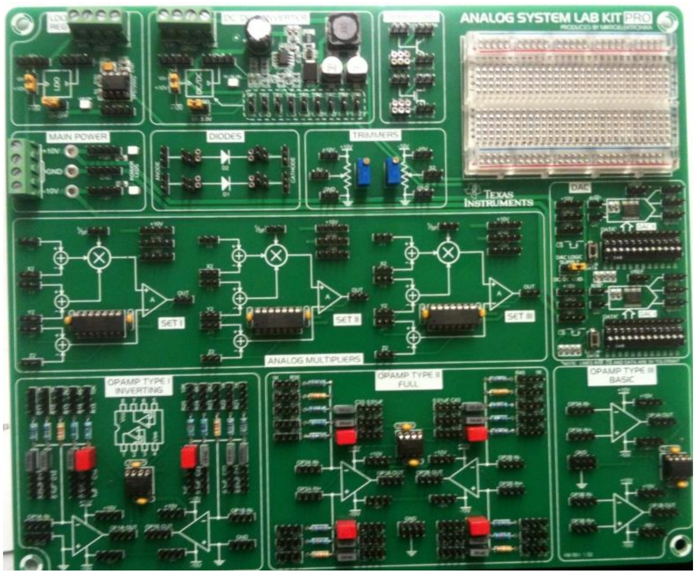
T9

Operational Amplifiers

In this lab you will investigate the use of a standard operational amplifier (op-amp) and investigate its frequency limitations. You will construct a basic op-amp amplifier and see how it compares to its predicted ideal performance. In addition you will investigate an adder circuit. The final part involves comparing the TL081 op-amp with the older 741 device to see how things have improved.



This lab uses the ASLK PRO kits, which have been kindly donated to ECS by Texas Instruments.

Schedule

Preparation time	:	3 hours
Lab time	:	3 hours

Items provided

Tools	:	
Components	:	741 op-amp
Equipment	:	Oscilloscope, Signal Generator, Bench PSU, Multimeter, Texas Instruments ASLK Pro kit.
Software	:	A circuit simulator, eg LTSpice, for preparation

Items to bring

Essentials. A full list is available on the Laboratory website at https://secure.ecs.soton.ac.uk/notes/ellabs/databook/essentials/

Before you come to the lab, it is essential that you read through this document and complete ***all*** of the preparation work in section 2. If possible, prepare for the lab with your usual lab partner. Only preparation which is recorded in your laboratory logbook will contribute towards your mark for this exercise. There is no objection to several students working together on preparation, as long as all understand the results of that work. Before starting your preparation, read through all sections of these notes so that you are fully aware of what you will have to do in the lab.

Academic Integrity – *If you undertake the preparation jointly with other students, it is important that you acknowledge this fact in your logbook. Similarly, you may want to use sources from the internet or books to help answer some of the questions. Again, record any sources in your logbook.*

Revision History

September 04, 2013	Nick R. Harris (nrh)	Minor updates
January 30, 2013	Nick R. Harris (nrh)	Lab created, based upon previous B5 lab

1 Aims, Learning Outcomes and Outline

This exercise aims to:

- Provide you with an introduction to the linear application of operational amplifiers
- Give you experience of the use of data sheets to identify important differences between different op-amps
- Give you practical experience of using op-amps.

Having successfully completed the lab, you will be able to:

- understand what is meant by linear operation
- demonstrate an understanding of what is required to successfully utilise an op-amp
- design a basic inverting amplifier, and appreciate the operation of the analogue adding circuit

In this lab you will use the data sheet of an operational amplifier to gain some practical insight into the behaviour of the device. You then build and investigate two different linear operational amplifier circuits: an inverting amplifier and an analog adder.

---

2 Preparation

Read through the course handbook statement on safety and safe working practices, and your copy of the standard operating procedure. Make sure that you understand how to work safely. Read through this document so you are aware of what you will be expected to do in the lab.

2.1 Operational Amplifiers

Read this sub-section carefully, and be sure you understand what an operational amplifier is and how it is used in the simple linear circuits of this exercise.

The operational amplifier (op-amp) is essentially a high-gain, directly-coupled linear amplifier. In many respects practical op-amp devices can be regarded as ideal, and the exercise concentrates on this, and does not explore practical limitations other than frequency response.

