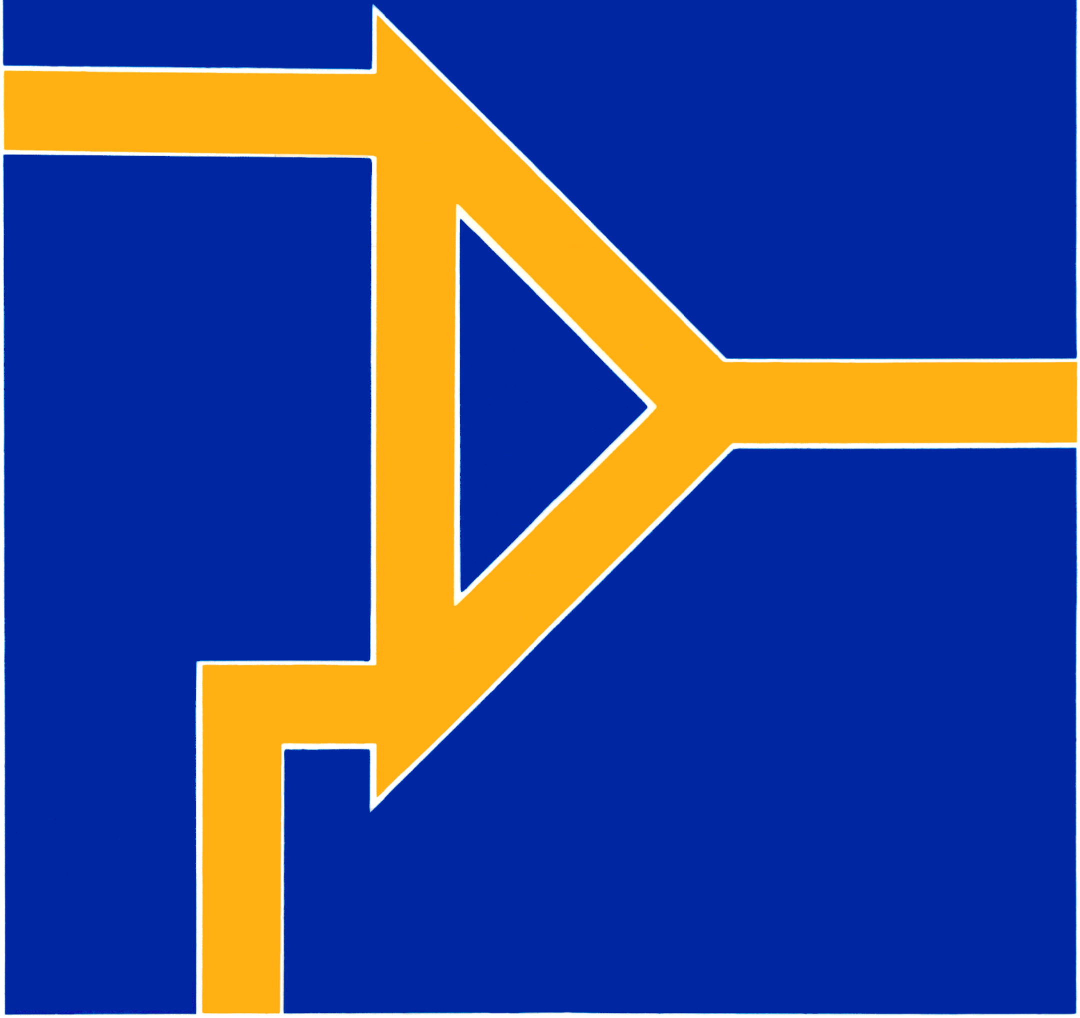
MEgaCyCAL
Software limited

electronics series

'OP-AMP'

Operational Amplifiers



OPERATIONAL AMPLIFIERS

by G.B. Clayton

The program and booklet which make up this package have been designed to provide a modelling and investigation approach to exploring the action of operational amplifier feedback circuits. The program features the following sections:

1. An inverting feedback amplifier.
2. A non-inverting feedback amplifier.
3. An operational integrator.
4. A test section on circuit performance equations.

Loading the program

BBC Model B: 40 and 80 track disc systems.

Insert disc in drive 0. Hold down the SHIFT key and tap the BREAK key.

