Experiment 5 - Design of an Operational Amplifier Using PSpice

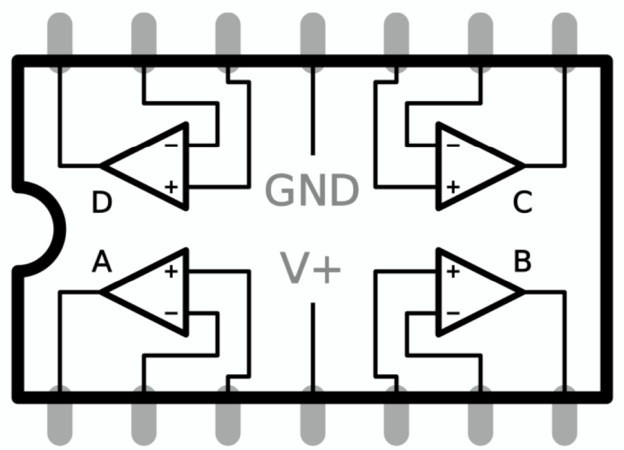
Department of Electrical Engineering & Electronics

September 2019, Ver. 4.1

Experiment specifications

Module(s)	ELEC271
Experiment code	5
Semester	2
Level	2
Lab location	Computer lab, third floor
Work	In Groups
Timetabled time	7 hrs
Subject(s) of relevance	Transistor Circuits, Differential/Operational Amplifiers
Assessment method	• Pre-lab test (5% of module mark) • Formal report, using the report template (20% of module mark)
Submission deadline	On Friday midnight, 7 days after the date of the laboratory, submitted in Microsoft Word or PDF format via VITAL only.

Important: Marking of all coursework is anonymous. Do not include your name, student ID number, group number, email or any other personal information in your report or in the name of the file submitted via VITAL. A penalty will be applied to submissions that do not meet this requirement.



Instructions:

- **The Pre-Lab Questions must be answered before the lab day (deadline is 9am). They are available on VITAL-ELEC273/222 Modules (Online)**
- **This is a design experiment. You are expected to do work and self-study before the lab day. Read this script before attempting the experiment. Prepare the design before attending the lab to save time.**
- **Review PSpice software before attempting the experiment. Check VITAL for PSpice resources (Learning Resources→Supporting Material folder). See online material and resources as well.**
- **As you complete each part of the experiment, ensure that your results and calculations are viewed and approved by one of the demonstrators before proceeding.**
- **Keep a record of all schematics and results.**
- **Refer to the hints and guidance given in the lectures of Module ELEC271 whenever needed during the lab. Bring the lecture notes to the lab with you.**
- **Use the report template (available on VITAL) to write your formal report after the lab.**
- **If you have any feedback on your laboratory experience for today, please write it down in the last page of this script.**

1 Learning outcomes

At the end of this lab, you will:

- be able to produce a functioning operational amplifier circuit by combining different stages.
- be aware of problems and challenges to meet a specification for designing and characterising an operational amplifier.

2 Objectives

It is required to design an operational amplifier with the aid of PSpice software to satisfy the following design specifications:

a) Differential input impedance greater than 100 kΩ.
b) Voltage gain (that is, 'open loop gain') greater than 500,000.
c) Output impedance less than 1 kΩ.
d) Output voltage to be approximately zero volts for zero input.
e) Frequency response down to DC (0 Hz).
f) Supply voltage +9 to -9 volts.
g) Total current consumption not greater than 5 mA.

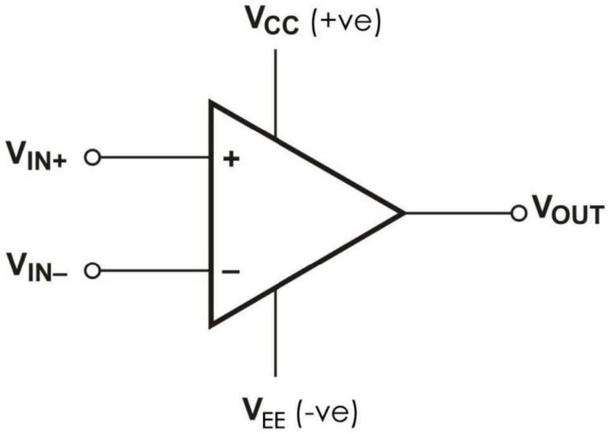
3 Introduction

This experiment requires you to **design** and **simulate** an operational amplifier circuit. A practical integrated circuit version (e.g. a 741 type) would in addition contain a 'push pull' output stage and extra components to provide further temperature and supply variation immunity.