The device has two input terminals to which voltages v_- and v_+ are applied, and one output terminal at which v_o is produced. The conventional symbol for the op-amp is shown in Figure 1 together with its ideal equivalent circuit model. Note that power supply connections are not relevant to the model and hence are not normally shown.

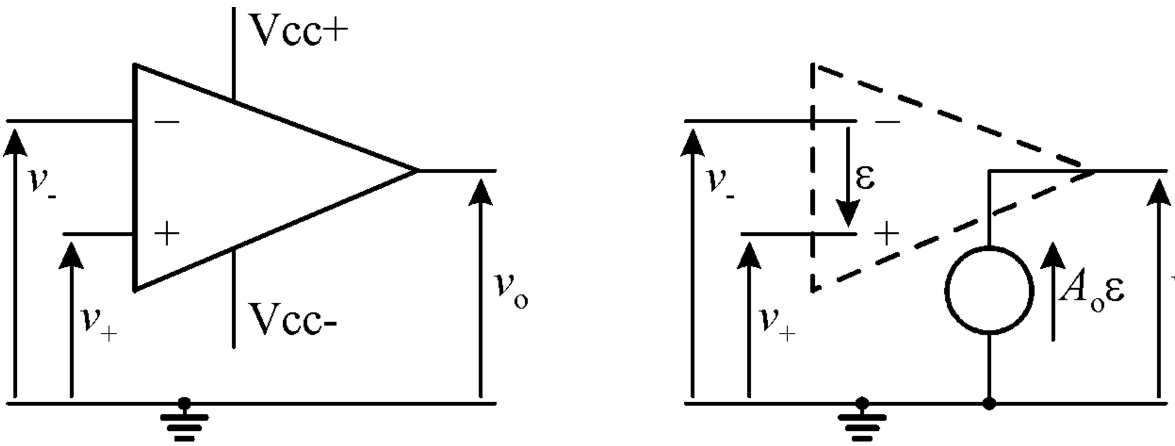


FIGURE 1. Op-amp symbol and ideal equivalent circuit.

The device acts as a *differential* amplifier, producing an output voltage which is proportional to the *difference* between the two input voltages:

$$v_o = A_o(v_+ - v_-) \tag{1}$$

Note that A_0 is the **open loop** gain of the amplifier and is very high, usually in excess of 100,000. Feedback is used to reduce the gain to more sensible levels. The equivalent circuit in Figure 1 and its description by equation (1) are simplistic but give a good idea of performance at low frequencies. A more complete equivalent circuit contains a resistor and capacitor in the output circuit (Figure 2) to model behaviour at higher frequencies. Analysis of this circuit reveals that

$$v_o = -\frac{A_o}{1 + j\omega CR}(v_+ - v_-)$$

If we now make a substitution of f for ω remembering that $\omega = 2\pi f$, and also define the cut off frequency as:

$$f_o = \frac{1}{2\pi CR}$$

then: $v_o = -\dfrac{A_o}{1 + \dfrac{jf}{f_o}}(v_+ - v_-)$,

or alternatively:

$$v_0 = -\frac{A_o}{1 + j\omega/\omega_o}(v_+ - v_-) \text{ where } \omega_o = \frac{1}{CR} = 2\pi f_o \tag{2}$$

So you can have it defined in either f or ω depending on what you prefer!

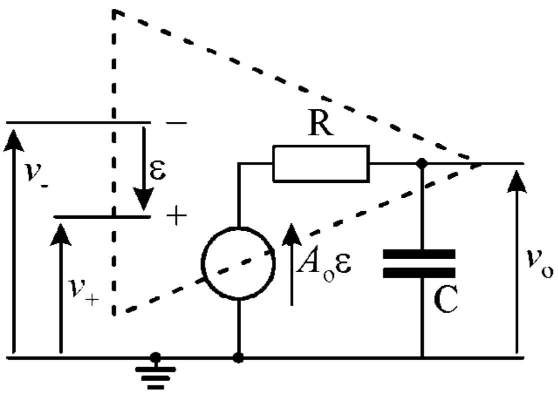


FIGURE 2. Improved op-amp equivalent circuit.

