UCL DEPARTMENT OF PHYSICS AND ASTRONOMY
Gower Street Teaching Laboratories

Experiment NX 741

Operational Amplifiers

4 Sessions

Experiment Aims

To investigate some of the properties of an operational amplifier and to establish and extend students' proficiency in using oscilloscopes.

About the Script

This script is in three parts: the first covers the principles of an oscilloscope, the second introduces operational amplifiers and the third is about the experiment that you will conduct. The first two parts are crucial background, but may not necessarily feature heavily in your lab book which should be a record of the experiment you undertook, *including calibration.*

Relevant Lecture Courses

There are no related lecture courses. The experiment is to develop practical skills only. It will, however, be directly related to a course in year 2.

Progress markers

Session 1: *Oscilloscope calibration; 741 introduction and experiment details*
Session 2: *741: Data taking*
Session 3: *741: Repeat data taking as necessary; data analysis*
Session 4: *741: Complete data analysis and conclusion*

Revisions

PAB/JRG	20.12.14
KD/JRG	5.12.15
JRG	4.1.17

Risk Assessment Form Operational Amplifiers

WORK/PROJECT TITLE : Operational Amplifiers

LOCATION(S): First year teaching laboratory, Gower Street

DESCRIPTION OF WORK: To investigate the frequency response of an operational amplifier with negative feedback applied

PERSONS INVOLVED: Undergraduate students and academic staff

HAZARD IDENTIFICATION *(state the hazards involved in the work)*

Low voltage supplied via a mains connection

RISK ASSESSMENT (make an assessment of the risks involved in the work and where possible state high, medium or low risk)

Risk of electrocution. (Low risk).

CONTROL MEASURES *(state the control measures that are in place to protect staff and others from the above risks. Put in place adequate control measures for any risks that have been identified as uncontrolled.)*

Students must not tamper with the power-transformer system.
Departmental safety procedures are followed.

DECLARATION

I the undersigned have assessed the work, titled above, and declare that there is no significant risk / the risks will be controlled by the methods stated on this form *(delete as applicable)* and that the work will be carried out in accordance with Departmental codes of practice.

Name P Bartlett

Signed

Date

1. Equipment Background: The Oscilloscope

1.1 Introduction

The cathode ray-tube oscilloscope (CRO) is one of the most versatile instruments available for electrical measurements. Any quantity which can be expressed in terms of a time-dependent voltage can be measured with the instrument. The shape of its variation with time can be observed for frequencies from zero up to many megahertz (MHz). By using switched-beam oscilloscopes the variation with time of two or more quantities can be observed simultaneously.

The purpose of the oscilloscope is to show the variation in voltage of a signal with respect to time. The basic principles of the CRO can be explained with reference to figure 1.

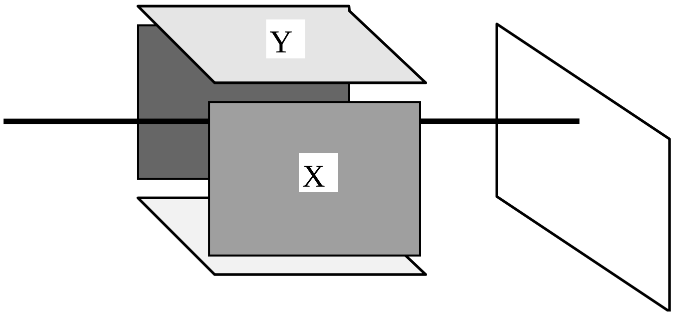


Figure 1 CRO Electron-beam steering system

The CRO consists of an electron gun that directs a focused beam of electrons onto a screen, which emits light when hit by the electrons. The focusing and intensity of the beam can be modified with the **focus** and **intensity** knobs on the scope. ***It is important to ensure that the traces produced on the screen are as sharp and faint as possible using these controls. If this is not done, additional uncertainties may be introduced into your measurements.***

There are two pairs of parallel plates onto which voltage signals can be applied. In the absence of any voltages on these plates the beam of electrons would hit the centre of the screen giving a stationary central spot.

In the basic mode the signal voltage is applied to the Y plates. If this is a time varying signal of the form shown in figure 2, the spot would appear to travel, in a line, up and down the screen at the X = zero position.

The vertical displacement of the spot depends on the magnitude of the voltage applied to the signal plates and on the **volts/division** setting of the dial on the scope. In order to see a trace similar to that shown in Figure 2 it is necessary to draw the signal in the X or time direction. This is achieved by applying a slowly ramped voltage (figure 3) to the second set of voltage plates which deflects the electron beam from the left hand side (LHS) of the screen to the right (RHS) in a given time (set by the **time base knob**).

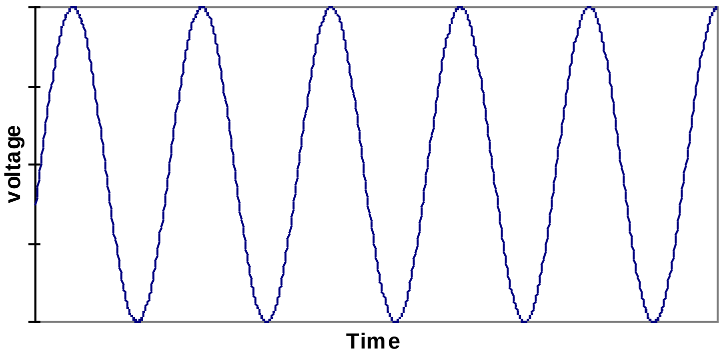


Figure 2. Oscilloscope screen trace showing time-varying voltage input

Care should be taken to ensure that the ×10MAG button is not pressed in the timebase section of the CRO.