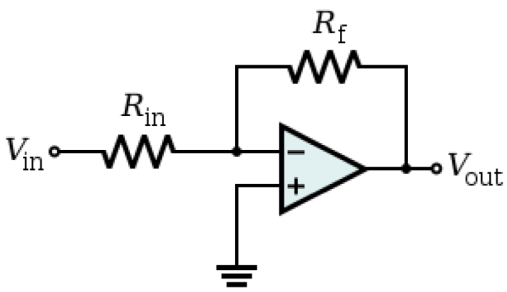
Other circuit complications arise due to problems integrating NPN and PNP high gain transistors together on the same chip. The experiment is intended to reinforce lecture material in module **ELEC271**, and reference to the relevant lecture notes is essential.

3.1 Operational amplifier

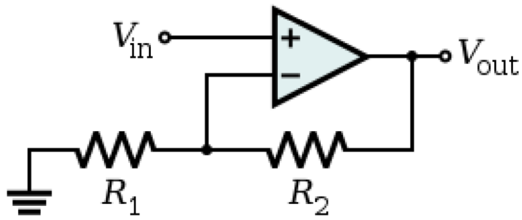
An operational amplifier (op-amp) is a high-gain voltage amplifier with a differential input and a single-ended output (Figure 1 (a)). It is among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific devices, with very low cost. The op-amps had their origins in analogue computers where they were used in many linear, non-linear and frequency-dependent circuits. Their popularity in circuit design largely stems from the fact that characteristics of the op-amp circuits with negative feedback (such as their gain) are set by external components with little dependence on temperature changes and manufacturing variations in the op-amp itself. Examples of op-amp circuits are shown in Figure 1 (b) and (c).



(a) Op-amp symbol



(b) Inverting amplifier circuit (Gain=-R_f/R_{in})



(c) Non-inverting amplifier circuit (Gain=1+(R_2/R_1))

Figure 1. Operational amplifier and circuit applications

The op-amp is one type of a differential amplifier. Other types of differential amplifiers include the fully differential amplifier (similar to the op-amp, but with two outputs), the instrumentation amplifier (usually built from three op-amps), the isolation amplifier (similar to the instrumentation amplifier, but with added tolerance to common-mode voltages that would destroy an ordinary op-amp), and negative feedback amplifier (usually built from one or more op-amps and a resistive feedback network).

3.2 The design

The op-amp you are required to design can be constructed from four basic 'building block' circuits:

a) An emitter follower
b) A common emitter amplifier

c) A current mirror circuit
d) A differential input stage (long-tailed pair)

The designed operational amplifier schematic will be simulated using PSpice software library models located in the EVAL library using the following devices:

- Q2N2222 NPN transistor
- Q2N2907 PNP transistor

The output from your differential amplifier should be fed into the input of the common emitter stage. It is also necessary to include an emitter follower circuit as a buffer between the two amplifier stagers. Figure 2 shows a block diagram of the op-amp.

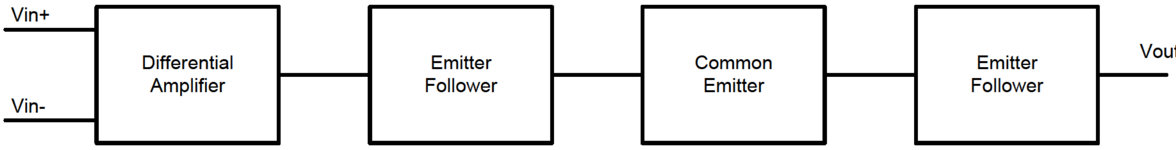


Figure 2. Block diagram of the op-amp

The properties of these blocks should have been investigated and design procedures established in the exercise 'Pre-lab Test for Experiment 5'. **It is essential that this is done before commencing.**

4 Experimental work

4.1 Part I: Transistor output characteristics

Objective: To obtain a set of output characteristics for the two transistor types to be used in this experiment.

Obtain a plot of the output characteristics of the 2N222 transistor, i.e. I_C vs. V_{CE} (0 to 20 V in steps of 0.5 V) for a range of I_B (0 to 40 µA in steps of 4 µA).

