Second article in our new series:

Op-Amps without tears–2

Continuing his practical, down to earth introduction to modern operational amplifier ICs and their use, the author looks this month at basic feedback amplifier configurations. He also gives the circuit for a sensitive electronic microammeter using a low cost 741 IC.

by J. BRIAN DANCE, M.SC

Last month we discussed some of the limitations of operational amplifiers used without any feedback. We will now consider some practical circuits in which negative feedback is used to stabilise the gain, increase the frequency response, and otherwise improve performance. When a suitable amount of negative feedback is employed, the differences between integrated circuit operational amplifiers of the same type number can be made negligible for all practical purposes.

As the 741 device is a very economical general purpose operational amplifier which is readily available, we will continue to base our circuits on it. However, almost all of the ideas discussed also apply to other operational amplifier devices. In later articles we shall discuss circuits using other devices for applications in which the 741 is unsuitable.

INVERTING AMPLIFIER

The basic circuit of a 741 inverting amplifier is shown in Fig. 9. The input signal is fed to the inverting input of the 741 via R1 and therefore the output is inverted in sign with respect to the input. For simplicity, the power supply connections are not shown in this circuit, but they must of course be included, as in the circuits discussed last month. By omitting these connections and the offset nulling circuit, we can concentrate more easily on the parts of the circuit to be discussed.

If there is a small rise in the input potential fed to the resistor R1, this will tend to produce a very small rise in the potential of the inverting input of the 741 (marked "–"), and this results in a fall in the output potential. This fall is fed back through R3 and tends to cancel the rise at the inverting input.

We have already seen that operational amplifiers are designed to have an extremely high gain, so the fall in the output voltage is adequate to almost completely cancel the rise in voltage at the inverting input of the amplifier. It cannot completely cancel the input rise, since a minute change of input potential is needed to produce the output voltage change. However, the inverting input of the 741 remains virtually at earth potential and is therefore usually described as a 'virtual earth' point.

Operational amplifiers are designed to have a very high input impedance. The currents which flow to the inputs of the 741 circuit of Fig. 9 are therefore very small. As the inverting input is virtually at ground potential, the current which flows through R1 is equal to the input voltage, Vi, divided by R1. Similarly, the current flowing through R3 is Vo/R3 where Vo is the output voltage. These two currents are almost equal, since the current flowing to the inverting input is very small indeed.

$$Vi/R1 = Vo/R3$$

$$\text{Hence } Vo/Vi = R3/R1$$

But Vo/Vi is equal to the gain of the circuit with feedback. Thus the gain is equal to the ratio of the resistor values R3/R1, and is unaffected by the gain of the amplifier used.

In actual fact this result is only an approximation, since we have assumed that the potential at the inverting input is always zero and this cannot be quite true. Nevertheless, if the gain of the amplifier device itself without feedback is much greater than R3/R1, the gain with feedback is very closely equal to R3/R1.

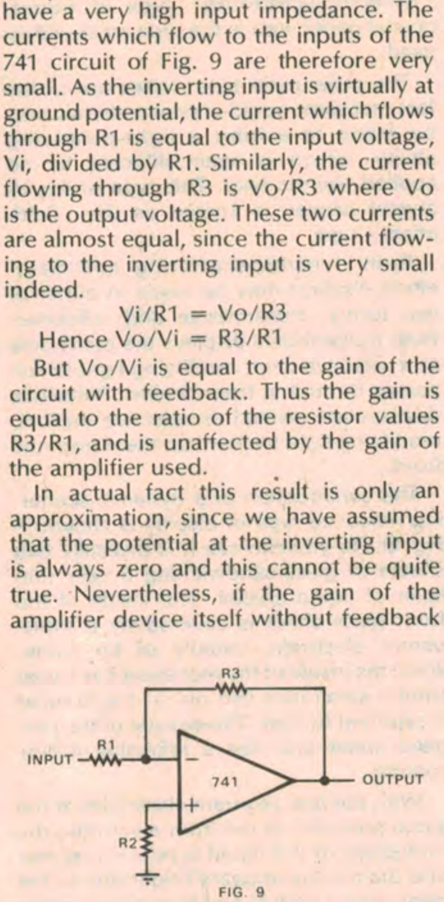

FIG. 9

The input impedance of the circuit of Fig. 9 is almost exactly equal to the resistance of R1, since the one side of this resistor always remains at about earth potential. If one wishes to minimise the effect of small currents flowing into the amplifier inputs, the value of R2 should be approximately equal to the value of R1 in parallel with that of R3.