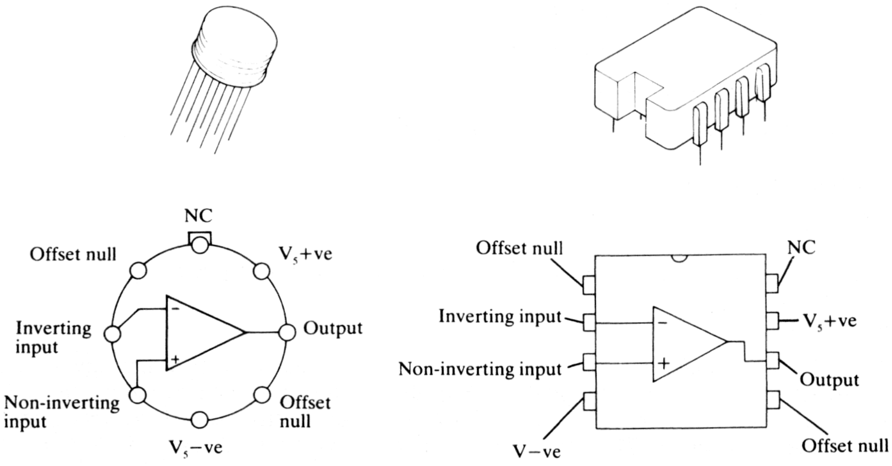
Running the program

The program should be used in conjunction with this booklet which gives you explanations about the various models. To facilitate interaction with the models, in each section a series of letters signifying various commands is displayed at the lower right hand edge of the screen. The cursor shift left and shift right keys are used to select one of these command letters. The function performed by the selected command is indicated at the lower left hand edge of the screen. In this program when the command function involves increasing or decreasing a parameter value, the value is increased by pressing the cursor shift up key, or decreased by pressing the cursor shift down key. Other commands are executed by pressing the RETURN key. Interaction with the program models is entirely via the four cursor shift keys and the RETURN key.

OP AMP

Introduction

The term operational amplifier is used to signify a type of amplifier which is intended specifically for use in negative feedback circuits. Operational amplifiers are designed to amplify both steady, (d.c.) and varying signal voltages. This package will help you to understand the meaning and significance of the term negative feedback and will introduce you to some of the basic ways in which operational amplifiers are applied in practical systems. A prerequisite for the package is that you should be familiar with the functional nature of the amplification process and the general terms which are used in specifying the performance of an amplifier. This topic is covered in the Megacycal package 'AMPLI'.



(Top view)
Metal Package

(Top view)
Plastic Package

Fig. 1. I.C. operational amplifier packages.

There are many different types of practical operational amplifiers commercially available. The ones most frequently used are the general purpose integrated circuit types. These devices are the functional units which act as the basic circuit building block in most analogue signal processing systems. In an integrated circuit operational amplifier all the transistors, resistors and interconnections needed to make the amplifier circuit are formed on a small silicon chip, which is housed in a small package not much bigger than a discrete transistor package. Most general purpose integrated circuit operational amplifiers are compatible as to the functions served by their external pins; the most commonly used circuit packages are the dual-in-line plastic package and the T.O.5 metal can illustrated in Fig. 1.

Electrical access to the integrated circuit is provided by external pin connections on the circuit package. The pins are simply plugged into a matching socket mounted on a printed circuit board and the amplifier is then ready for use as a functional unit.

An understanding of the nature of operational amplifier applications does not require a knowledge of the nature of the circuitry inside an amplifier. What you need to know are the functions performed by the external pin connections, that is, you need to understand the nature of the relationships which exist between the electrical signals at the pin connections. This package helps you understand these relationships by creating a model which simulates the behaviour of an operational amplifier.

The properties of the operational amplifier model used in this package are given in the next section. You can examine how the model behaves in a negative feedback circuit by running the program. You should follow your examination of the model feedback circuits with practical experimentation performed on real amplifier circuits (Ref. 1).

The Op. Amp. Model Defined

In circuit diagrams an operational amplifier is normally represented by a triangle pointing in the direction of signal flow from input to output, as shown in Fig. 2. Most operational amplifiers have two input terminals and a single output terminal. The two input terminals are normally distinguished from each other by a (+) and a (−) sign. The (+) and (−) notation at the input does not mean that positive voltages are applied to the one terminal and negative voltages to the other. It means that signal voltages applied to the (−) terminal cause output voltage changes of opposite polarity whilst signal voltages applied to the (+) terminal cause signal changes of the same polarity to occur at the output. The (−) input is the inverting input, the (+) input is the non inverting input.

The output signal produced by an amplifier is controlled by its input signal but the energy source for the output signal is the amplifier power supply. All amplifiers have to be connected to a power supply in order to make them active. Operational amplifiers are normally designed for use with dual power supplies. The two supplies are connected to a common point as shown in Fig. 2. The potential of this common connection point is normally taken as the zero signal reference point or ground point of the circuit. The circuit symbol (⏚) is used to indicate connections which return to the system's ground point. Input signals are applied with respect to ground and the output signal is produced with respect to ground.

The use of dual power supplies with an operational amplifier allows the amplifier output voltage to swing both positive and negative with respect to the potential of the circuit's ground point. An amplifier cannot normally produce an output voltage bigger than its power supply voltages, it has output voltage limits, these limits are usually a volt or so less than the power supply values. If the input signals applied to an amplifier are such that its output reaches one of its limit values the amplifier ceases to respond to any further increase in input signal and is said to be in saturation.