Procedure:

- **Task-1:** Input the circuit schematic of Figure 3 in PSpice schematics.
- **Task-2:** In the 'Analysis' menu, select 'Setup..' and check the 'DC sweep' option and input the variable as 'V_{CE}' with the desired range. Click on 'Nested

sweep' option to set the base current I_B steps. Thus, for each value of I_B (0, 4, 8.....40 µA), V_{CE} is swept from 0 to 20 V.

- **Task-3:** Close the 'Analysis setup' window. In the 'Analysis' menu, select 'Simulate' (you can do that by pressing on F11 key as well). A response curve will appear. Take a screenshot of this response.
- **Task-4:** From the curve, estimate the DC current gain, β (also known as h_{FE}) at I_C~2 mA. Estimate also the AC (small signal) current gain, β_0(also known as h_{fe}). **Hint:** see your notes on how to do this. Record your results.

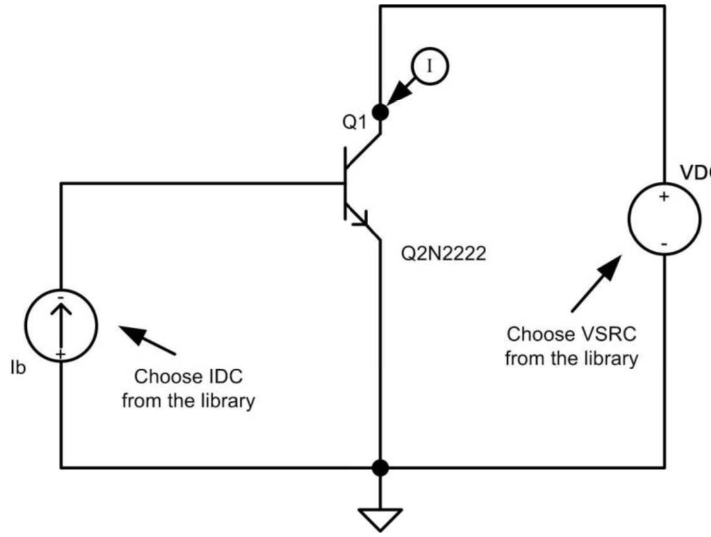


Figure 3. Schematic of Part I.

4.2 Part II: Achieving the specification of the operational amplifier

Objective: To build the complete operational amplifier circuit and obtain the required specification.

Start now building the complete circuit of the operational amplifier (see the given 'tutorial' lecture for ELEC271 on VITAL).

Procedure:

- **Task-1:** Combine the required stages to build a complete operational amplifier in PSpice. **Hint:** Match the differential amplifier and common emitter stages with an emitter follower stage, make the $R_{in}^{EF} \sim 10R_{out}^{DA}$.
- **Task-2:** Obtain the transfer characteristics of your amplifier by grounding one input and performing a DC sweep from -9V to +9V on the other input. Identify

the useful operating range from your plot. You will need to narrow the sweep range to achieve an accurate useful range.

- **Task-3:** Find the open loop gain (A_{ol}) of the amplifier from the useful range in the above step.
- **Task-4:** Determine the required DC voltage offset from the transfer characteristic. Use this value to help balance the amplifier - you can apply a small DC offset to one of the inputs to try to centre the output close to zero volts. **Hint:** Alternatively, you could use the technique mentioned in the lecture notes to obtain A_{ol} which would also give you the DC offset.
- **Task-5:** Obtain a set of input/output waveforms (in useful range) from a transient simulation, and from which, calculate the gain of the amplifier. Verify that the specification has been met. Record your results.
- **Task-6:** Obtain a set of input waveforms (in useful range) in an AC sweep simulation, add an input impedance trace and calculate the average value of it. Change the trace and calculate the average output impedance. **Hint:** The screenshots of the corresponding impedance (V/I) should be taken – the impedance values can be found in the bandwidth.
- **Task-7:** Display the currents and voltages on the schematic and watch out the DC voltage levels and total current consumption.

4.3 Part III: Obtaining the frequency response of the designed amplifier

Objective: To obtain the gain and phase Bode plots of the designed amplifier.

Now, obtain the frequency response of the designed amplifier by determining the gain and phase Bode plots.

Procedure:

- **Task-1:** Determine Bode plots (gain and phase) of your amplifier by replacing the VSIN input sources with VAC parts in PSpice and run an AC sweep. The parameters of the VAC part should be set to match those used in your VSIN part. Take screenshots of the Bode plots. **Hint:** The function DB(-) and P(-) may be used for the plots.
- **Task-2:** Add phase compensating capacitor (say 30 pF or any suitable value) between the collector of the common emitter stage and the base of the first emitter follower. Investigate the effect on the Bode plots. Take screenshots and record your findings.

