Feedback Cover Sheet

Complete at least one item and up to three items in each section

Section One

Reflecting on the feedback that I have received on previous lab reports, the following issues/topics have been identified as areas for improvement:

1. It is suggested to put the figure notations at the bottom of each figure.
2. It would be better that the introduction could provide the reader with a preview of the report structure.
3.

Section Two

In this assignment, I have attempted to act on previous feedback in the following ways:

1. I put the figure notations at the bottom of each figure.
2. I wrote a preview of the report structure in the introduction.
3.

Section Three

Feedback on the following aspects of this assignment (i.e. content/style/approach) would be particularly helpful to me:

1. The way equations should be numbered, do I need to number the equations that are not mentioned in the main text?
2. What software package is suitable for sketching circuits?
3.

EE2B Lab Report

Yang Li 1962731

You must complete this checklist. Otherwise, your report will not be marked.

- All members of the group have made contribution to the laboratory work and this report. NA
- The report is written in my own words with data taken and graphs drawn by myself. No material has been copied from the lab sheet or elsewhere without proper reference. Yes
- The report is produced using Word processors without any handwritten content unless otherwise stated. Yes

Abstract

This lab report consists of 4 parts. Lab 1 consists of the design and test of an asymmetric Schmitt trigger; the constructed circuit's switching thresholds' most significant error margin from the designed value is +0.212 V, which is acceptable. Lab 2 used the knowledge on Gauss' Law and capacitors to calculate the value of the permittivity of free space experimentally, and the calculated value is 2.279×10^{-12} $m^{-3}kg^{-1}s^4A^2$ smaller than the standard value. However, as they are in the same order, it is a good result. Lab 3 in this report is only written to prove an equation about the current gain. It is intuitive to derive knowing that $\beta = \frac{I_c}{I_b}$. Lastly, lab 4 has two parts: theoretical two-stage amplifier gain calculation and comparison between a two-stage amplifier with feedback, one without feedback and an equivalent op-amp. The calculated gain is -296, the response of the two-stage amplifier without the feedback loop is less linear than the other two, and the two-stage amplifier with feedback has a larger bandwidth.

Introduction

Four experiments were conducted throughout the semester to practice the construction and behaviour of circuits consisting of an op-amp, capacitor, and two-stage amplifiers. 4 experiments were conducted throughout the semester. This report is like an uncompleted jigsaw of those experiments – only segments of those experiments are reported in the following text.

1. Lab 1

1.1. Pre-lab workout

This experiment aims to design and test an asymmetric Schmitt trigger with threshold levels of +2 V and +1 V. The first step was to draw a circuit diagram for the trigger. The general drawing from the lecture slides is shown in Figure 1 below.

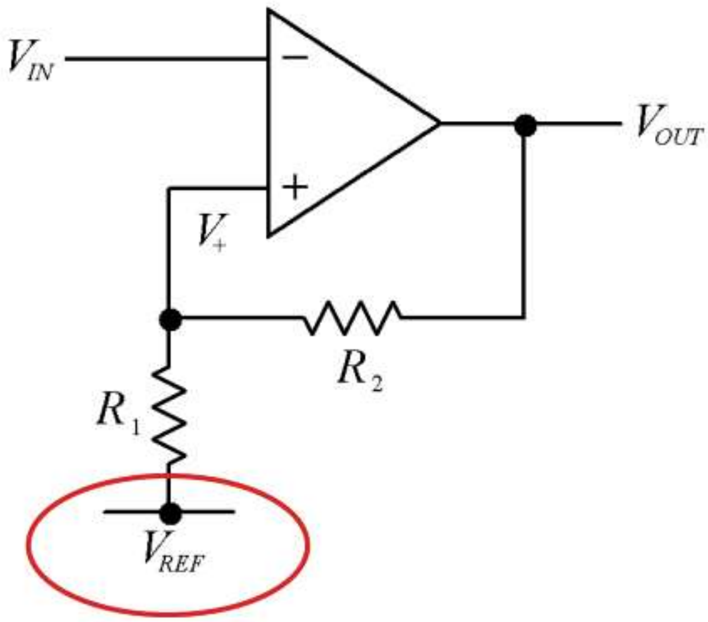

Figure 1. General Construction of an Asymmetric Schmitt Trigger

The V_{REF} circled in red partly determines the threshold voltage of the trigger, which was calculated in the second step along with the magnitudes of the resistors – R_1 and R_2. The calculation is demonstrated as follows:

$$V_{THRESH} = \pm V_{SAT}\frac{R_1}{R_1 + R_2} + V_{REF}\frac{R_2}{R_1 + R_2} \qquad (Eq. 1)$$