Q: What would happen if it were?

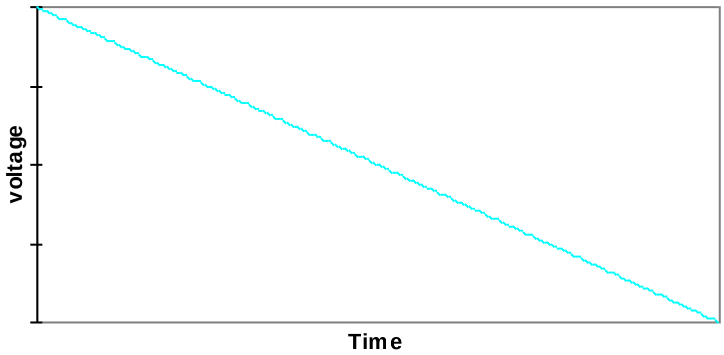
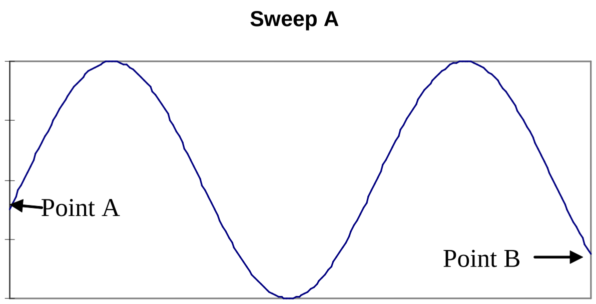


Figure 3 Voltage sweep applied to the x-deflection (time base)plates against time

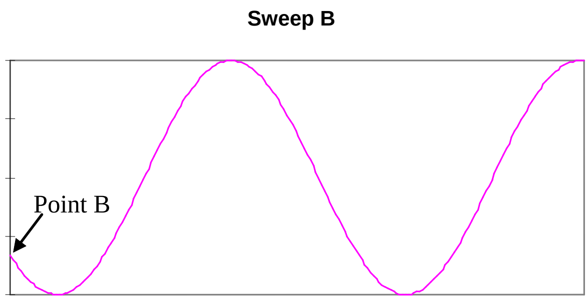
1.2 Principle of triggering

If the slow ramping voltage applied to the X (time base) plates were simply repeated once the spot had reached the far right hand side of the screen (known as free running) then the second sweep of the signal voltage across the screen might not necessarily be in phase with the first. This is illustrated in figure 4.

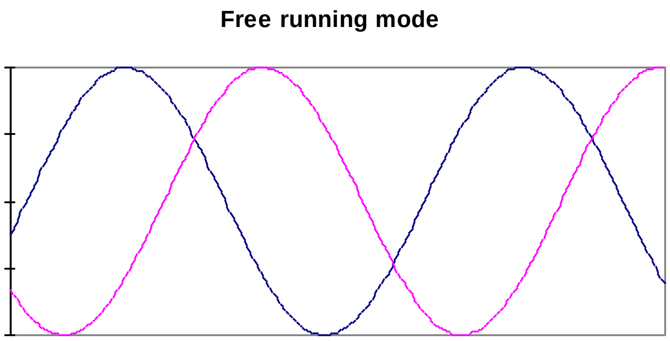
This condition arises if the **AUTO** button on the oscilloscope is selected. To avoid this problem, the oscilloscope can be operated in triggered mode where the same button is set to the **NORM** position. In this mode the second sweep of the electron beam from the LHS to the RHS of the screen is delayed until the two superimposed traces are in phase. This is done by choosing a suitable voltage (V_t) on the applied signal at which the time base will be "triggered" so that the 'refresh' of the screen results in in-phase displayed signals. This is illustrated in figure 5.



First trace as the beam is pulled across the screen. The starting and finishing voltages of the sweep at point A and B respectively are indicated.



If the second sweep were to occur immediately after the first it would start at the voltage it was at point B of the first trace.



The eye would see both of these traces (and possibly further sweeps) superimposed, with the whole display giving the impression of drifting over the screen.

Figure 4: Plots showing how 'free-running' a CRO will result in out of phase signal sweeps

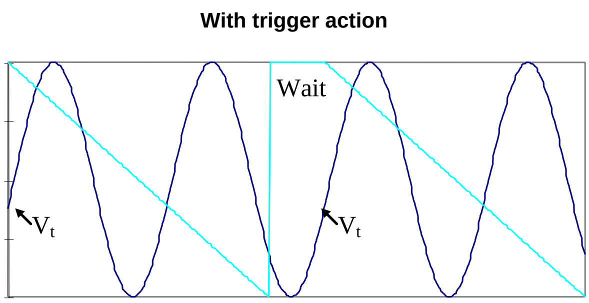


Figure 5: Plot showing how the triggering system ensures that subsequent signal sweeps are displayed in phase on the CRO

The voltage V_t, (the trigger threshold voltage), is set with the **trigger level** knob. As this is turned it will be noted that the starting voltage of the trace changes. If the magnitude of V_t is set above the maximum applied voltage then it would be expected that the time base would never be triggered and the spot would remain indefinitely on the LHS of the screen with the time base waiting for the trigger voltage to be reached.

