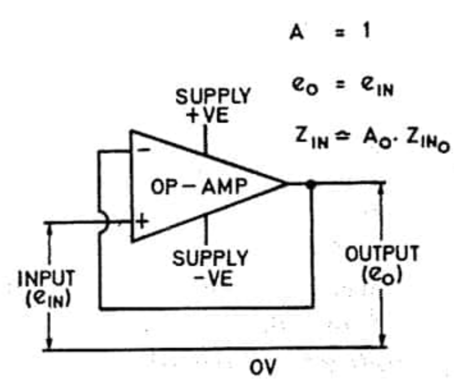

Figure 1.4b. Basic unity-gain d.c. voltage follower.

Op-amp parameters

An ideal operational amplifier would have an infinite input impedance and zero output impedance, would have infinite gain and infinite bandwidth, and would give perfect tracking between input and output.

Practical op-amps fall far short of the ideal, and have finite gain, bandwidth, width, etc., and give tracking errors between the input and output signals. Consequently, various performance parameters are detailed on op-amp data sheets, and indicate the measure of 'goodness' of the particular device type in question. The most important of these parameters are detailed below.

Open-loop voltage gain, A_o This is a measure of voltage gain occurring directly between the input and output terminals of the op-amp, and may be expressed in direct terms or in terms of dB. Typical gain figures of modern op-amps are 100 000, or 100 dB.

Input impedance, Z_{in} This is a measure of the impedance looking directly into the input terminals of the op-amp, and is usually expressed in terms of resistance only. Values of 1 MΩ are typical of modern op-amps.

Output impedance, Z_o This is a measure of the output impedance of the basic op-amp, and is usually expressed in terms of resistance only. Values of one or two hundred ohms are typical of modern op-amps.

Input bias current, I_b Most op-amps use bipolar transistor input stages, and draw a small bias current from the input terminals. The magnitude of this current is denoted by I_b, and is typically only a fraction of a microamp.

Supply voltage range, V_s Op-amps are usually operated from two sets of supply rails,* and these supplies must be within maximum and minimum limits. If the supply voltages are too high the op-amp may be damaged, and if the supply voltages are too low the op-amp will not function correctly. Typical supply limits are ± 3 V to ± 15 V.

Input voltage range, $V_{i(max)}$ The input voltage to the op-amp must never be allowed to exceed the supply line voltages, or the op-amp may be damaged. $V_{i\,(max)}$ is usually specified as being one or two volts less than V_s.

Output voltage range, $V_{o(max)}$ If the op-amp is over driven its output will saturate and be limited by the available supply voltages, so $V_{o\,(max)}$ is usually specified as being one or two volts less than V_s.

Differential input offset voltage, V_{io} In the ideal op-amp perfect tracking would exist between the input and the output terminals of the device, and the output would register zero when both inputs were grounded. Actual op-amps are not perfect devices, however, and in practice slight imbalances exist within their input circuitry and effectively cause a small offset or bias potential to be applied to the input terminals of the op-amp. Typically, this *differential input offset voltage* has a value of only a few millivolts, but when this voltage is amplified by the gain of the circuit in which the op-amp is used it may be sufficient to drive the op-amp output to saturation. Because of this, most op-amps have some facility for externally nulling out the offset voltage.

*rails or buses

Common mode rejection ratio, c.m.r.r. The ideal op-amp produces an output that is proportional to the difference between the two signals applied to its input terminals, and produces zero output when identical signals are applied to both inputs simultaneously, i.e., in common mode. In practical op-amps, common mode signals do not entirely cancel out, and produce a small signal at the op-amps output terminal. The ability of the op-amp to reject common mode signals is usually expressed in terms of common mode rejection ratio, which is the ratio of the op-amps gain with differential signals to the op-amps gain with common mode signals. C.M.R.R. values of 90 dB are typical of modern op-amps.

Transition frequency, f_T An op-amp typically gives a low-frequency voltage gain of about 100 dB, and in the interest of stability its open-loop frequency response is tailored so that the gain falls off as the frequency rises, and falls to unity at a transition frequency denoted f_T. Usually, the response falls off at a rate of 6 dB per octave or 20 dB per decade. *Figure 1.5* shows the typical response curve of an op-amp with an f_T of 1 MHz and a low frequency gain of 100 dB.

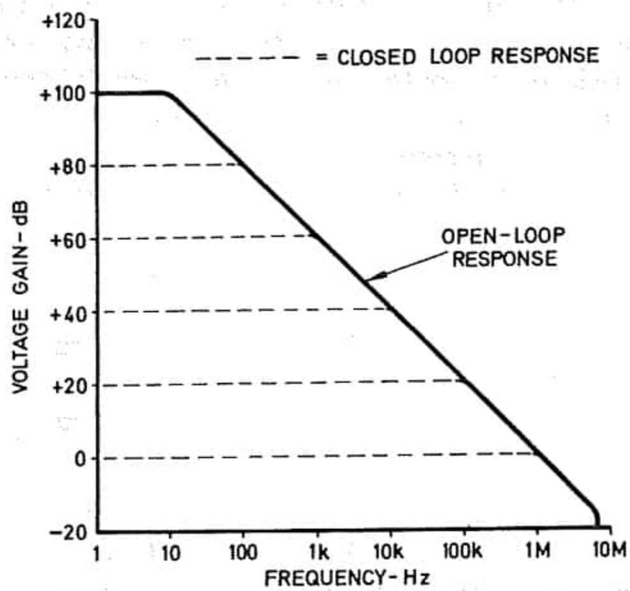

Figure 1.5. Typical op-amp frequency response curve.