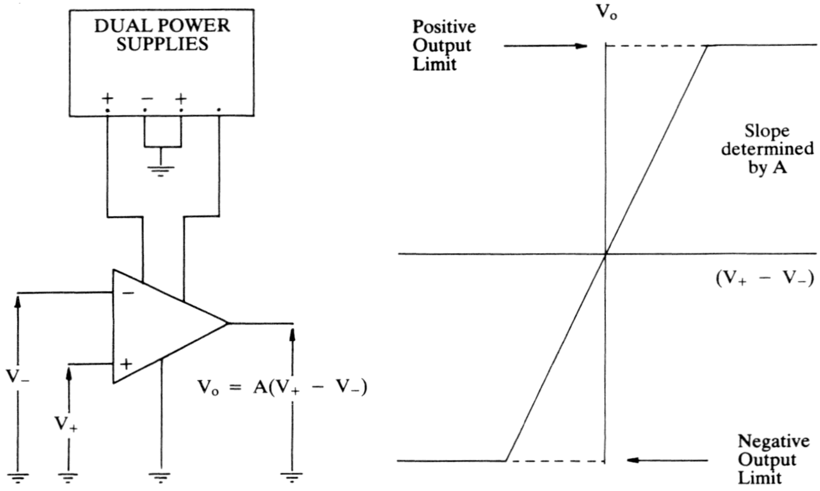


Fig. 2a. Circuit symbol

Fig. 2b. Transfer curve

Fig. 2. The op. amp. model

The program simulates the behaviour of an operational amplifier having an input/output transfer curve of the form illustrated in Fig. 2. (b) The output voltage produced by the amplifier is related to the signals applied to its inverting input terminal, V(−) and non-inverting input terminal, V (+) by the equation:

$$V_o = A_{ol} \times [V(+) - V(-)] \qquad \textbf{Eq. 1}$$

A_{ol} is called the **Open Loop Gain** of the amplifier. This represents the gain of the amplifier when there is no feedback applied to it. The slope of the amplifier transfer curve is determined by the open loop gain of the amplifier.

Real operational amplifiers have a very large open loop gain, (in range 10^4 to 10^6), in this program a value for the open loop gain of the model amplifier is set by you as the user.

The amplifier model simulated by the program has zero output resistance and an infinite input resistance. Real amplifiers are not quite like this, they have a small but non zero output resistance and a large but non infinite input resistance.

The amplifier model gives a zero output voltage when the voltage between its differential input terminals is zero. Real amplifiers have so called offset errors which cause them to give a non zero output for zero input. Operational amplifier offset errors and other performance errors are treated in another program in the Megacycal series.

Feedback Amplifier Circuits

An operational amplifier used on its own with no other components connected to it is of limited usefulness. Although the open loop gain of an operational amplifier is very large, its value is ill defined and is not stable. Practical amplifier applications require an amplifier to have a stable, accurately defined gain.

The real versatility of operational amplifiers is only realised when a few external components are connected to them in such a way as to provide a signal path between their output and input terminals. Such a path is called a feedback path and the amplifier system thus formed is called a feedback amplifier.

Appropriate feedback connections made to an operational amplifier change it from an amplifier with a very large ill defined and unstable gain into an amplifier system with a smaller but accurately defined stable gain.

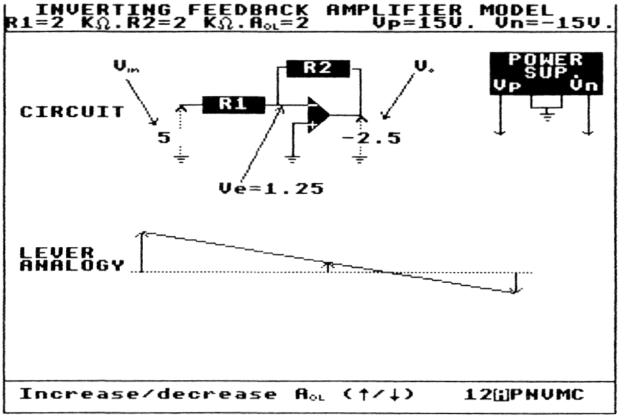
In an operational amplifier feedback system the signal which is applied between the differential input terminals of the amplifier is derived from two sources, part from an externally applied input signal and part from the amplifier output. The term negative feedback signifies that a signal is returned from output to input in such a way as to oppose the effect of any externally applied input signal.

Negative feedback reduces the effective gain of an amplifier but in other respects it leads to improved amplifier performance.

There is another kind of feedback called positive feedback. In a positive feedback amplifier system a signal is returned from output to input in such a way as to enhance the effect of an externally applied input signal. The gain of a positive feedback amplifier system is bigger than the gain of the amplifier used in the system, but this large gain is very ill defined and unstable. Positive feedback can transform an amplifier into an oscillator. An oscillator produces an output signal even though there is no external input signal applied to it. Positive feedback is not further discussed in this package.

PROGRAM SECTION 1:
THE INVERTING FEEDBACK AMPLIFIER MODEL

There are two basic types of operational amplifier feedback circuit, the inverting feedback circuit and the non-inverting or follower feedback circuit. The words inverting and non-inverting describe the way in which the polarity of output voltage changes are related to the polarity of a change in the external input signal which is applied to the circuit. The significance of these terms will become clear to you as you experiment with the computer simulations of the two different types of circuit.



```
  INVERTING FEEDBACK AMPLIFIER MODEL
R1=2 KΩ.R2=2 KΩ.AOL=2       Vp=15V. Vn=-15V.
```

```
Increase/decrease AOL (↑/↓)    12▣PNVMC
```

Fig. 3.   An inverting feedback circuit.