In figure 5, the time base triggers when the incoming signal reaches a given level, *Vt*, while increasing. This is a choice made by rotating the knob to either the "+" or "–" directions. Rotating in the "–" direction will cause the trace to trigger when the threshold value V_t is reached while the signal is negative and decreasing.

1.3 Observing Two Signals using an Oscilloscope

The 'scope has two independent channels so that the time varying properties of two signals can be viewed simultaneously. There are therefore two coaxial connection points marked **ch 1** and **ch 2**. It is possible to set the triggering voltage from either of the channels by depressing the appropriate trigger buttons.

A common problem arises from trying to look at the voltage signal from channel 1 while trying to trigger from channel 2 when there is no input signal to this second channel. This will result in the time base staying in a continuous "wait" condition (if set to Norm) or free running (if set to Auto).

1.4 AC/DC Mode

An alternating signal may have a *DC component* – in other words it may be oscillating about a steady DC level rather than about 0 volts. The oscilloscope can be set to display the signal *including* any DC component (DC mode) or with the DC component *removed* (AC mode). Normally we are only interested in the AC component of a signal, but DC mode can be useful under some circumstances.

1.5 Calibration of the Oscilloscope

Although it might be expected that the oscilloscope (or any other piece of test equipment) is already calibrated, ***it is an assumption that can result in erroneous results if the device is out of calibration.*** Consequently, the first task in this experimental set is to ensure that the CRO is calibrated.

This is the only place in this course where you will have to follow a prescribed method. Calibrating equipment must be done exactly.

To calibrate an oscilloscope:

1. Connect a CRO probe cable to the **1 KHz 2V (peak to peak)** calibration lug on the bottom left of the 'scope. Connect the BNC connector to **Ch1**. This built-in calibration

signal will help you to ensure that the voltages and frequencies displayed on the 'scope accurately reflect the parameters of the signal you subsequently supply to it.

2. Select a suitable **Volts/Div** level on the channel 1 section of the 'scope. The selected level will then mean that each vertical division on the display will be of that voltage. Select a time base value via the **Time/Div** knob so that the displayed waveform has at least two periods visible. The selected level will then mean that each horizontal division on the display will be of that time period.

3. Check that the display indicates that the signal is 2V (peak to peak). If the trace needs to be moved horizontally, this can be achieved via the **Position** knob in the channel 1 section of the 'scope.

If the displayed voltage is *not* 2V (peak to peak), the 'scope can be calibrated by rotating the **Var** knob until it shows this voltage.

4. Repeat these three steps for Channel 2.

5. To check that the time base is displaying a 1kHz signal, measure the time for one cycle and then convert this to an equivalent frequency. This can be achieved with the probe connected to either **CH1** or **CH2**.

If the displayed period is *not* equivalent to 1 kHz the 'scope can be calibrated by rotating the **Swp Var** knob until it shows the appropriate period for one cycle.

Once the 'scope has been calibrated, **care should be taken** so that the **Var** knobs are not rotated again or the calibration sequence will need to be repeated.

You should log that you have calibrated the CRO in your laboratory notebook, stating how and when this was done.

Q: When is it necessary to calibrate equipment?

There is an **audio-visual tutorial** about the oscilloscope on Moodle at https://moodle.ucl.ac.uk/pluginfile.php/326687/mod_resource/content/0/scopes1.swf. If you are not familiar with oscilloscopes, you are **strongly recommended** to go through this tutorial *before you come into the lab.*

2. Experimental Background: Introduction and Theory

2.1 Introduction to Operational Amplifiers

Electronic circuits can be broadly classified into two types – analogue circuits and digital circuits. Digital circuits are used in computers, where only two signal levels ('high' and 'low') are needed. In analogue circuits the level of an electrical signal can vary continuously. Operational amplifiers ('op-amps') are amongst the most useful analogue circuits in electronics. Apart from the discrete transistor, the op-amp may be considered to be the most fundamental element in analogue circuit design and a very useful device for any practical physicist.

An op-amp amplifies the **difference** in voltage between two inputs, known as the non-inverting (V_n) and inverting (V_i) inputs. It has a very high gain ($\sim 10^5$) at low frequencies, which reduces significantly as the frequency increases.

The op-amp behaves like any other amplifier in that it requires power to produce an amplified verson of a relatively small input-signal. This means that the absolute maximum output signal that is possible from the op-amp will be at either/both the positive or negative rail values for a given amplified waveform.

Power is supplied to an op-amp as steady (DC) voltages (positive and negative) separate from the input signal. These connections are often referred to as ‘power rails’. There may be more than two power rails, at different polarities (+ and –) and/or different voltages. One – conventionally shown at the bottom of the circuit diagram – is normally referred to as “0 volts” or “earth”.

The layout of a typical op-amp is shown in Figure 6. Note that power rails and offsets are not usually shown in circuit diagrams.