The output voltage thus depends on the frequency of the input voltage $\varepsilon = (v_+ - v_-)$ according to equation (2). Above frequency f_0, the relative amplitude of the output drops by 20dB (voltage drops by a factor of 10) for every tenfold (decade) increase in frequency. This characteristic may be described by the voltage transfer function

$$A(j\omega) = \frac{A_o}{1 + j\omega/\omega_o} \qquad \omega_o = \frac{1}{CR} = 2\pi f_o$$

Thus

$$v_0 = A(j\omega)(v_+ - v_-)$$

Compared with the ideal equation

$$v_o = A_o(v_+ - v_-)$$

Note the introduction of A(jω) which is frequency dependant. f_o (or ω_o) is called the breakpoint (or, sometimes, turnover) frequency — the frequency at which the gain starts to drop from its low frequency value of A_o. You may recognise this as a **low-pass** response, so you should expect the op-amp performance to reduce at high frequencies.

In the circuits demonstrated in this exercise, the op-amp will be assumed to be **ideal** and have infinite input impedance and zero output impedance. No op-amp achieves these ideals and in many circuit designs some account must be taken of the non-ideal behaviour.

Using the Figure 1 equivalent circuit for the operational amplifier and equation (1), derive equation (3) for the circuit of Figure 3.

The exercise uses the TL081. It is a good basic op-amp. On the TI demo boards you will find TL082 op-amps fitted. These are the same as TL081 devices, except that each chip package contains 2 op-amps. It is possible to buy packages that have 4 op-amps inside (TL084), which can allow space saving designs.

2.2 Op-Amp Circuits

Either do the following work directly in your logbook or, as appropriate, on a computer package such as Excel and stick it in your logbook. Do not use scrap paper.

Using op-amp datasheets, compare the 1970s' 741 with the more recent TL081, and also with the TS954.

What are the features that have been improved in your opinion? Justify your answers with a reason why you think the features are important.

Using a mathematics reference text or by searching on the internet, look up the standard algebraic trigonometrical conversions. Use this information to convert the expression sin(A) + sin(B) into an expression involving A+B and A-B.

Work out what the output signal of Figure 4 will be if the input signals are $\sin(\omega t)$ and $\sin((\omega+60\pi)t)$.

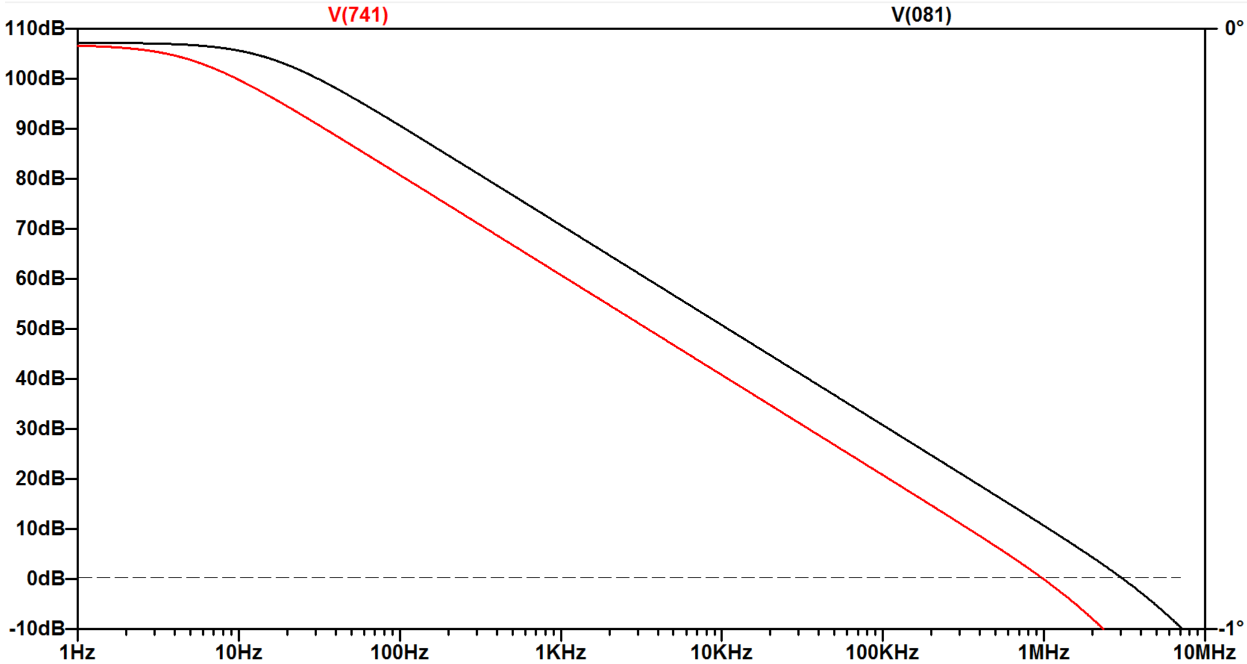
Hence describe and sketch what the output signal of Figure 4 will look like:

a) if the input signals are sine waves of equal amplitude, one being of frequency 300Hz, the other of frequency 330Hz

b) if one signal is a sine wave of amplitude 2V p-p and frequency 3kHz, the other is a square wave of amplitude 2V and frequency 300Hz.