If one requires a voltage gain of 50 times (34dB), one may select a value of 50k for R3 and 1k for R1. The bandwidth using a typical 741 device will be about 20kHz at –3dB down, for this gain. However, the bandwidth is essentially inversely proportional to the gain. Thus one can obtain a gain of 5 for a 200kHz bandwidth, or a gain of 500 for a 2kHz bandwidth. The 741 can be used as an audio preamplifier with a gain of up to 50 (or 100 for a more limited frequency response), but special audio preamplifier devices are available which are operational amplifiers with lower noise level than the 741.

Readers wishing to try this circuit may use two 9V batteries as the source of power. Alternatively a supply derived from the mains and regulated by a suitable device may be used, but there is no point in applying more than ±15V and risking damaging the amplifier device.

NON-INVERTING AMPLIFIER

The input voltage is applied to the non-inverting input of the circuit of Fig. 10 and no inversion of the signal waveform therefore occurs. A potential divider, R1 and R2, is included across the output circuit and the negative feedback signal taken from the junction of these resistors is applied to the inverting input of the 741 device.

If the input potential rises by a small amount Vi, the output voltage will rise by an amount we will call Vo. A fraction of Vo is fed back to the inverting input to provide negative feedback. The potentials at the two inputs rise by almost equal amounts; if this were not so, the difference in potential between these inputs would be multiplied by the very high open loop gain of the 741 device so as to cause a very large change in the output voltage.

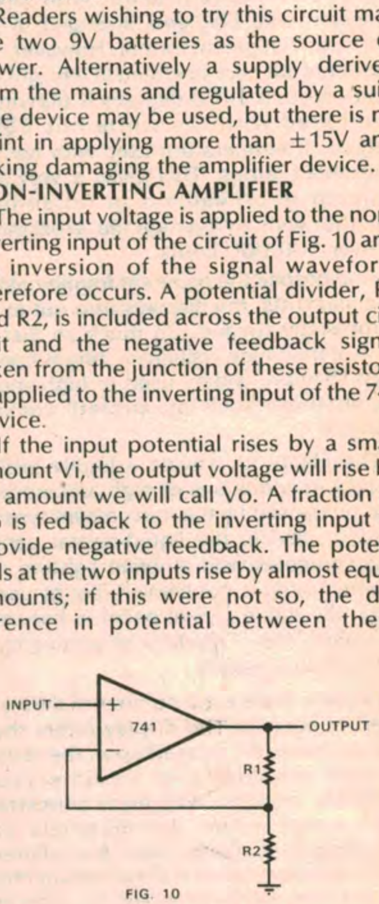

FIG. 10

The voltage across R2 is equal to the fraction R2/(R1 + R2). If we assume that the gain of the 741 is so high that the potentials at the two inputs of the device are equal,

$$\begin{aligned} Vi &= Vo\,R2/(R1 + R2) \\ \text{and Gain} &= Vo/Vi \\ &= (R1 + R2)/R2 \\ &= R1/R2 + 1 \end{aligned}$$

If R1 is much larger than R2, the gain of the circuit is approximately equal to R1/R2, and as before is independent of the particular amplifier in use.

OFFSET

One may include an offset nulling potentiometer in either of the circuits of Figs. 9 and 10. This involves connecting a potentiometer (perhaps 10k ohm) between pins 1 and 5 of a standard 8 pin 741 device, with the slider of the potentiometer connected to the negative supply line (see Fig. 5 of last month's article). If one selects the feedback resistor values for moderate gain (10 to 100), one will immediately notice that the adjustment of the nulling potentiometer is far less critical than when the 741 is used at full gain without any negative feedback.

Indeed, the adjustment of the potentiometer changes the output voltage by only a small fraction of a volt in the Fig. 9 and Fig. 10 circuits at moderate values of gain, whereas in the Fig. 5 circuit a small adjustment of the nulling potentiometer would cause the output to sweep from one extreme to the other. The voltage offset at the input in these circuits is multiplied by the gain of the circuit at zero frequency. Thus in the practical circuits of Figs. 9 and 10, the output potential can be set to zero fairly accurately. It will drift somewhat with temperature, but this drift will be far less than if the 741 is used in the Fig. 5 circuit without feedback.