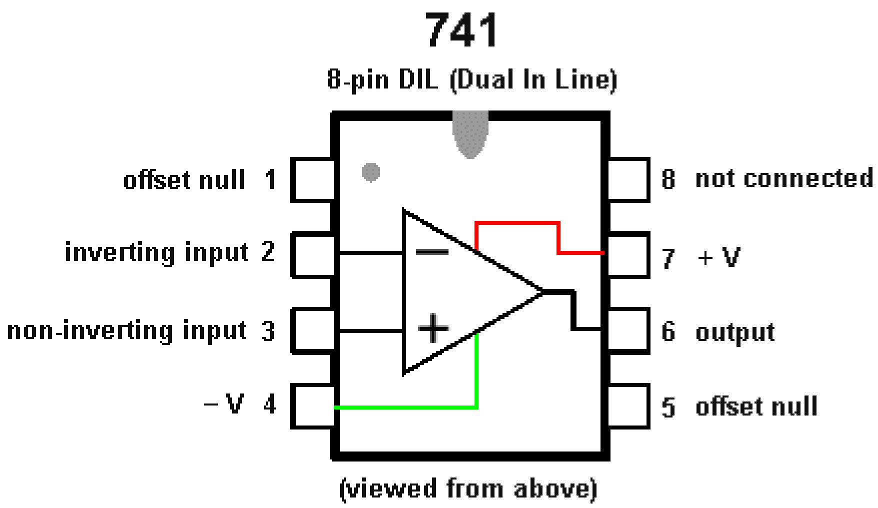


Figure 6. Schematic of a 741 op-amp integrated circuit packaged as an electrical component.

In this diagram, the inverting and non-inverting input pins can be seen as well as the pins that supply the power to the op-amp (+V and –V power rails). A triangle is the symbol for an amplifier; the output is shown at one vertex and the inputs on the opposite side.

Since the main function of an op-amp is as an amplifier, one of the most important characteristics is the **gain**, defined as the ratio of input and output voltages. The output signal V_{out} from the op-amp expressed as a function of the frequency-dependent gain *G(f)* and the difference between the V_n and V_i inputs is:

$$V_{out} = G(f)[V_n - V_i] \qquad (1)$$

Op-amps can be operated in either inverting or non-inverting mode, depending on whether the input voltage is to the inverting or non-inverting input pin.
These, and many other possible configurations, are detailed here:
http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/opampvar.html

In this experiment, $V_{in} = V_n$ and the op-amp is operated in non-inverting mode.

2.2 Open Loop Operation

If the voltage input signal V_{in} is connected to either of the op-amp inputs V_n or V_i, with the other input set to earth (0 volts), then the magnitude of the output voltage will be

$$V_{out} = G(f)V_{in}$$

This is known as *open loop operation*, and the gain of the circuit is known as the open loop gain.

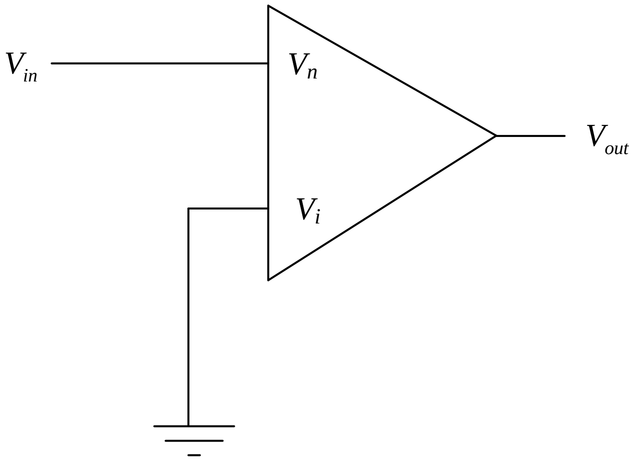


Figure 7. Representation of an op-amp used in open loop non-inverting mode. The symbol shown connected to V_i is the "earth" or 0 volts power rail symbol.

Typical characteristics of the open loop gain are shown in figure 8.

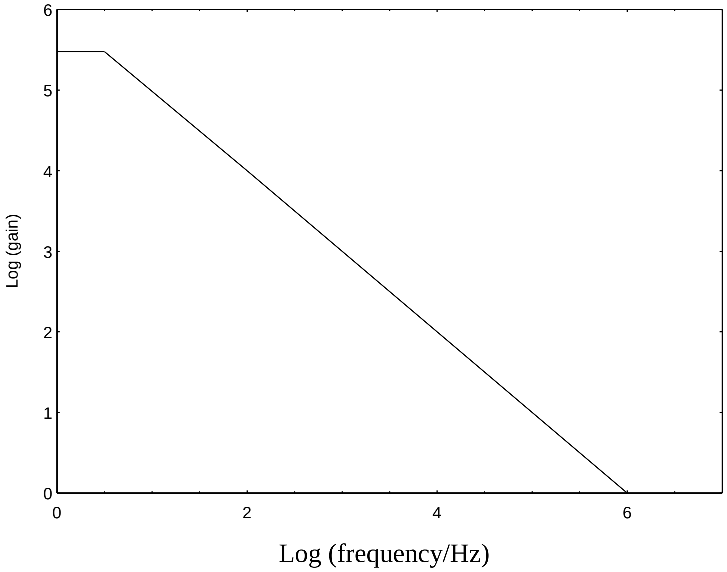


Figure 8. At very low frequencies the 'open-loop' gain, G(f), can be very large, but it falls off very rapidly with increasing frequency. (Note that this is a "log-log" plot).

In practice op-amps are not often used in this open loop mode because of the frequency dependence of the amplification and the prohibitively high gains at lower frequencies. Usually, an amplifier that provides a smaller gain that is ***constant*** over a wide range of frequencies is wanted. This is achieved by operating the op-amp in *closed loop* mode.

