OP-AMPS

An operational amplifier is just a high gain amplifier — you stick a voltage in and a much larger one comes out. But you'd never know this from the data sheets. 'Overkill' confuses all but the most experienced. It really doesn't have to be so. Tim Orr explains. . .

OP-AMPS HAVE TWO inputs, inverting and non-inverting, denoted by – and + respectively. The op-amp amplifies the difference in the voltages applied to these two inputs, the output going positive if the + input is positive with respect to the – input, and vice versa. Without extra circuitry, though, an op-amp is virtually useless, for the gain is too high to be useable and distortion is excessive. Fortunately both parameters can be controlled by feedback.

An op-amp with negative feedback is shown in Fig. 1. Two resistors set the closed loop voltage gain, and as long as this is small compared to the open loop gain, it will be determined by the resistor ratio RF/RI. The open loop gain, the voltage gain when RF is removed, is typically 1 000 000. This massive gain is clearly much too large to be used without feedback. Closed loop voltage gains of 100 are about as much as it is practical to use.

Biased example

The arrangement in Fig. 1 is known as a 'virtual earth' amplifier. The non-inverting input is connected to earth, and the inverting input is maintained by the feedback applied via RF at a voltage which is virtually earth potential.

The input impedance of the amplifier in Fig 1 is simply R1. The output impedance is a little more complicated, approximately:—

$$\frac{\text{output impedance of the op amp} \times \text{closed loop gain}}{\text{open loop gain}}$$

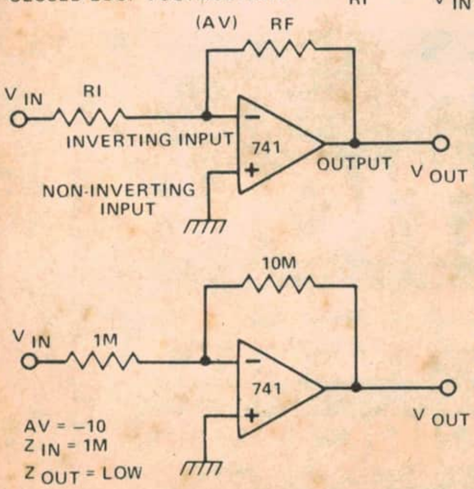
Suppose we want an amplifier with a gain of 10, and an input impedance of 1M. This means that RI is 1M. Therefore RF must be 10 M (see Fig. 2). With a 1 V sinewave as the input signal we get a 10 V sinewave as the output. However, when the input signal is held at 0V, it is positive! This is an error voltage, which may be undesirable. The cause of the problem is the 'INPUT BIAS CURRENT' of the op-amp. The input of many op-amps looks like the circuit shown in Fig. 3. If these transistors are to operate correctly they need a standing emitter current which implies that they need an input base current. It is this base current which is the op-amp's 'INPUT BIAS CURRENT'. For a 741 this current can be as large as 0.5 μA. In the arrangement of Fig. 2 this current can only come through RF, which means that the output voltage could be as large as 0.5 μA x 10 M, which is +5 V! One way to remedy this error is to use the circuit shown in Fig. 4. A resistor has been inserted between the non-inverting input and ground. This resistor has the value of RF in parallel with RI. It allows both the inputs to sink slightly and thus maintain the voltage balance at the inputs. The output voltage is then nearly 0 V. However, the two input transistors may not be that well matched, so the bias currents into each input may be different. This is known as the 'INPUT OFFSET CURRENT' and its effect can be nulled by making the 910 k resistor in Fig. 4 a variable resistor. But even if the bias currents (for say a 741) were zero, then the output voltage would still not be 0 V.

Get set, they're off

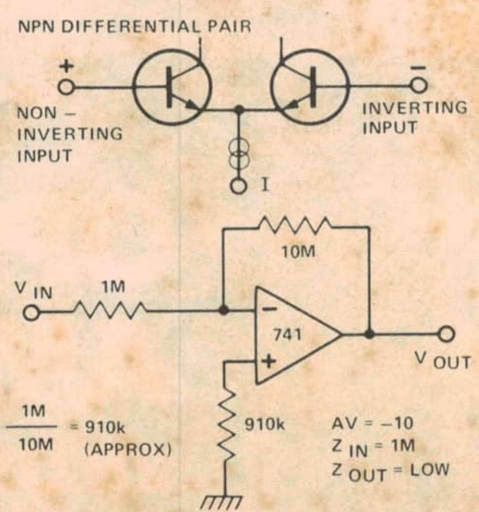
The output voltage could range between ±60 mV. This is due to the 'INPUT OFFSET VOLTAGE' which for a 741 can be as much as ±6 mV, which is then multiplied by the closed loop voltage gain of the stage (in this case 10 giving us ±60 mV. This can be compensated by using the circuit shown in Fig. 5. Terminals 1 and 5 on a 741 can be used to compensate for the input offset voltage. The input offset voltage is the V_{be} imbalance between the two input transistors.