Check this by using a simulator such as LTSpice and put example waveforms in your logbook. As standard LTSpice has many op-amps from the company Linear in its standard library, you can choose one of these op-amps but make sure it is a general purpose op-amp, by checking its data sheet on the web. Alternatively you can find downloadable models of the TL081 on the web, but you will have to find out how to import them into LTSpice (a useful skill to develop!). It is left to the reader to work out how to do this.

Below is a representation of the "Open-Loop Large-Signal Differential Voltage Amplification vs Frequency" graph for both the 741 and 081 Op-amps. Note that this shows intrinsic open-loop gain A_o and breakpoint frequency f_o.



This can be drawn using straight line approximations and notice that there is a logarithmic gain axis in decibels, where voltage gain in dB = $20\mathit{log}|v_o/v_{in}|$), and a logarithmic frequency axis scaled from 1Hz to 10MHz.

A graph of this type is known as a Bode plot, and the frequency response for the op amp alone (ie in the absence of feedback elements) is known as the **open-loop** frequency response.

Note: Take a copy of this graph and stick it in your log book. You will use it later to plot experimental results on.

Unity gain is the frequency at which the gain is 1 (0dB). What are the unity gain frequencies for each amplifier? Label these on your graph

Find datasheets online for the TL081 and the UA741 amplifiers. Find the manufacturers values for the unity gain frequencies. Are they the same as the values obtained from the graph?

3 Laboratory Work

The op-amp is utilised in simple circuits by connecting appropriate linear impedances to the input terminals and between the output and input terminals. These impedances are known as input and feedback impedances respectively. The simplest such configuration, formed by connecting resistors in the input and feedback paths, as shown in Figure 3, results in an inverting amplifier. We are going to use the TI experimenter board and you should connect +/-10V supplies to the board. Note the very important point that the centre connection of the power supplies becomes the voltage reference node (ground) of the circuit. Do not let your power supplies "float".

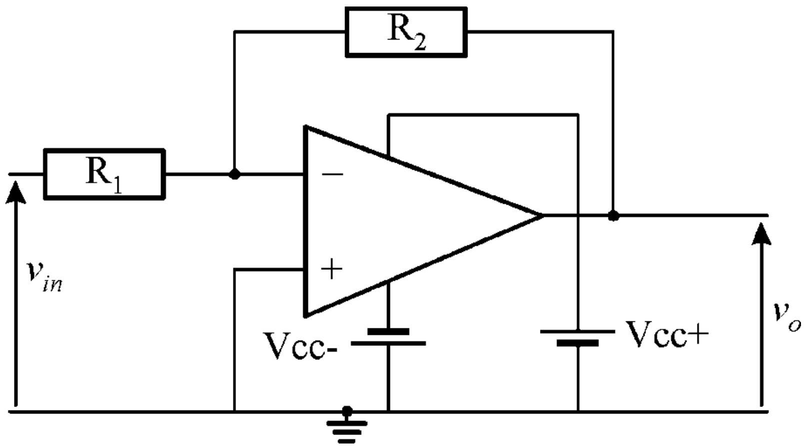


FIGURE 3 The Inverting Amplifier

The gain of this circuit is given by:

$$\frac{v_o}{v_{in}} = -\frac{R_2}{R_1\left(1 + \frac{R_1 + R_2}{AR_1}\right)} \qquad (3)$$

The input resistance is approximately R_1 (if v_o is finite, and A is large, the voltage on the inverting input is approximately zero).