From the datasheet of the LM741 operational amplifier [1], the typical saturation voltage V_{SAT} of the op-amp is ±13 V with a load resistance between 2 kΩ and 10 kΩ. However, when the load resistance is more significant than 10 kΩ, V_{SAT} goes up to ±14 V. As the load resistance is unknown in this experiment, the average value of ±13.5 V was taken. With the upper and lower limit of V_{THRESH} known, two equations were obtained:

$$\begin{cases} 1 = -13.5\dfrac{R_1}{R_1+R_2} + V_{REF}\dfrac{R_2}{R_1 + R_2} & (Eq. 2) \\ 2 = 13.5\dfrac{R_1}{R_1 + R_2} + V_{REF}\dfrac{R_2}{R_1 + R_2} & (Eq. 3) \end{cases}$$

After subtracting Eq. 2 from Eq. 3, a relationship between R_1 and R_2 was obtained:

$$R_2 = 26R_1 \qquad (Eq. 4)$$

A thought experiment was conducted to choose R_1 and R_2, with the constraint of available resistor values listed in the lab sheet [2]. In the end, the decision was:

$$\begin{cases} R_1 = 1.5\ k\Omega \\ R_2 = 39\ k\Omega \end{cases}$$

Substituting the above resistor values into Eq. 2 or Eq. 3, the value of V_{REF} was calculated:

$$V_{REF} = \frac{81}{52}V$$

However, as this is a unique value, a regular power supply cannot supply this voltage. Therefore, Thevenin's theorem was used to derive an equivalent circuit for V_{REF} and R_1, as shown in Figure 2.

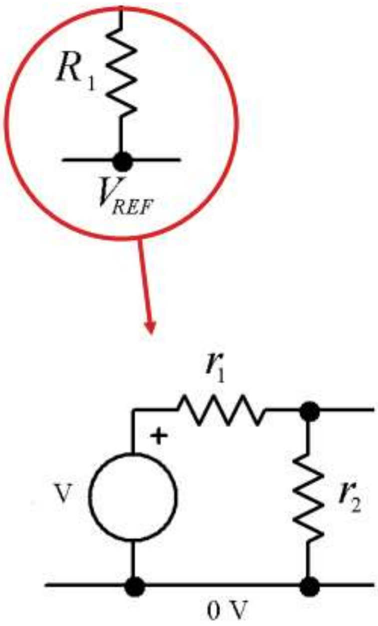

Figure 2. Thevenin's Equivalent (bottom) Circuit for V_{REF} and R_1

The power supply that was selected was 15 V. The calculations for approximated r_1 and r_2 are shown below:

$$I_{S/C} = \frac{V_{REF}}{R_1} = \frac{\frac{81}{52}}{1.5k}\ A = \frac{15\ V}{r_1} \to r_1 = 14.4\ k\Omega$$

$$V_{O/C} = V_{REF} = \frac{81}{52}\ V = 15\frac{r_2}{2.7\ k\Omega + r_2} \to r_2 = 1.8\ k\Omega$$

These values were approximated because they can be realised by connecting the available resistors specified in the lab sheet [2]. With all the parameters set, a detailed circuit diagram for the trigger was constructed in Multisim, as shown in Figure 3 on the next page.