Now that we know how to eliminate the spruious dc offsets, we can try designing some dynamic circuits and find out why they don't work as expected! For example, try

$$\text{CLOSED LOOP VOLTAGE GAIN (AV)} = -\frac{RF}{RI} = \frac{V_{OUT}}{V_{IN}}$$



Figs 1 and 2 show (upper) the basic inverting op-amp stage. Gain is given by the ratio of resistors RF/RI, input impedance is simply RI, while the output impedance is more complicated (see (text). Fig. 2 (lower) shows a stage with a gain of 10 and an input impedance of 1 M.



Figs 3 and 4 (left) show (upper) a typical op-amp input stage. This is a differential amplifier made up of a pair of NPN transistors driven by a constant current source. Fig.4 (left) shows a 910 k resistor in series with the + input of the op-amp. This reduces the effects of the input offset current.

putting a 1 V sinewave at 200 kHz into the circuit shown in Fig. 5. What you would expect is a 10 V, 200 kHz sinewave at the output — but you don't get one. What appears is a rather bent 200 kHz triangle waveform. This is because the 'SLEW RATE' of the op-amp has been exceeded. The slew rate is the speed at which the output voltage can move, and for a 741 is typically 0.5 V/µs when it crosses zero, so the op-amp, faced with this demand, just gives up and slew limits, drawing out straight lines as it does so.

Listen to the band(width)

Another limitation is 'BANDWIDTH'. A 741 has a GAIN BANDWIDTH product of approximately 1 MHz. This means that the product of the voltage gain times the operating frequency cannot exceed 1 MHz.

For example, if you want the amplifier to have a gain of 100, then the maximum frequency at which this gain can be obtained is 10 kHz. Figure 6 illustrates this phenomenon. Curve A is the open loop response, note that the voltage gain is 1 at 1 MHz, hence the gain bandwidth product of 1 MHz. The slope of the curve is −20 dB/decade, which is caused by a single 30 pf capacitor inside the IC. Now, if the resistor ratio is set to give a voltage gain of 100, then the op-amp gives a frequency response shown by curve C, which is flat up until 10 kHz. A gain off 10 rolls off at 100 kHz (D) and a gain of 1 000 rolls off at 1 kHz (B). Thus it is very easy to see just what the closed loop frequency response will be. However, don't forget the slew rate problem. You may be able to construct an amplifier with a voltage gain of 10, which works up to 100 kHz, but the output voltage will be limited to less than 3 Vpp! Another problem is distortion in the op-amp. Negative feedback is used to iron out any distortion generated by the op-amp, but negative feedback relies on there being some spare voltage gain available. For instance, say the op-amp generates 10% distortion and there is a surplus voltage gain of 1 000,

$$\text{i.e. } \left(\frac{\text{open loop gain}}{\text{closed loop gain}}\right),$$

then the distortion will be reduced to approximately,

$$\frac{\text{open loop distortion}}{\text{surplus voltage gain}} = \frac{10\%}{1\ 000} = 0.01\%$$

So, negative feedback is used to eliminate distortion products, However, if there is no surplus voltage gain, as in the case of a 741 amplifier working at 10 kHz, with a closed loop gain of 100, the distortion will rise dramatically at this point.

Current thinking

Most op-amps have a voltage output, although some have a current output. If you short-circuit a voltage output then large currents could flow and thermal destruction might follow. To overcome this problem, most op-amps have a current limited output so that they can tolerate an indefinite short to ground. A 741 is limited to about 25 mA. Another current of note is the supply 'BIAS CURRENT'. This is the current consumed when the op-amp is not driving any load. For a 741 this current is typically 2 mA, which makes it unsuitable for some battery applications.