Select section 1 from the main program menu and you will obtain the screen display illustrated in Fig. 3. A circuit diagram of the inverter is shown and also a diagram of a lever analogy which should help in your understanding of circuit behaviour. Values of circuit parameters are shown in the text line next to the top of the display.

In the inverter circuit the externally applied input voltage V_{in} is applied to the inverting input terminal of the operational amplifier through the resistor labelled R_1. The resistor labelled R_2 connected between the inverting input terminal and the output terminal of the amplifier completes a negative feedback loop around the operational amplifier. The action of the negative feedback loop is to oppose the effects of change in V_{in}, it makes the voltage which is applied between the differential input terminals of the operational amplifier less than the externally applied input signal V_{in}.

In the lever analogy the lengths of the vertical pointers, reading from left to right, are analogous to the circuit voltages V_{in}, V_e and V_o. V_e is the voltage applied between the differential input terminals of the operational amplifier, causing it to produce its output voltage V_o. The value of V_o is determined by the value of V_e and by the open loop gain A_{ol} of the operational amplifier.

$$V_o = -A_{ol}.V_e \qquad \textbf{Eq. 2}$$

Notice the minus sign. It indicates that the polarity of V_o is the opposite of V_e because V_e is applied to the inverting input terminal of the operational amplifier.

The assumption is made that the operational amplifier draws no current at its input terminals (infinite differential input impedance) and with this assumption the voltage across the series connected resistors R_1 and R_2 is $V_{in} - V_o$. In the lever analogy the difference in height between the left and right hand ends of the lever is proportional to the voltage $(V_{in} - V_o)$, the fulcrum of the lever is at a height proportional to the voltage V_e and the lengths of the lever arms either side of the fulcrum are in the same ratio as resistors R_1 and R_2.

Experimentation with the Model

On first running the program it is suggested that you spend a few minutes simply 'playing' with the model in order to familiarise yourself thoroughly with its system of commands. You should then adopt a more thinking attitude to your experimentation to help in your learning process. Try to ask yourself questions about the model's behaviour – what will happen if I change this parameter?, why does it happen? then change the parameter, see if the expected behaviour takes place, try and get an explanation of why it happens. Some suggestions to help with your experiments are now given.

Demonstrating the Virtual Earth Concept

In a simplified analysis of the behaviour of an operational amplifier inverter circuit it is usual to assume that the operational amplifier which is used in the circuit is an ideal one with an infinitely large open loop gain. The resistor R_2 connected between the inverting input terminal and the output terminal of the amplifier then causes the output voltage to take on that value which maintains the inverting input terminal of the amplifier at the same potential as that of its non-inverting input terminal. In the inverter circuit the non-inverting input terminal is connected to and maintained at ground potential. The negative feedback thus forces the inverting input terminal of the amplifier to remain at ground potential.

When an ideal operational amplifier is connected in an inverting feedback circuit, its inverting input terminal although not actually connected to ground, is maintained at ground potential. This is called a **virtual ground** or **virtual earth point.**

The open loop gain of the model operational amplifier, when you first run the program is set at the value 2, this is, of course, much less than the open loop gain of a real operational amplifier. The inverting input terminal of the model amplifier with this small value of open loop gain is clearly not a virtual earth point. The voltage at the inverting input terminal, V_e, may be regarded as a superposition of the effects of V_{in} and V_o and expressed as

$$V_e = -V_o/A_{ol} = V_{in} \cdot \left[\frac{R_2}{R_1 + R_2}\right] + V_o \cdot \left[\frac{R_1}{R_1 + R_2}\right] \qquad \textbf{Eq. 3}$$

Use successively larger values for A_{ol} and check that for each value signal voltages satisfy Eq. 3. You will see that as A_{ol} is made very large V_e becomes vanishingly small and for large values of A_{ol} we may rewrite Eq. 3 as,

$$V_{in} \cdot \left[\frac{R_2}{R_1 + R_2}\right] + V_o \cdot \left[\frac{R_1}{R_1 + R_2}\right] \simeq 0$$

and rearranging gives,

$$V_o = - R_2/R_1 . V_{in} \qquad \textbf{Eq. 4}$$

Measurement of Closed Loop Signal Gain

The ratio of the output voltage V_o divided by the externally applied input signal V_{in}, V_o/V_{in}, is called the closed loop signal gain. 'Closed loop' signifies that this is the gain of the complete circuit with the negative feedback loop connected around the amplifier rather than the gain of the operational amplifier itself.

Inspection of Eq. 4 reveals that provided the open loop gain of the operational amplifier is very large **the closed loop signal gain of the inverting feedback circuit is equal to the ratio of the values of the feedback resistor and input resistor, $-R_2/R_1$,** the negative sign denotes the signal inversion.

Set the open loop gain of the model amplifier to a value greater than 10^5 and measure the ratio V_o/V_{in} for a range of values of V_{in} and using different values for resistors R_1 and R_2. Notice that the signal gain equation is not valid if the amplifier output voltage reaches its saturation limits. Notice also the influence of the power supply voltages on these saturation limits.