2.3 Closed Loop Operation

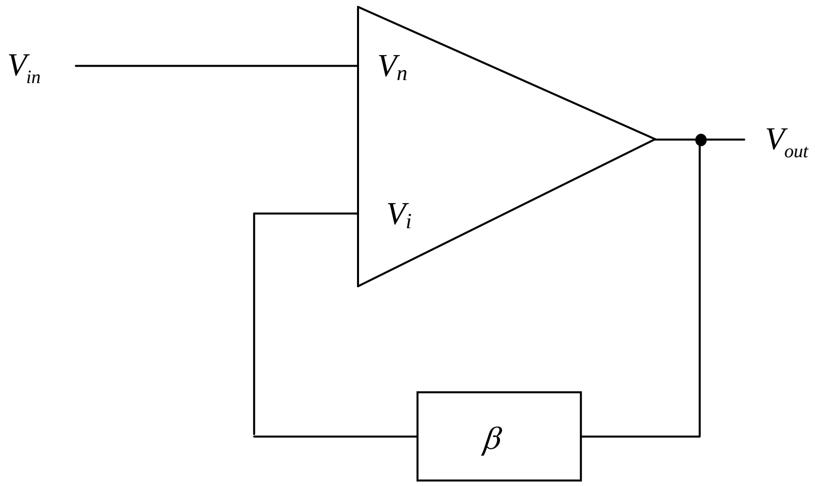


Figure 9. Representation of an op-amp used in closed loop non-inverting mode. A fraction β of the output signal is fed back into the inverting input.

Referring to equation (1), if we want the op-amp to give a gain that that is independent of frequency (i.e. constant V_{out} for a given V_{in} as frequency varies), then the differential voltage signal $[V_n - V_i]$ must increase as $G(f)$ decreases. This is achieved by "feeding back" a fraction of the output signal V_{out} so that the op-amp input depends on its output as in figure 9 (a feedback loop).

In closed-loop non-inverting operation, $V_{in} = V_n$ and a fraction β of the output signal V_{out} is fed into the inverting input. Then equation (1) becomes :-

$$V_{out} = G(f)\left[V_{in} - \beta V_{out}\right] \qquad (2)$$

As $G(f)$ decreases, V_{out} tends to drop (in accordance with the open-loop behaviour in figure 8), but this reduces βV_{out} which increases the differential input signal ($V_{in} - \beta V_{out}$). Thus V_{out} can be kept constant.

Note that the signal which is fed back has the opposite sign to the input signal, so we have ***negative feedback*** with respect to the input signal. Positive feedback is possible (by feeding a fraction of the output to the non-inverting input) but this just results in the output signal quickly reaching the power supply rail values in an uncontrolled fashion.

Rearranging equation (2) gives the *closed loop gain G*.

$$G = \frac{V_{out}}{V_{in}} = \frac{G(f)}{1 + \beta G(f)} \qquad (3)$$

At lower frequencies when $G(f)$ is very large ($\beta G(f) >> 1$) (3) can be approximated to :-

$$G_{lf} = \frac{G(f)}{G(f)\beta} = \frac{1}{\beta} \qquad (4)$$

where G_{lf} indicates the "low" frequency gain of the circuit. Thus a closed loop gain that is independent of frequency can be obtained, provided $G(f)\beta >> 1$ which from equation (4) is equivalent to $G(f) >> G_{lf}$.

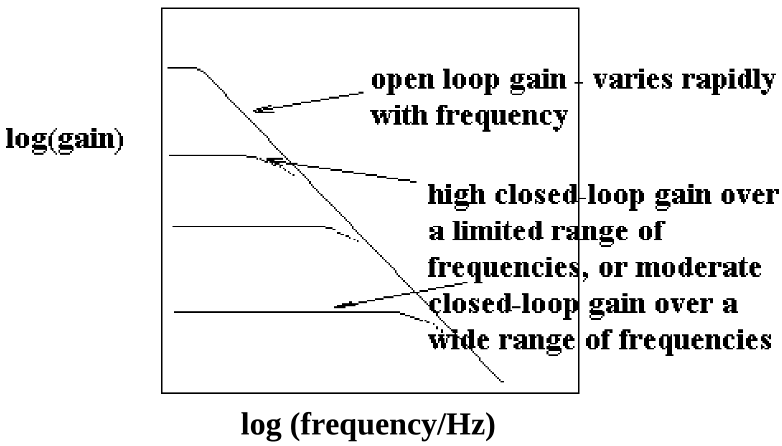


Figure 10. Open and closed loop gains against frequency for various feedback fractions

As the frequency is increased, there will be a point where this condition is no longer met, and $G(f)\beta \approx 1$. The gain will then fall in accordance with equation (3). At higher frequencies still, where $G(f)\beta << 1$, G approximates to the open loop gain and will follow the same envelope as the open loop circuit (see Figure 10). The range of frequencies over which the amplifier gain is constant is known as the *bandwidth*.

It can be seen from figure 10 that there is a “trade-off” between the value of G_{lf} and the range of frequencies over which it will remain constant. The higher the value of G_{lf} that we want, the smaller the bandwidth. In practice G_{lf} is usually chosen to have a value in the range 1 – 1000. When G_{lf} ~ 1 the op-amp acts as a *buffer* or *power amplifier*, in that it provides only a small amount of voltage gain, but is capable of supplying a relatively large current into a medium-resistance load. At high values of G_{lf} op-amp circuits tend to be rather unstable and sensitive to noise.