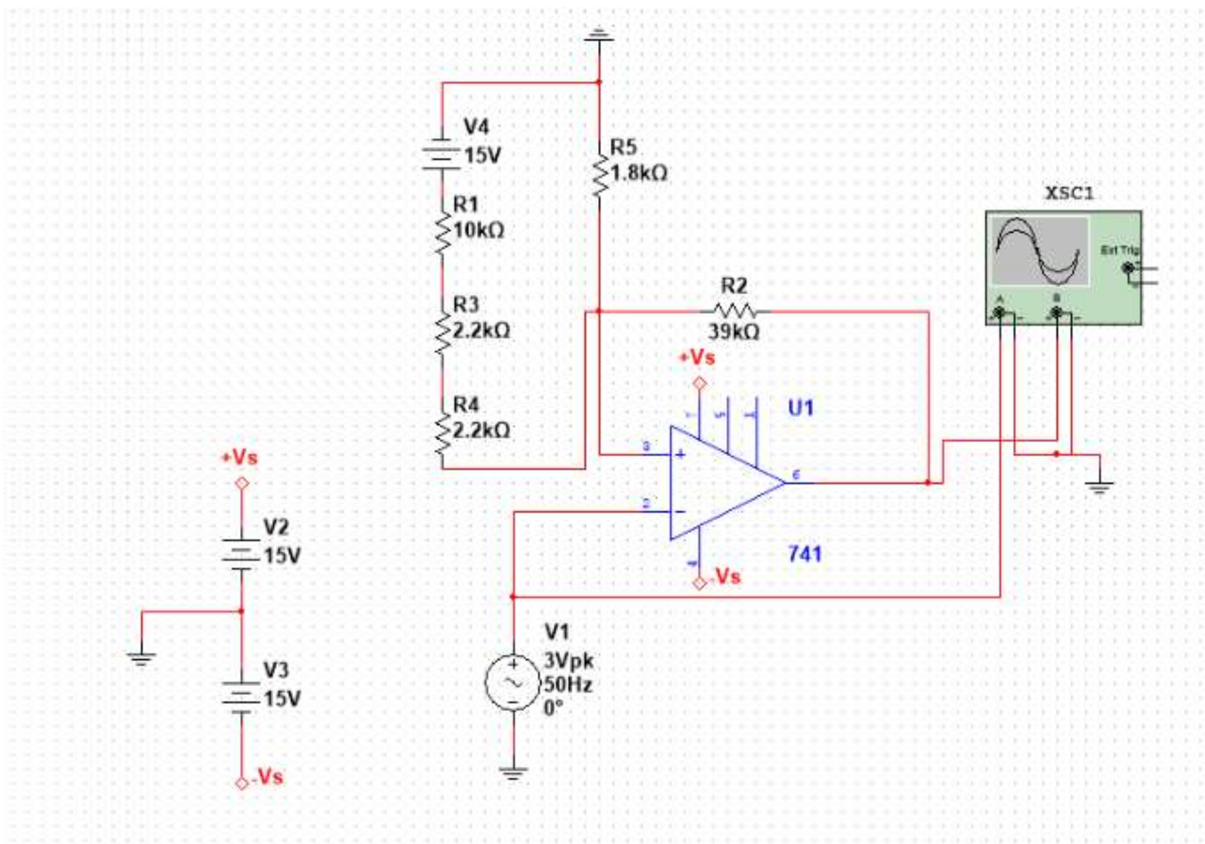

Figure 3. Detailed Asymmetric Schmidt Trigger Design in Multisim

1.2 Results and discussion

The first measurement performed was using Channel A of the oscilloscope to measure the inverting input of the op-amp and Channel B for the output. A screenshot of the oscilloscope display is included in Figure 4.

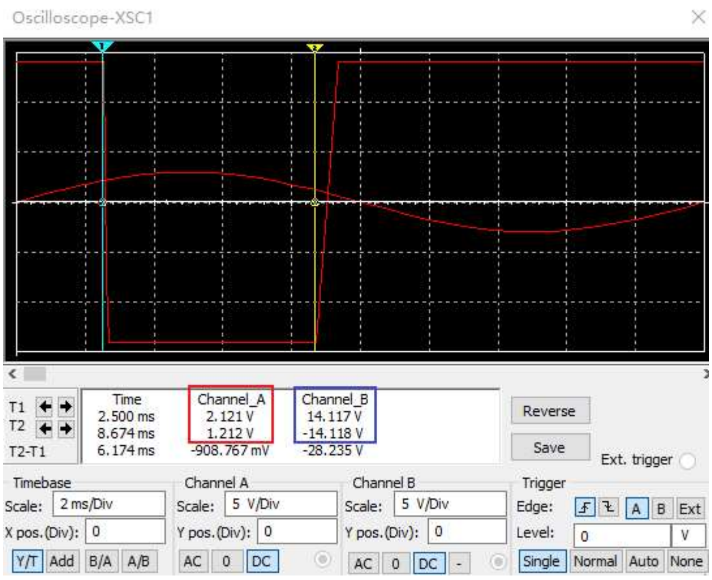

Figure 4. Inverting Input and Output Waveform

The second measurement is the same as the first one, only presented in a different graphical form, as shown in Figure 5. Note that in Figure 5, the vertical axis represents V_{OUT}, and the horizontal axis represents V_{IN}.