There are some op-amps which can be programmed by inserting a current into them so that their supply current can be controlled. This means that they consume only micropower when in their 'standby' mode, and can be quickly turned on to perform a particular task.

Voltages differently

In the few examples shown so far, the op-amp has been used to amplify voltages which have been generated with respect to ground. However, sometimes, it is required to measure the difference between two voltages. In this case you would use a 'Differential' amplifier, Fig. 7. By using two matched pairs of resistors, the formula for the voltage gain is made very simple. It is thus possible to sumperimpose a 1 V sinewave on both the inputs, and yet have the output of the amplifier ignore this common mode signal and amplify only differential signals. The amount by which the common mode signal is rejected is called the CMRR (the Common Mode Rejection Ratio) and is typically 90 dB for a 741. Thus a common mode 1 V signal would be reduced to 33 µV.

Another rejection parameter to be noted is the supply voltage rejection ratio. For a 741 the typical rejection is 90 dB; that is, if the power supply changes by 1 V the change in the output voltage will be 33 µV.

When designing with op-amps it is very important to know what voltage range the inputs will work over, and the maximum voltage excursion you can expect at the output. For instance, the 741 can operate with its inputs a few volts from either power supply rail, and its inputs can withstand a differential voltage of 30 V (with a power supply of 36 V).

This is not true of all op-amps, some have a very limited differential input voltage range, for instance the CA3080 will zener when this voltage exceeds 5 V and the amplifier performance will then be drastically changed.

The output excursion of the op-amp is also important. The 741 can only typically swing within about 2 V of either supply rail, whereas the CMOS op-amp can swing to within 10mV of either rail so long as the load into which they are driving is a very high impedance.

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$$\text{VOLTAGE GAIN } A_V = \frac{V_{OUT}}{V_{IN}}$$

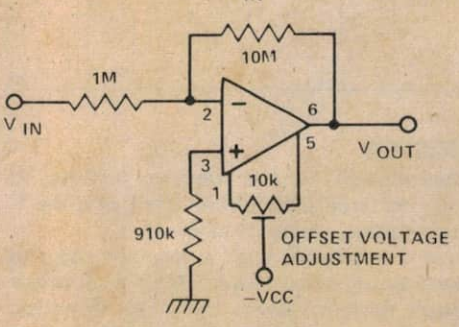
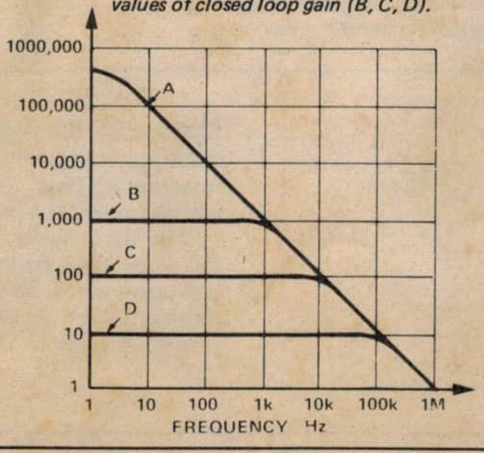


Fig. 5. A variable resistor connected between pins 1 and 5 of a 741 can be used to reduce the effects of the input offset voltage.

Fig. 6. Graph of open loop response of a 741 (A) together with curves showing response at various values of closed loop gain (B, C, D).



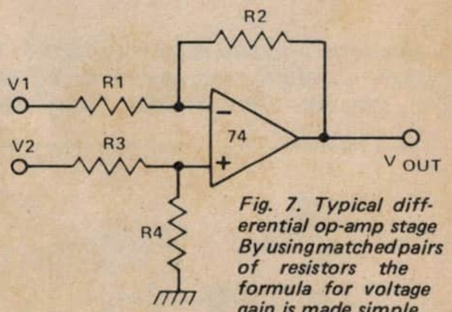


Fig. 7. Typical differential op-amp stage By using matched pairs of resistors the formula for voltage gain is made simple.

$$V_{OUT} = \left[\left(\frac{R1 + R2}{R3 + R4}\right)\frac{R4}{R1} V2\right] - \frac{R2}{R1} V1$$

BUT IF WE MAKE R1 = R3 AND R2 = R4

$$\text{THEN } V_{OUT} = \frac{R2}{R1}(V2 - V1)$$