2.4 The 741 Op-Amp Chip

The feedback circuit we shall use in this experiment is illustrated in figure 11. The feedback fraction βV_{out} is provided by a potential divider resistor network. The voltage V_{out} is dropped between the output of the op-amp and earth through the resistors R_1 and R_2. The voltage at the inverting input V_i is given by:-

$$V_i = V_{out}\frac{R_2}{R_1 + R_2} \qquad (5)$$

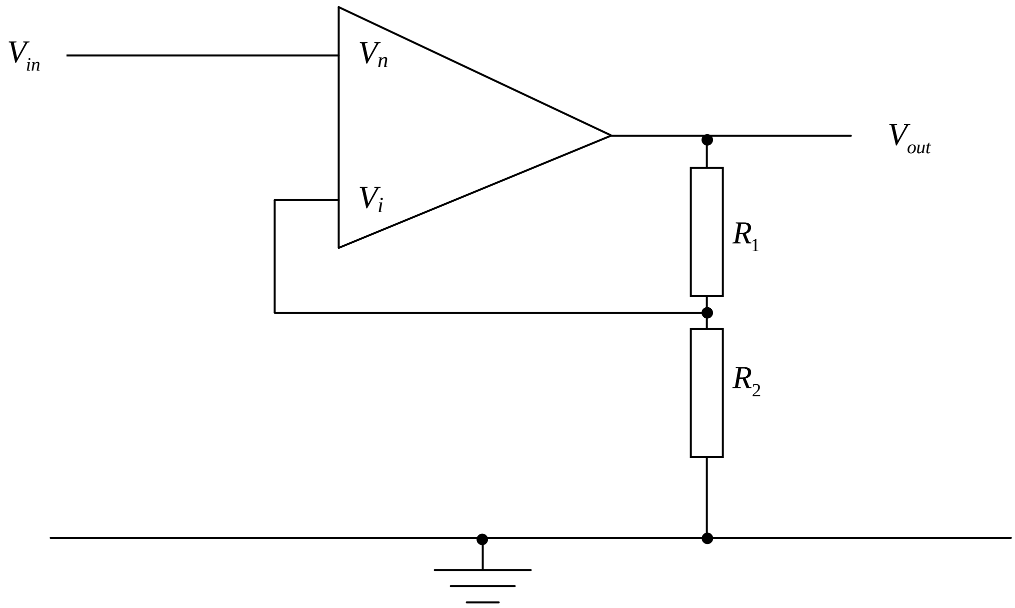


Figure 11. Circuit diagram of non inverting amplifier with feedback resistor network.

Remembering that $V_i = \beta V_{out}$, we find that $\beta = \frac{R_2}{R_1 + R_2}$ and the “low” frequency gain is given by (from (4)):

$$G_{lf} = \frac{1}{\beta} = \frac{R_1 + R_2}{R_2} \qquad (6)$$

3. The Experiment

In this experiment, the closed loop gain as a function of frequency will be measured for various feedback fractions β.

3.1 Experimental Set-Up

The feedback fraction β will be varied by choosing different values of the feedback resistors R_1 and R_2 (figure 11). A small oscillating signal is fed into the non-inverting input, and a fraction β of the output is fed back to the inverting input. The output voltage is measured.

The circuit will be made up on the operational amplifier printed circuit board provided, which is shown schematically in figure 12. Note that this is a circuit board *layout*, *not* a circuit diagram.

A circuit diagram follows a simple set of rules [1]: straight horizontal and vertical lines show wires; connections are dots, wires crossing are without dots; don't draw semi-circle loops to show jumps; use standard circuit element symbols only. Figure 11 is a simple diagram of only *part* of the circuit; figure 12 covers the *layout* of the circuit board (but not all the components used in the experiment) but is *not* suitable for understanding how the circuit functions. It also includes features that are irrelevant to this experiment.

Q: Can you see which are the irrelevant features?

Q: What items that you will be using are missing from both diagrams?

Your circuit diagram should show all the equipment on the bench, but **not** those parts that are not being used, or those parts that it is conventional to omit (*hint: see page 8*). A theoretical diagram enables you to easily follow a signal from input to output, regardless of where the components are physically situated on the circuit board (which is usually dictated by their physical size and ease of assembly)

Q: Fig. 12 shows two resistors labelled R1 and three labelled R2. Only two of these will be used at any one time. Do you need to show all five resistors in your circuit diagram?

There is nothing wrong with several diagrams showing different aspects of the set-up of an experiment. A theoretical diagram shows you how a circuit works; a layout diagram may help you to understand how to wire the circuit up.

The values of R_1 and R_2 are selected by placing the short banana plug leads (yellow) between the appropriate connection points (see figure 12). The operational amplifier is the small, eight legged integrated circuit (IC) situated near the centre of the board. It is not soldered directly to the board, but is mounted in an eight pin dual-in-line (DIL) socket. The indentation on the op-amp chip shows which is the top end and a small dot locates the position of pin (leg) 1 (see Figure 7). The board has an integrated power supply that provides the power rails to the op-amp. This is switched on and off by means of a switch on the right hand side of the board.