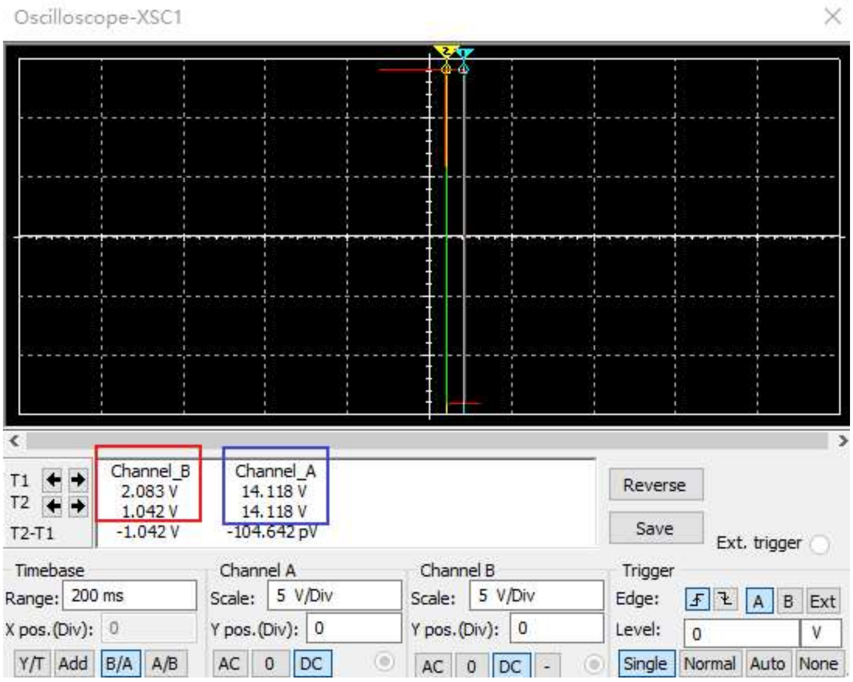

Figure 5. V_{OUT}/V_{IN} Hysteresis Curve

The results are very close to the expectations with an acceptable margin. The most significant error of V_{THRESH} is +0.212 V. There is a consistent error with V_{SAT} of +0.618 V. The cursor measurements for Channel A (boxed in red) correspond with the pre-set threshold levels V_{THRESH}. The saturation voltage V_{SAT} was measured by cursors on Channel B (boxed in blue). As mentioned, it is consistently larger than 13.5 V that was used for pre-lab theoretical calculations.

The ignorance of the oscilloscope's input impedance might act as a load for the op-amp when its probe is connected to the output of the op-amp might be the leading cause of the existing errors of V_{SAT}. The input impedance of the oscilloscope is generally in the order of 10^6 Ω. In the circuit shown in Figure 3, Channel B is connected to the trigger circuit's output and is considered a load for the trigger. According to the datasheet, the saturation voltage of the op-amp is ±14 V when the load resistance is more significant than 10 kΩ, which is approximately the value measured (boxed in blue).

The other cause of the errors is the approximation used when calculating and choosing resistor values.

Cursor placement errors and the slight fluctuation of the signal might be the causes of the difference of the measured V_{THRESH} and V_{SAT} between Figure 4 and Figure 5.

2. Lab 2

Data processing

During the experiment, a large area parallel plate capacitor was discharged and then connected across a voltage supply of 20 V. After removing the power supply, the parallel plate capacitor was connected across a known large uncharged internal capacitor of 10^{-7} F in the electrometer. According to the rule of conservation of charges and

$$Q = CV \qquad (Eq. 5)$$

A new equation that can be used for finding the experimental capacitance with the systematic error of C_{cable} included can be derived, as shown below:

$$C_{pp} + C_{cable} \approx \frac{V_{int}}{V_{ext}} C_{int} \qquad (Eq. 6)$$

For theoretical C_{pp}, an analysis using Gauss' law leads to the following equation:

$$C_{pp} \approx \frac{\varepsilon_0 A}{d} \qquad (Eq. 7)$$

This lab aims to verify Eq. 7 by comparing the theoretical capacitance of the parallel plate capacitor calculated using Eq. 7 and the experimental C_{pp} calculated using Eq. 6. To minimise possible errors, multiple readings were taken with different d (distance between the plates) used. Figure 6 illustrates the parallel plate capacitor set-up for the experiment.