4.4 Bonus Part: Response to common-mode signal

Investigate the response of your amplifier to common-mode signals.

5 General questions

a) What can you deduce about the stability of your amplifier from the Bode plots in Part III?

b) What is the purpose of the 'Phase compensating capacitor'?

6 Report writing guidelines for Experiment 5

- This experiment is assessed by means of a formal report. Use the formal report template (available on VITAL) to write your report. The idea behind this report is to document your experience and technical findings in this experiment.
- In your 'Results' section, include the following:
  - All your findings and measurements along with all the screenshots of schematics and simulations. **Make sure to comment on each result and simulation.**
  - The table shown overleaf (Table I) with your own results. **Make sure to write relevant comments in the fourth column.**
- In your 'Discussions and Conclusions' section include the following:
  - Describe any problems you have experienced while carrying out both experiments and explain your problem-solving methods that you have followed.
  - Include the answers to the general questions (Section 5 above).
  - Does your designed op-amp achieve the specification? If not, explain the reasons.
- **Important:** Make sure that all of your figures (schematics and simulations) are **clear** and all the numbers on the figures are **readable**.

Table I. Design specifications table

Parameter	**Specification**	**Your value**	**Comment on the value obtained**
Differential input impedance	> 100 k		
Open loop voltage gain	> 500,000		
Output impedance	< 1 k		
DC output voltage	~0 V		
DC offset voltage	None given		
Frequency response	Down to DC (0 Hz)		
Total current consumption	< 5 mA		
Bandwidth with compensation capacitor	None given		

7 Report marking scheme

The report is worth 20% of the ELEC271 final mark. The report will be first marked out of 100% (this is the mark you will see in VITAL) and then the mark will be scaled to 20% to produce the contribution to the ELEC271 final mark.

The report marking scheme is as follows:

- Results of Part II (calculations, schematics, screenshots, etc.) with explanation and comments: **35 Marks**
- Results of Part III (calculations, schematics, screenshots, etc.) with explanation and comments: **10 Marks**
- The design specifications table with comments: **24 Marks**
- Discussions and Conclusions section (including answers to the general questions of Section 5): **26 Marks**
- Overall report presentation: **5 Marks**

Note: High marks require **very good** comments and explanations.

8 Plagiarism and Collusion

Plagiarism and collusion or fabrication of data is always treated seriously, and action appropriate to the circumstances is always taken. The procedure followed by the University in all cases where plagiarism, collusion or fabrication is suspected is detailed in the University's Policy for Dealing with Plagiarism, Collusion and Fabrication of Data, Code of Practice on Assessment, Category C, available on http://www.liv.ac.uk/tqsd/pol_strat_cop/cop_assess/appendix_L_cop_assess.pdf.

Follow the following guidelines to avoid any problems:

a) Do your work yourself.
b) Acknowledge all your sources.
c) Present your results as they are.
d) Restrict access to your work.

References

[1] S Hall, Lecture notes-Module ELEC271, 2015.

Version history:

Name	Date	Version
Dr M López-Benítez	September 2019	Ver. 4.1
A Al-Ataby	February 2015	Ver. 4.0
A Al-Ataby	February 2014	Ver. 3.2
A Al-Ataby	February 2013	Ver. 3.1
A Al-Ataby	March 2012	Ver. 3.0
S Hall	September 2011	Ver. 2.2
S Hall	March 2011	Ver. 2.1
T Dowrick/S Hall	December 2009	Ver. 2.0
T Dowrick/S Hall	August 2008	Ver. 1.0

Feedback:

If you have any feedback on your laboratory experience for this experiment (e.g. timing, difficulty, clarity of script, demonstration...etc) and suggestions to how the experiment may be improved in the future, please write them down in the space below. This feedback is important for future versions of this script and to enhance the laboratory process, and will not be assessed. If you wish to provide this feedback anonymously, you may do so by detaching this page and submitting it to the Student Support Centre (fifth floor office).

Script re-writing award
If you think that this experiment could do with enhancement or changes and you have some ideas that you'd like to share, why not re-write this script yourself and you may get an award from the lab organisers with an official letter of thanks, and your name will be added to the version history list in future versions of the script. Something good for your CV.
Contact one of the lab organisers for more details.