BUFFER AMPLIFIER

A simple buffer amplifier having a high input impedance and a low output impedance is shown in Fig. 11. It is essentially similar to the circuit of Fig. 10, but the whole of the output voltage is fed back to the input instead of only a fraction of the output voltage. This type of circuit is known as a voltage follower, since the output voltage follows changes in the input voltage.

In the circuits of Figs. 10 and 11, all of the input current flows into the non-inverting input of the operational amplifier device. The 741 is designed so that this current is quite small and therefore the input impedance of these circuits is much higher than that of Fig. 9 where approximately equal currents flow through R1 and R3.

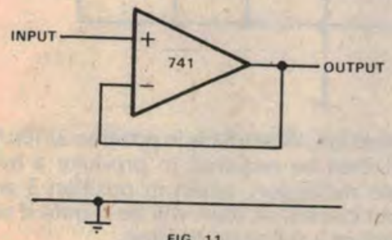

FIG. 11

The circuit of Fig. 11 is therefore very useful when one requires a circuit of fairly high input impedance which will not impose an appreciable load on most circuits which are likely to be used to feed it. Apart from the name 'voltage follower', this type of circuit is sometimes called an 'impedance converter', since it converts the high impedance at its input

to a relatively low output impedance. The input impedance of the circuit of Fig. 11 is typically 1 megohm with a minimum value of about 0.3 megohm for any 741 device, whilst the output impedance of the circuit is somewhat less than 1 kilohm.

The circuit of Fig. 11 can be used when no voltage gain is required, whereas the circuits of Figs. 9 and 10 can provide gain. If desired, one of the feedback resistors may be made variable so that the gain can be controlled.

A typical circuit which can provide a very wide range of gain values is shown in Fig. 12.

Many other variations on the basic operational amplifier circuits are possible. For example, the circuit of Fig. 13 shows how a high gain inverting amplifier can be made with a high input impedance. If the circuit of Fig. 9 is to have a very high gain and the value of R3 is not to be excessively high, R1 must be fairly small and this will result in a relatively low input impedance. However, R1 can be quite large in Fig. 13 even if the gain is to be very high, since R3 and R4 can be chosen so that the fraction of the output voltage fed back is small and R2 does not then need to be especially high.

SENSITIVE MICROAMMETER

The circuit of Fig. 14 shows how a 741 device can be employed to make a sensitive meter with a full scale deflection of 1 microamp. Apart from being a really useful circuit, the inexperienced reader will learn much about the practical use of operational amplifiers by making such simple circuits.

If an input current flows into the circuit, an almost identical current flows through R3, since the input impedance of the device is high. If the input current is 1uA, this current flowing through R3 will produce a potential of 0.22V across this resistor. As pin 2 remains at zero voltage, the 1uA input current thus produces an output voltage of 0.22V. If the total resistance of the meter M1 and the variable resistor VR2 is 4.4k ohm, a current of 50uA will flow through the meter. Thus the 1uA input current causes a full scale deflection of the meter.

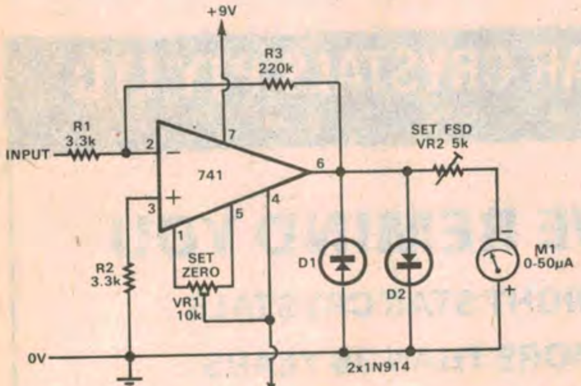

FIG. 14

The diodes D1 and D2 will not pass any appreciable current unless the output voltage exceeds about 0.6V; in this case one of the diodes will conduct and will prevent the meter from being overloaded and possibly damaged. The equal input resistors R1 and R2 help to reduce drift of the offset voltage.

If the input is positive (that is, if a conventional current flows into the resistor R1), the output will become negative. The positive side of the meter must therefore be grounded and the negative side connected to the 741 output. If desired a 50-0-50 microammeter may be employed, in which case currents of either polarity can be measured with the centre reading meter.