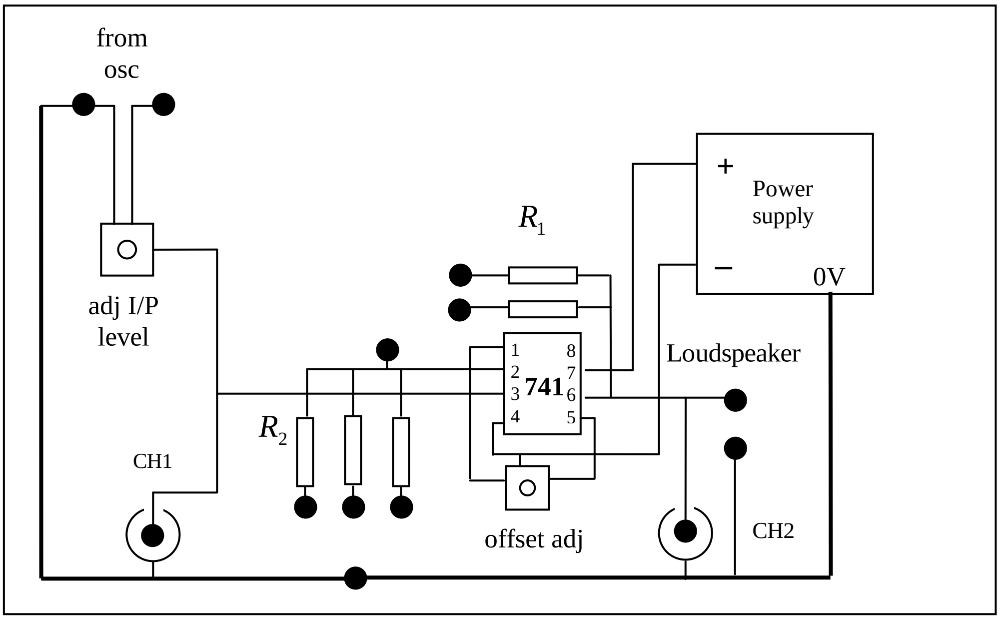


Figure 12. Operational amplifier printed circuit board layout.

Note that the output of the function generator is not fed directly to the chip. To see why, consider the following:

Q: What is the maximum peak-to-peak output that is possible from this circuit? (Hint: see page 8)
Q: What is the maximum gain you expect to be able to achieve? (Hint: see equation (6))
Q: From the answers to the above two questions, what is the maximum input voltage that you can supply to the op-amp without creating distortion?

The function generator has a *minimum* voltage level that it can supply reliably, in the region of 100 mV. Depending on your answers to the above, this voltage may have to be reduced further before applying it to the op-amp. For this purpose, a 10KΩ variable resistor or *potentiometer* ("Adj I/P Level") has been inserted at this point of the circuit. A variable resistor takes the form of a conventional resistor with a "slider" which moves along it and hence can "tap off" a proportion of the applied voltage. It is represented in a circuit diagram by the symbol shown in Figure 13 (it is usually round but is represented as straight).

Q: Fig. 13 shows that a variable resistor has 3 external connections. Fig. 12 shows 3 tracks emanating from the component labelled "Adjust I/P level". Can you work out which is which?

You will need to create your own circuit *diagram* from the information available. Do *not* copy out fig. 12; it is provided merely to show connections which are not immediately obvious because they are on the underside of the printed circuit board.

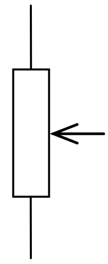


Fig. 13: Variable resistor circuit symbol

3.2 Procedure

Safety Note: (NB this is not the full risk assessment for this experiment) Make sure the power supply is off before wiring up the circuit, and **get a demonstrator to check that the circuit is connected before you switch it on** if you are at all unsure.
Never turn the power supply on until the circuit is complete, and avoid removing components or modifying component values with the power turned on unless you are sure it is safe to do so. Not adhering to the above risks damaging the op-amp and possibly any external components.

(NB The "Procedure" section in your lab book should explain *why* you are doing things!)

3.2.1 Set up the circuit:

- Connect function generator output to oscilloscope (Ch1) and select a sine wave of frequency approximately 100 Hz, peak-to-peak voltage 100mV
- Connect the same output to sockets marked 'from osc' on board using red/black cables, and transfer the oscilloscope lead to the socket marked "ch1" on the circuit board.
- Adjust "Adj I/P Level" variable resistor so input to op-amp is 10mV peak-to-peak.
- Use short yellow leads to connect R1 and R2 into the circuit. (The resistances are given by the coding of the bands on the resistors; how accurate are these? Can you make measurements to improve this accuracy?)
- Start with a combination that gives a theoretical gain of 100. *(What combination of R1 and R2 do you use?)*
- Connect a coaxial cable from the socket marked 'CH2' to channel 2 of the oscilloscope. *(What does this display?)*
- Make sure you have selected AC mode on the oscilloscope.

!!! Before turning on the power supply (the first time you set up the circuit), you must get a demonstrator to check the wiring of the circuit. !!!

3.2.2 Offset zeroing procedure

After inserting the yellow leads, getting the circuit checked and switching the power supply on, but **before taking data**, carry out the following **offset zeroing procedure:**

- Disconnect the function generator output from the circuit board.
- Set the MODE switch on the oscilloscope to "Ch 2"

- Set VOLTS/DIV on channel 2 to 5 V per division.
- Press in the AC/DC button on channel to to set DC mode.
- Press GND button in on channel 2.
- Use the channel 2 POSITION control to move the trace to the centre line of the screen.
- Unpress GND.
- If the trace moves *at all* on unpressing GND, adjust the OFFSET control on the circuit board until the trace moves to the centre line. Pressing and unpressing GND should now have no effect.

Now re-configure the circuit for data taking: set MODE switch on the oscilloscope to DUAL, set AC/DC back to AC, and reconnect the function generator. Make sure GND is unpressed. **Don't touch the offset control again**. (See section 3.3.1 for more information on the offset).