Significance of Feedback Fraction and Loop Gain

In a feedback amplifier circuit a quantity called the **feedback fraction,** β, is defined as **the fraction of the amplifier's output voltage which is returned to its input terminals.** The value of the feedback fraction is determined by the values of the components which are externally connected to the amplifier.

Another important quantity in feedback circuits is the loop gain. **Loop Gain** is defined as the **product of the fcedback fraction and the open loop gain, βA_{ol}.** Loop gain is the total gain in the closed loop signal path through the amplifier and back to the amplifier input via the feedback network.

In the inverter circuit resistors R_1 and R_2 act as a potential divider on the output voltage and the fraction of the output voltage returned to the inverting unit terminal is,

$$\beta = R_1/(R_1 + R_2)$$

By introducing β into Eq. 3 we obtain,

$$-V_o/A_{ol} = V_{in}.\beta.R_2/R_1 + \beta.V_o$$

which may be rearranged as,

$$V_o = -V_{in}.R_2/R_1.\left[\frac{\beta A_{ol}}{1 + \beta A_{ol}}\right] \qquad \textbf{Eq. 5}$$

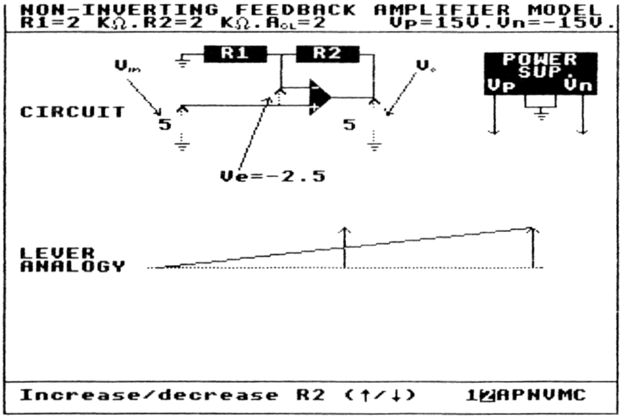
The ideal signal gain of the inverter is $-R_2/R_1$. The quantity $\left[\frac{\beta A_{ol}}{1 + \beta A_{ol}}\right]$ is called the **gain error factor**.

The amount by which the gain error factor differs from unity shows by how much the actual signal gain of the circuit differs from its ideal value. This amount, usually expressed as a percentage, is called the **gain error**.

Measure the signal gain of the model using different values of R_1, R_2 and A_{ol}, ($A_{ol} < 10^3$). Calculate values of the feedback fraction β, the loop gain βA_{ol}, the ideal gain $-R_2/R_1$ and the gain error factor and test the validity of Eq. 5.

PROGRAM SECTION 2:
THE NON-INVERTING FEEDBACK AMPLIFIER MODEL

The screen display produced when you run section 2 of the program is reproduced in Fig. 4. A circuit diagram and a diagram of a lever analogy for the non-inverting feedback amplifier is shown. The non-inverting circuit differs from the inverting circuit in respect of the point in the circuit to which the external input signal is applied. In the non-inverter or follower, the external input signal is applied directly to the non-inverting input terminal of the operational amplifier.



```
NON-INVERTING FEEDBACK AMPLIFIER MODEL
R1=2 KΩ.R2=2 KΩ.AOL=2        Vp=15V.Vn=-15V.
```

```
Increase/decrease R2 (↑/↓)      12APNVMC
```

Fig. 4. Non-inverting feedback amplifier.

The resistor R_1 connected to the inverting input terminal of the amplifier has one end connected to the circuit's ground point. The resistor R_2 connected between the output terminal and the inverting input terminal completes a negative feedback loop around the amplifier.

The equations governing the circuit's behaviour and features which you should note are now given. You should experiment with the model with the object of verifying these equations. The model is controlled using the control system previously described.

Resistors R_1 and R_2 act as a potential divider on the output voltage of the amplifier and establish the feedback fraction β.

$$\beta = R_1/(R_1 + R_2)$$

The external input voltage V_{in} is applied to the non-inverting input terminal of the amplifier and the feedback loop applies a voltage $\beta.V_o$ to its inverting input terminal. The voltage V_e which is actually impressed between the differential input terminals is thus,

$$V_e = -V_o/A_{ol} = \beta.V_o - V_{in} \qquad \textbf{Eq. 6}$$

Note that the arrows on the circuit diagram indicate the assumed positive directions for the voltages. A positive input voltage produces a positive output voltage and a negative value for V_e.

In the lever analogy the fulcrum point remains at a fixed height representing the fact that the left hand end of resistor R_1 is connected to ground. The vertical pointer at the right hand end of the lever represents the amplifier output voltage. The other vertical pointer represents the input voltage which is applied to the non-inverting input terminal, lever lengths either side of it are proportional to the values of resistors R_1 and R_2. The difference in height between the top of the 'V_{in}' pointer and the lever represents the voltage which is actually applied between the differential input terminals of the amplifier V_e.