Note that, when the op-amp is used in a closed-loop amplifier circuit, the bandwidth of the circuit depends on the closed-loop gain. If the amplifier is used to give a gain of 60 dB its bandwidth will be only 1 kHz, and if it is used to give a gain of only 20 dB its bandwidth will extend to 100 kHz. The f_T figure can thus be used to represent a gain-bandwidth product.

Slew rate, S As well as being subject to normal bandwidth limitations, op-amps are also subject to a phenomenon known as slew rate limiting, which has the effect of limiting the maximum rate of change of voltage at the output of the device. Slew rate is normally specified in terms of volts per microsecond, and values in the range 1 V/μs to 10 V/μs are common with the most popular types of op-amp. One effect of slew rate limiting is to make a greater bandwidth available to small output signals than is available to large output signals. Another effect is to convert sine wave input signals into triangle wave output signals when the op-amp is operated beyond its slew rate.

Power supplies for op-amps

Op-amps require the use of two power supply sources for satisfactory operation. One of these supplies must be positive relative to the common input signal point, and the other must be negative. In most applications these supplies are obtained by using two independent supply sources connected at a common point, as shown in the circuit of *Figure 1.1b*. Normally, these supplies are of the balanced types, in which the supply voltages are equal in magnitude but opposite in polarity. It should be noted, however, that the use of balanced supplies is not mandatory, and unbalanced supplies can be used in cases where the maximum possible symmetrical peak-to-peak output signal is not required from the op-amp.

It is not essential to use two independent supplies to provide the two power sources for the op-amp, since two power sources can be obtained from a suitably adapted single power supply unit. *Figure 1.6a* shows one

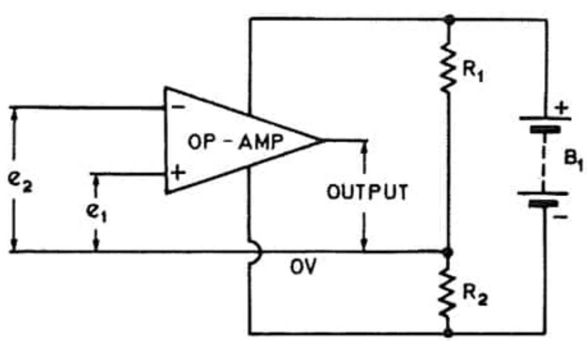

Figure 1.6a. Potential divider method of powering an op-amp from a single supply source in d.c. applications.

method of obtaining the supplies from a single power unit. Here, potential divider* $R_1 - R_2$ is wired across the single supply, and the $R_1 - R_2$ junction is used as the common signal point, thus making a positive supply rail available at the top of R_1 and a negative supply rail available at the bottom of R_2. In d.c. applications the values of R_1 and R_2 must be chosen so that the quiescent current flowing through them is much greater than the peak output current that is to be taken from the op-amp output, since these resistors are effectively in series with the op-amp output.

*potential divider or voltage divider

In cases where the op-amp is to supply a high peak output current the above requirement may result in the need for unacceptably high quiescent currents in R_1 and R_2. One way round this problem is to replace R_1 and R_2 with a zener diode potential divider, as shown in *Figure 1.6b*. The zener diodes present a low dynamic impedance in series with the op-amp output, so in this case their quiescent currents need be only slightly greater than the peak output current of the op-amp, and can be adjusted via R_1.

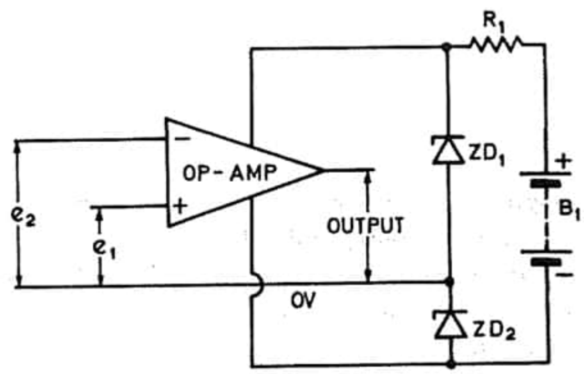

Figure 1.6b. **Zener potential divider method of powering an op-amp from a single supply source in d.c. applications.**

The two single-supply circuits that we have looked at so far are designed to power d.c. amplifiers, and need to pass fairly high quiescent currents because both the signal and the supply currents are d.c. and flow through common resistive elements. In the case of a.c. circuits alternative supply networks can be used, and quiescent currents can be much lower.