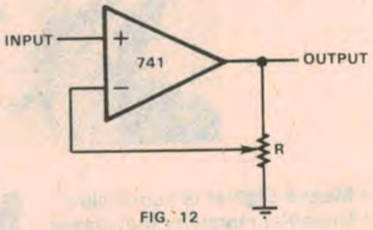

FIG. 12

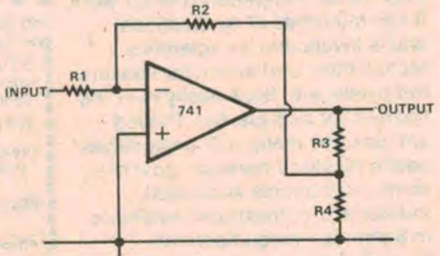

FIG. 13

When the meter is to be used, VR1 should first be adjusted so that the meter indicates zero with no input current. A current of 1uA is then passed into the input. One way of doing this is to connect a 10V source through a 10 megohm resistor to the input of the circuit, the negative side of the source being connected to the zero volt line. The 'Set FSD' control VR2 is then adjusted until the meter shows a full scale deflection.

It is also possible to use a 0-100 microammeter in this circuit, but the value of VR2 should then preferably be reduced to about 2.5k ohm. Other fairly sensitive meters can also be employed, with FSD figures up to about 500uA, by reducing the value of VR2 to suit.

The input bias current to a typical 741 device is 0.2uA (maximum value 0.5uA); it is the average of the two input currents. The input offset current is the difference in the currents to the two inputs when the output is at zero voltage; the input offset current has a typical value of 0.03uA (maximum 0.2uA) for the 741 and varies with temperature. Thus errors will occur if an attempt is made to increase the sensitivity of the Fig. 14 circuit by a large factor so as to obtain a full scale deflection with much lower input currents. In due course we shall show how other devices can be used to measure much smaller currents than those for which the Fig. 14 circuit using the 741 is suitable.

The circuit of Fig. 14 can also be used as a voltmeter for measuring steady voltages; VR2 can be adjusted so that the full scale deflection is 200mV. The power supply and offset nulling circuits shown in Figs. 14 and 15 are also suitable for use in the circuits of Figs. 9 to 13 inclusive.

MULTI-RANGE METER

The circuit of Fig. 15 shows the use of a 741 device in a microammeter having several input ranges. When S1 is in position 1, a current of 5uA flowing through R1, R2 and R3 (total of 200 ohm) will produce 1mV across these resistors and this can be used to produce a full scale deflection. When S1 is in position 2, 10uA will then be required to produce a full scale deflection, whilst in position 3 an input current of 20uA will be required to produce a full scale reading.

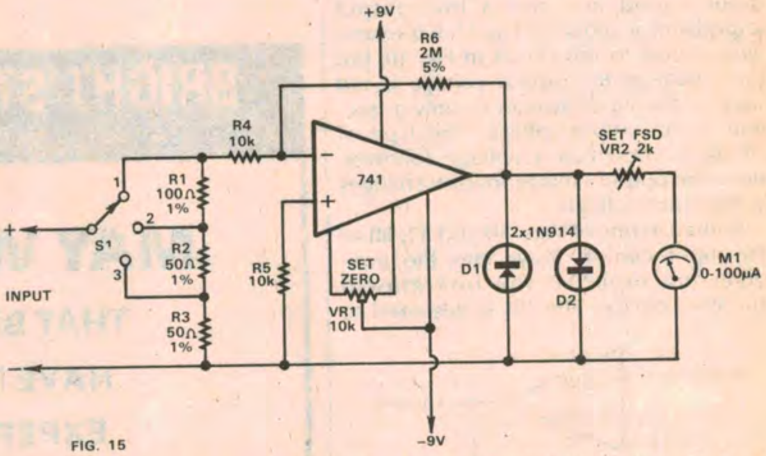

FIG. 15

The gain of this circuit is approximately 200 (= R6/R4), so 200mV is available at the output for driving a current of 100uA through the meter. The adjustment of VR1 is carried out as for the Fig. 14 circuit. The correct full scale deflection is set using VR2 on any one of the current ranges and the full scale deflection on the other ranges will then also be correct, since R1, R2 and R3 are close tolerance components.

Next month we will cover further practical 741 circuits and learn more about operational amplifiers.