If you start with a small value of A_{ol} and increase it you will see that the larger A_{ol} the smaller is the value of V_e. If A_{ol} is sufficiently big the actual value of A_{ol} has a negligible effect on the output voltage produced by the circuit. As A_{ol} approaches an infinitely large value the ouput voltage takes on that value which forces the voltage between the differential input terminals to approach the value zero. The action of the feedback loop is then to force the potential of the inverting input terminal to follow or 'track' any variations in potential of the non-inverting input terminal.

The value which the output voltage takes on for this tracking condition is readily found by subsitituting $V_e = 0$ in Eq. 6, giving $\beta V_o = V_{in}$ or

$$V_o = (1 + R_2/R_1).V_{in} \qquad \textbf{Eq. 7.}$$

If A_{ol} is extremely large the **closed loop gain** of the follower circuit (V_o/V_{in}) is equal to $(1 + R_2/R_1)$.

If we wish to see the effect of A_{ol} we manipulate Eq. 6. Thus,

$$-V_o/A_{ol} = \beta.V_o - V_{in}$$

$$(1 + \beta.A_{ol}).V_o = A_{ol}.V_{in}$$

and $$V_o = \left[\frac{A_{ol}}{1 + \beta.A_{ol}}\right].V_{in} \qquad \textbf{Eq. 8}$$

or $$V_o = V_{in}.1/\beta.\left[\frac{\beta A_{ol}}{1 + \beta.A_{ol}}\right] \qquad \textbf{Eq. 9.}$$

Note that $1/\beta = (1 + R_2/R_1)$ **is the 'ideal gain' of the follower circuit** and as before $\beta.A_{ol}/(1 + \beta A_{ol})$ is the **gain error factor.** The amount by which the gain error factor differs from unit shows by how much the actual gain of the feedback circuit differs from its ideal value.

PROGRAM SECTION 3: INTEGRATOR MODEL

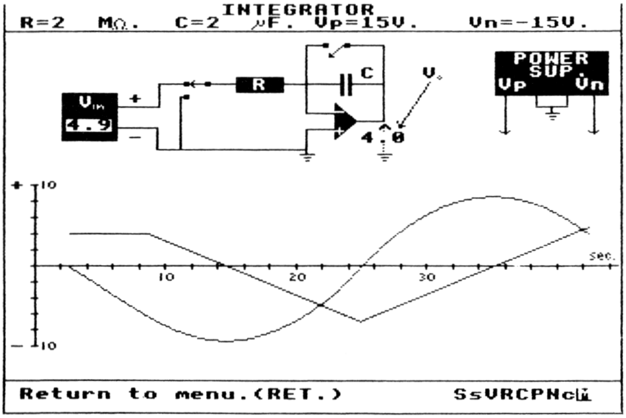


Fig. 5. Integrator model.

An inverting feedback circuit in which a capacitor is connected between the output terminal of an operational amplifier and its inverting input terminal acts as an integrator. Program section 3 allows you to investigate the behaviour of a model integrator. Fig. 5 shows the screen display produced by this section, where the operational amplifier is shown connected as an integrator.

We assume that the operational amplifier has an infinitely large open loop gain. With this assumption the amplifier output voltage acting via the feedback capacitor must maintain the inverting input terminal as a virtual earth point and cause any current arriving at the inverting input terminal to flow as a capacitor charging current.

The virtual earth at the inverting input terminal means that the output voltage V_o is equal in magnitude but opposite in sign to the voltage across the capacitor V_c. Now $V_c = Q/C$ where Q is the charge on the capacitor. And

$$\frac{dV_c}{dt} = \frac{1}{C} \cdot \frac{dQ}{dt} = \frac{I_{in}}{C}$$

Substituting $V_o = -V_e$ and $I_{in} = V_{in}/R$ gives

$$\frac{dV_o}{dt} = -\frac{1}{C.R} \cdot V_{in}$$

and $V_o = -\ 1/CR \, . \int V_{in}.dt$ **Eq. 10**

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The circuit produces an output voltage which is proportional to the integral with respect to time of the input voltage.

The model has two simulated switches. One of these (control letter S) enables the input to be switched between zero and a variable input signal voltage. The other (control letter s) acts as an integrator reset switch; when it is closed the capacitor is shorted out and the output voltage is set to zero. A graph showing the values of the input voltage and the output voltage as a function of time is displayed in the lower half of the screen. You can change the input voltage by selecting command letter 'V', then if you press the cursor shift UP key V_{in} is increased, while pressing the cursor shift DOWN key decreases V_{in}. The graph plot is halted by selecting any command letter to the right of 'V'.

Suggested Experiments

Apply steady input signal voltages using different values for the integrator CR product. In each case measure the slope of the output voltage graph (volts/sec) and verify that the slope is governed by the expression V_{in}/CR.

Note that the output voltage limits of the integrator are the output saturation limits of the operational amplifier which depend upon the values of the power supply voltages. The circuit stops integrating when saturation limits are reached, but the output voltage can be reset to zero by using the reset switch.

Note that the output voltage does not go to zero when the input voltage is zero but its value 'holds' at the value it had at the instant the input was switched to zero. The output voltage of a practical integrator does not remain constant when the integrator is switched into its hold mode, it changes or 'drifts' with time. Integrator drift is caused by the bias current and offset voltage of practical operational amplifiers.