Figure 1.7 shows one method of powering an a.c. op-amp circuit from a single power unit. Here, potential divider $R_1 - R_2$ is again wired across

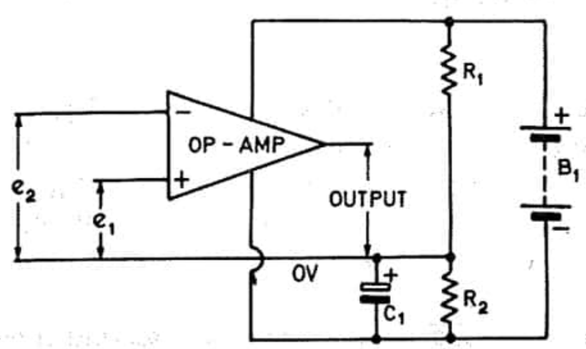

Figure 1.7. **Method of powering an op-amp from a single supply source in a.c. applications.**

the single supply unit, and the $R_1 - R_2$ junction is used to act as the common signal point, but in this case R_2 is shunted by large-value capacitor C_1. Consequently, a very low a.c. impedance exists between the common signal line and the negative supply rail (via the low impedance of C_1), and between the common signal line and the positive supply rail (via the low internal impedance of supply unit B_1 in series with C_1), and the a.c. current-driving ability of the op-amp is thus not influenced by the values or quiescent currents of R_1 and R_2. In fact, the only current-related requirement of R_1 and R_2 is that their quiescent currents be large relative to the input bias current (I_b) parameter of the op-amp, and in most cases quiescent currents of only a few microamps can be used.

Practical op-amps: The 709 and the 741

Many types of operational amplifier are commercially available. Some are specifically designed to have exceptional high-frequency parameters, some are designed to give exceptionally high input impedances or to exhibit exceptional thermal stability, and some are designed simply for general purpose use. Two of the best known general purpose types are the 709 and the 741, and the main parameters of these two devices are listed in *Table 1.1*. The 709 and 741 op-amp types are available from a number of manufacturers, under a variety of codings and in a variety of packagings.

Table 1.1 Typical characteristics of the 709 and 741 operational amplifiers.

	Parameter	*709*	*741*
A_o	Open-loop voltage gain	93 dB	100 dB
Z_{in}	Input impedance	250 kΩ	1 MΩ
Z_o	Output impedance	150 Ω	150 Ω
I_b	Input bias current	300 nA	200 nA
$V_{s(max)}$	Maximum supply voltage	±18 V	±18 V
$V_{i(max)}$	Maximum input voltage	±10 V	±13 V
$V_{o(max)}$	Maximum output voltage	±14 V	±14 V
V_{io}	Differential input offset voltage	2 mV	2 mV
c.m.r.r.	Common mode rejection ratio	90 dB	90 dB
F_T	Transition frequency	5 MHz	1 MHz

The 709 op-amp is a slightly old-fashioned 'second generation' operational amplifier. It has a number of design weaknesses, but is still widely used. The device is subject to a phenomenon known as *input latch up*, in which the input circuitry may switch into a locked state if special precautions are not taken when connecting the input signals to the input terminals, and the op-amp can easily be destroyed by short circuits inadvertently placed across the output terminals. In addition, the device is prone to bursting into unwanted oscillations when used in the linear mode, and makes use of external frequency compensation components for stability control. A major advantage of the 709 op-amp is that it has a higher slew rate and better bandwidth than the 741 op-amp. In the present volume the 709 is used in only a few circuits, and in these is used purely in a switching capacity, so that the high slew rate is utilised without incurring the disadvantages that accrue when the device is used in the linear mode.

The 741 op-amp is a greatly improved 'third generation' version of the 709 op-amp. It is immune to input latch up, has a short circuit proof output, and has built-in frequency compensation and is not prone to instability when used in the linear mode. The frequency response characteristics of the device are identical to those shown in *Figure 1.5*, and the unity gain bandwidth is typically 1 MHz. The device can be fitted with external offset nulling by wiring a 10 kΩ pot between its two null terminals, and taking the pot slider to the negative supply rail, as shown in *Figure 1.8*.

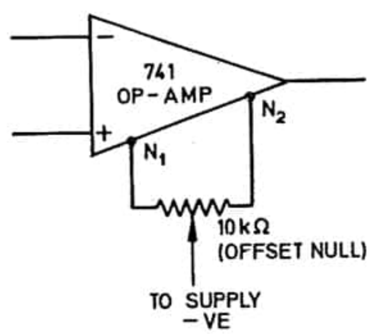

Figure 1.8. **Method of applying offset nulling to the type 741 operational amplifier.**

All one hundred and ten of the circuits described in the following chapters of this volume are designed around the type 741 op-amp, and the pin connections shown in each of the respective circuit diagrams apply to the 8-pin dual-in-line* version of the device only. If alternatively packaged 741 op-amps are used in these circuits, the pin connections may have to be changed. A variety of 741 pin connection arrangements are shown in the appendix to this volume.

*dual-in-line abbreviated D.I.L. or DIP