3.2.3 Data taking

Measure V_{in} and V_{out} on the oscilloscope for frequencies varying from 10 Hz to 1MHz. (In choosing frequency values, remember that you will be plotting the *logarithm* of the frequency). Remember to record the estimated uncertainties. The ratio of these two voltages gives the experimental gain G_{ex}:

$$G_{ex} = \frac{V_{out}}{V_{in}} \tag{7}$$

Q: *What happens to the V_{out} trace if you switch to DC mode on the oscilloscope and back again? Can you explain this?*

Q: *Values of 1 MΩ and 100 kΩ for R1 and 100 kΩ, 10 kΩ and 1 kΩ for R2 are printed on the circuit board. How precise do you think these values are? Can you check them?*

- Make sure you cover a sufficient range of frequencies.
- When taking voltage measurements, pay attention to the volts/division setting used and the changes in the uncertainty of your measurements.
- Take data for R1/R2 ≈ 1, 10, 100, 1000 (do 100 first), always recording the values of R1 and R2 used and why.
- You may need to change the input voltage (V_{in}); if you do, say what, when (which readings are affected), how, and why.
- Collect sufficient data to plot log G_{ex} against log f for different combinations of resistors. (A single log-log graph of 3 R1, R2 combinations.) Use log axes if possible. **Do *not* allow the computer to plot a line** unless you are able to work out the theoretical equation for the line and fit it (It is not a polynomial!) Anything else will produce an unphysical graph.

Q: *Is the gain constant over a range of frequencies?*

Q: *Is there any **significant** difference between the theoretical (G_{lf}) and measured (G_{ex}) values? Any ideas why? Remember that G_{lf} has an uncertainty, arising from* *uncertainites in the resistor values, and that G_{ex} also has an uncertainty; in assessing whether $|G_{lf}–G_{ex}|$ is significant, you will need to combine these uncertainties.*

3.3 Possible Problems:

You will probably encounter four main problems.

3.3.1 Input offset: Op-amps don't have perfectly balanced input stages, owing to manufacturing variations. If the two inputs are connected together for zero input signal, the output will usually reach the limits of either the positive or negative chip supply from the rails. The difference in input voltages needed to bring the output to zero is called the input offset voltage. Usually op-amps have a provision for adjusting (trimming) the offset voltage for zero output. This is available as a potentiometer marked 'offset adjust'.

You may need to use this offset if you notice flattening of the peaks or troughs of the sine wave. This is due to the extremes of the amplified voltage "hitting" the power supply rail of the op-amp. The amplified signal can't exceed this rail voltage and will therefore bottom out to give a clipped response. By adjusting the offset you can bring the amplified signal more uniformly between the power supply rails. If you have carried out the zeroing procedure at the beginning of the experiment (see section 3.2.2) the offset should not need to be adjusted again. If the output is still distorted after the zeroing procedure, it indicates that the amplifier is saturated (the amplified signal exceeds the rail voltage). You will need to reduce either the amplification or the voltage input signal.

3.3.2 Large gain: You will find that it is quite hard to generate and to measure the small-amplitude input signals that you will have to use when the gain is large. The op-amp is not a perfect device, and you may find that the output signal is contaminated by high frequency noise. There are ways to reduce this, but they are not considered in this experiment.

Q: *What effect does this have on the results?*

3.3.3 High frequencies: At high frequencies and high gains the op-amp becomes progressively less stable, and you may have problems in obtaining a reliable, noise-free output.

3.3.4 Low frequencies: It is quite hard visually to measure very low frequency signals (< ~10 Hz) using the oscilloscope.

Q: *Does this affect the procedure?*

4. Further Work

If you have time after completing the experiment, you may wish to try measuring the open-loop gain. Discuss with a demonstrator how you might modify the circuit in order to do this.

Remember to manage your time so that you can complete the experiment in the four sessions.

5. Discussion/Conclusions

Q: *How well does the measured gain match the theoretical gain?*
Q: *Where are the dominant sources of uncertainty?*
Q: *What can be done to reduce the uncertainty in the final result?*

6. Op-amps and their applications

This experiment has only dealt with one particular mode of operation of the op-amp but it has many other important applications. For example, an important use is in open loop mode, as a level discriminator (threshold detector). Discriminators are used widely in particle physics and spectroscopy, particularly in pulse counting and energy measurement (pulse height analysers). The op-amp's advantages include:

- Stand-alone amplifier in a neat integrated circuit package
- High input impedance (presents a low load, so can handle weak input signals)
- Low output impedance (can drive high-power load)
- Easy to use, rugged and cheap.

The op-amp lends itself very well for applications such as amplifiers in personal stereos, radios and even control circuits in some toasters.

Further questions for the curious:

Q: *If you did not have a gain that was independent of frequency, what would happen if the circuit were used to amplify music?*
Q: *If the gain is represented by (a) a horizontal line, or (b) a downward-sloping straight line of gradient –m, on a log-log plot, what is the relationship between the gain and the frequency in each case? What is your value for m?*
Q: *The output signal is referenced to the 0 volt rail, but you may notice that this rail is not actually connected to the chip. Electric currents (especially those strong enough to feed a high-power device such as a loudspeaker) need a return path. What is the return path for currents flowing through pin 6 of the 741?*
Hint: *Where must this current originally emanate from?*

The simple op-amp in this experiment only gives useful performance in the range 0 – 20 kHz; other op-amps are useful for amplification at frequencies over 100 MHz.

References

[1] Horowitz, P. and Hill, W. (2015), *The Art of Electronics*. 3rd ed. Cambridge University Press