By alternatively increasing and decreasing the input voltages between a positive and negative value observe the output voltage waveform which an integrator produces in response to a triangular shaped input wave.

PROGRAM SECTION 4:
OPERATIONAL AMPLIFIER APPLICATIONS (Question Section)

Operational amplifier feedback circuits are used to perform a wide range of different analogue signal processing functions. Program section 4 sets you numerical questions which require you to make use of the equations which govern the behaviour of some of these signal processing circuits. You are shown a circuit diagram of the particular application and are given the values of the parameters which you need to use in the calculations. Don't worry if you make mistakes at first, the program provides you with screen prompts which show you which equation you should be using.

Questions are set on the following applications; the inverter, the follower, the subtractor, the inverting adder and the current to voltage converter. You make a choice of application from the list which is displayed when you run this program option. Commands which you can select with the cursor shift left and cursor shift right keys allow you to enter your answer (E), move on to the next question (N), obtain a help prompt (H), see the correct answer (A) or return to the menu (M). The program accepts your answer or reacts to your command when you press the RETURN key.

Five different questions are asked for each application. The first asks you to calculate the ideal output voltage and you will need to make use of the ideal gain equation for the particular application.

The second question asks you to calculate the value of the feedback fraction in the particular application.

The third question asks you to calculate the value of the loop gain in the application.

The fourth question asks you to calculate the gain error %. Gain error % shows the effect that a finite value of A_{ol} has on the output voltage. It shows the extent to which the output voltage may be expected to differ from the value given as the answer to question 1 because of a finite value for A_{ol}.

In our analysis of the inverter and follower circuit, (see Eqts. 5 and 9) we showed that the effect on circuit performance of a finite open loop gain was to multiply the ideal gain relationship by the gain error factor $\beta A_{ol}/(1 + \beta A_{ol})$. In other applications the effect of finite open loop gain may be taken account of similarly by multiplying the ideal performance equation by this same gain error factor. The performance equation for any operational amplifier feedback circuit can be put in the form,

$$\begin{pmatrix}\text{Actual Closed Loop}\\ \text{Perf. Eq.}\end{pmatrix} = \begin{pmatrix}\text{Ideal Closed Loop}\\ \text{Perf. Eq.}\end{pmatrix} \times \beta A_{ol}/(1 + \beta A_{ol})$$

The above relationship highlights the importance in an application of the loop gain βA_{ol}. Provided the loop gain is very large the actual value of the open loop gain of the operational amplifier has no significant effect on the closed loop gain and the performance of the circuit closely approximates the ideal. If linear components are used to set the feedback fraction the feedback circuit will behave linearly.

In all applications, gain error % = (1 − gain error factor).100% where the gain error factor is determined by the loop gain,

$$\text{Gain error factor} = \beta A_{ol}/(1 + \beta A_{ol}).$$

If the loop gain βA_{ol} is large the gain error factor may be approximated as $GEF = 1 - 1/\beta A_{ol}$ and,

$$\text{Gain error } \% = 100/\beta A_{ol}.$$

The fifth question asks you to calculate the closed loop bandwidth.

The bandwidth of an amplifier is the range of frequencies over which the gain does not decrease more than 3 dB, ($1/\sqrt{2}$). General purpose operational amplifiers have a very limited open loop bandwidth, (of order 10 Hz.). At frequencies higher than their open loop bandwidth their open loop gain decreases (rolls off) inversely with increase in frequency and the frequency at which the open loop gain has decreased to unity is called the **unity gain frequency**. The unity gain frequency f_1 is related to the open loop bandwidth by the equation,

$f_1 = A_{(o)}.f_{ol}$, where $A_{(o)}$ is the value of the open loop gain at zero frequency and f_{ol} is the open loop bandwidth.

The closed loop bandwidth is determined as the frequency at which the magnitude of the gain error factor becomes equal to $1/\sqrt{2}$. It may be shown (Refs 2, 3) to be related to the unity gain frequency f_1 by the equation,

$$\text{Closed loop bandwidth} = \beta.f_1$$

Negative feedback has the effect of increasing bandwidth. The greater the feedback fraction the smaller the closed loop gain but the wider the bandwidth.

We now derive the ideal performance relationships for the subtractor, the inverting adder and the current to voltage converter circuits. The ideal gain expressions for the inverter and follower applications have been derived in an earlier section, (Eqts. 4 and 7).