If A » 1, the gain of the circuit determined by (3) simplifies to $-R_2/R_1$

3.1 Preliminary Investigations

Connect up the circuit in Figure 3 with $R_1 = 10\text{k}\Omega$ and $R_2 = 100\text{k}\Omega$, and apply a sine wave to v_{in} with a peak-peak amplitude of approximately 1V and a frequency of around 300Hz. Hint: There are several op-amps fitted to the board. Choose a suitable configuration! Use the XY facility on the oscilloscope to display the transfer characteristic (v_o vertical against v_{in} horizontal), and record it in your laboratory logbook.

Determine the slope of the transfer characteristic and compare this with the predicted value of circuit gain.

What is the slope you have measured, and how does this relate to the gain? What is the gain?

Switch your oscilloscope to YT mode and measure the gain by comparing the amplitude of the input and output traces. It should be the same as seen in the previous section.

What is the gain you have measured

Switch back to XY mode and increase the amplitude of the input until the transfer characteristic is no longer a simple straight line, and sketch this characteristic in your lab book.

Without changing the input amplitude, put the oscilloscope back into conventional YT (amplitude vs time) mode to observe and sketch the input and output waveforms as voltage functions of time.

Explain the shapes of the transfer characteristic and the corresponding output waveform for large input amplitudes where the transfer characteristic is not a simple straight line.

3.2 More Complex Operation

Using a small-amplitude sine wave (eg 0.1V p-p at the input), and with the oscilloscope in YT mode, measure the voltage gain of the inverting amplifier over a range of frequencies. Plot the voltage gain against frequency on the log/log graph of open-loop frequency response prepared in section 2.3 (do not produce a new graph!) Make sure that the output signal is a sine wave and does not become distorted, clipped (top and/or bottom) or triangular. If the output shows any of these shapes, reduce the amplitude of the input signal until the output becomes sinusoidal, take new measurements and recalculate the gain.

From your experimental results, suggest a relationship between gain and bandwidth (breakpoint frequency) for an amplifier with feedback.

Try changing the value of R_1 to 1kΩ and see if the changes to the gain / frequency plot bear out your hypothesis.

Does it bear out your hypothesis?

3.3 The Analogue Adder

In the linear mode of operation with negative feedback, op-amps may be used to perform arithmetic operations on voltages such as addition, subtraction, multiplication by a constant etc. Such circuits are needed in an audio mixer, for example, to add together audio signals from different sources.

A simple circuit to add two signals is shown in Figure 4.

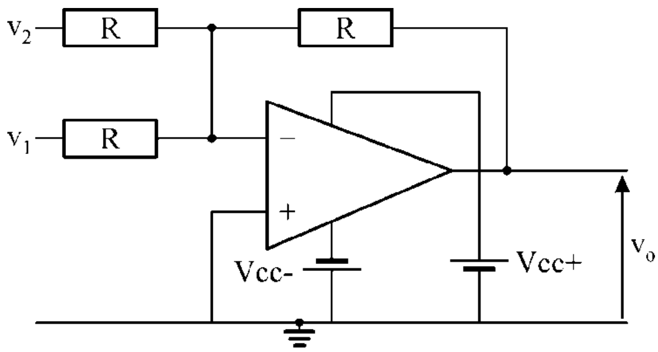


FIGURE 4. An analogue adder.

What is a suitable value for your chosen resistance R?

Build this circuit, using the value for R determined above and with +10V/0V/-10V supplies as before. With no connection to v_2, the circuit should be a unity-gain inverter (v_o relative to v_1). Verify this using a sinusoidal v_1 signal of around 4V peak-to-peak amplitude and around 300Hz frequency.

Now connect a second signal source to the v_2 input. Examine the output v_o on the oscilloscope and verify that the signals are being added together arithmetically. Depending on the choice of signal sources, it may be difficult to obtain a stable and useful oscilloscope display. Careful use of the timebase trigger controls may improve this situation. Sketch at least one oscilloscope display showing the the output waveform. Annotate this sketch with information about the signals being added to produce it.

How do your experimental results compare with those you predicted in the preparation?

4 Optional Additional Work

Marks will only be awarded for this section if you have already completed all of Section 3 to an excellent standard and with excellent understanding.

Repeat the frequency response experiment as described in section 3.2 with the TL081 replaced by a 741 op-amp from the laboratory component drawers. This op-amp can be used in the prototyping area on the TI experimenter board, so you will need to connect power supplies, and resistors manually. Plot the response on the graph you prepared earlier.

- How does the experimental frequency response of the 741 compare with that of the TL081?

- How does it compare with the predicted response from the datasheet?