The Subtractor Circuit (Differential Input Feedback Amplifier)

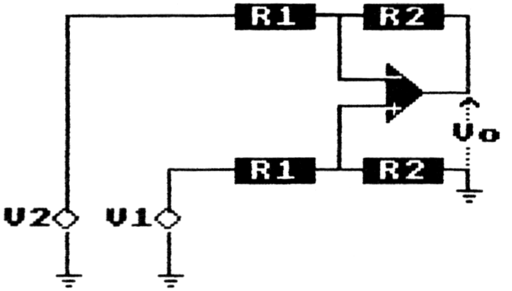

Fig. 6. Subtractor Circuit

Referring to the circuit shown in Fig. 6 we write an expression for the voltage at the inverting input of the operational amplifier as a superposition of the effects of the input signal V_2 and the output voltage V_o.

$$V_- = V_2.R_2/(R_1 + R_2) + V_o.R_1/(R_1 + R_2)$$

The voltage at the non-inverting input terminal, V_+ is determined by the value of V_1

$$V_+ = V_1 . R_2/(R_1 + R_2)$$

The operational amplifier, if it has an infinitely large open loop gain, forces V_- to equality with V_+. Equating the two and performing a line of algebraic manipulation gives the ideal expression for the output voltage as,

$$V_o = (V_1 - V_2). R_2/R_1 \qquad \textbf{Eq. 11}$$

The circuit produces an output voltage which is proportional to the difference between the two input signals. An application of this type of circuit is as a simple differential input amplifier, used where it is desired to reject interfering signals picked up on input leads.

The feedback fraction for the circuit is determined, as for the inverter and follower circuits by resistor R_2 connected between output and inverting input and resistor R_1 connected in series with the input signal source to ground.

$$\beta = R_1/(R_1 + R_2)$$

For simplicity we assume the output resistance of the signal source is negligibly small compared with R_1. If this is not so the resistance of the source must be added to R_1, and R_1 must be taken to include this source resistance. The resistors connected to the non-inverting input terminal do not influence the value of the feedback fraction.

The Inverting Adder

In an inverting feedback arrangement if the operational amplifier has an infinitely large open loop gain its output voltage takes on just that value which is required to cause any current arriving at the inverting input to flow through the feedback path and at the same time maintain the inverting input as a virtual ground point. If currents from several input sources arrive at the inverting input it is their sum which is forced to flow through the feedback path. The inverting input terminal is sometimes referred to as the circuit **summing point.**

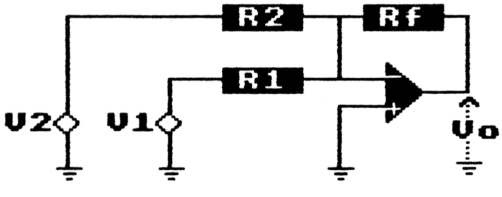

Fig. 7. The Inverting Adder Circuit

In the circuit shown in Fig. 7. input signals V_1 and V_2 cause currents $I_1 = V_1/R_2$ and $I_2 = V_2/R_2$ to flow through resistors R_1 and R_2 respectively. The output voltage V_o must take the value

$$V_o = -(I_1 + I_2).R_f$$

Substituting the values of I_1 and I_2 gives,

$$V_o = -(V_1.R_f/R_1 + V_2.R_f/R_2) \qquad \textbf{Eq. 12}$$

When evaluating β it must be noted that the inverting input is connected to ground through the parallel combination R_p of resistors R_1 and R_2;

$$R_p = R_1.R_2/(R_1 + R_2)$$

and,

$$\beta = R_p/(R_p + R_f)$$

Extra input signals can be added simply by connecting additional input resistors to the circuit summing point. In a practical circuit the number of inputs is limited by the requirement to maintain an adequate loop gain. Adding extra input resistors decreases R_p and hence decreases β and loop gain βA_{ol}.

The Current to Voltage Converter.

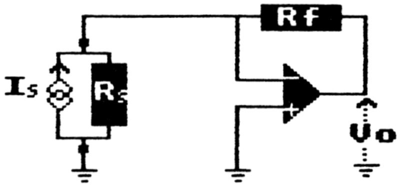

Fig. 8. The Current to Voltage Converter Circuit

In the circuit shown in Fig. 8 the input signal is provided by a current source which is connected directly to the inverting input terminal of the operational amplifier. The negative feedback holds the inverting input at ground potential and forces the input current to flow through the feedback resistor R_f. The amplifier develops an output voltage,

$$V_o = -I_s.R_f \qquad \textbf{Eq. 13}$$

The circuit provides the basis for an ideal current measurement since it introduces zero voltage drop in the measurement circuit.

The feedback fraction for the circuit is governed by the resistance of the input signal source, and is calculated from the equation:

$$\beta = R_s/(R_s + R_f)$$

Suggestions for further work

The insight which you gain about the behaviour of a model amplifier from running this Megacycal program will help you to better understand the behaviour of real operational amplifiers. You are strongly advised to follow your work on the program with investigations performed on real operational amplifier circuits. Practical operational amplifier circuits are not difficult to assemble and get working, (Ref. 1).

A detailed treatment of the frequency response characteristics of op. amps. and of the various error parameters which govern the accuracy of practical circuits is given in the Megacycal package 'OP. AMP. APPLICATIONS DESIGN'.

A full treatment of all aspects of the behaviour of operational amplifiers and their vast range of applications is to be found in Ref. 2.

References:

1. Clayton, G.B., 'Operational Amplifier Experimental Manual'. Butterworths, 1983.

2. Clayton, G.B. 'Operational Amplifiers'. 2nd. Ed. Butterworths, 1979.

3. Megacycal Software. 'Op. Amp. Applications Design'. 1985.

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