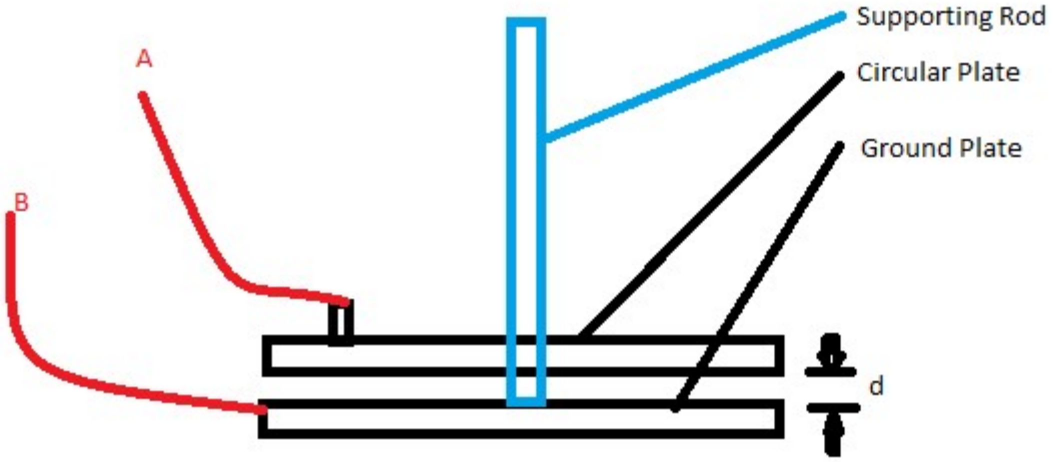

Figure 6. Parallel Plate Capacitor Experimental Set-up [2]

Data of measured V_{int} as a function of d are shown in Table 1. V_{int} decreases as d increases, which is correspondent with Eq. 6 and Eq. 7.

Table 1. Measured V_{int} as a function of the distance, d, between the plates

d (mm)	0.8	1.6	2.4	3.2
V_{int} (mV)	89.98	66.22	46.31	44.25

To see the relationship with more clarity, a graph of V_{int} against 1/d was plotted, as shown in Figure 7.

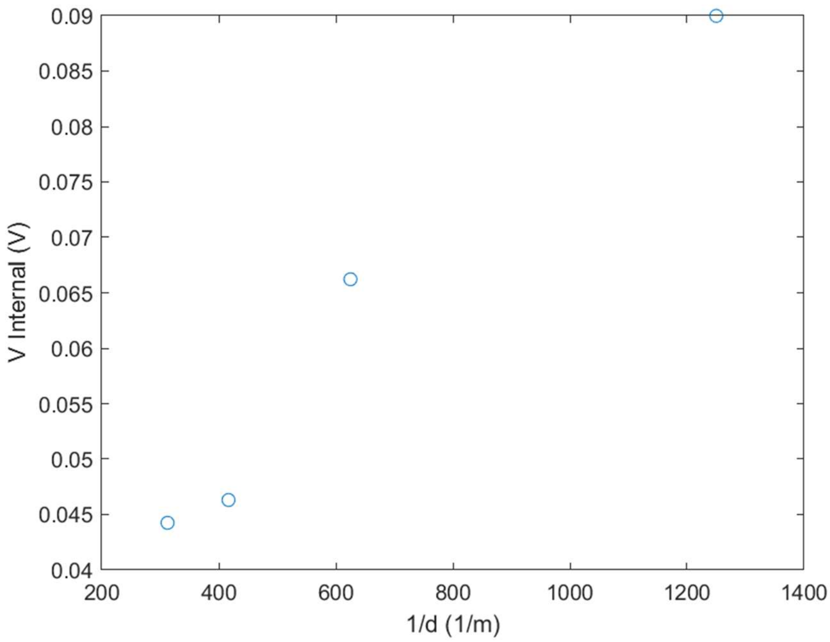

Figure 7. Experimental V_{int} against 1/d

A rough linear relationship can be seen in Figure 7. Using the polyfit() function in MATLAB, a linear function can be approximated and plotted. Thus, a new graph (Figure 8) was generated to show the approximated linear function.

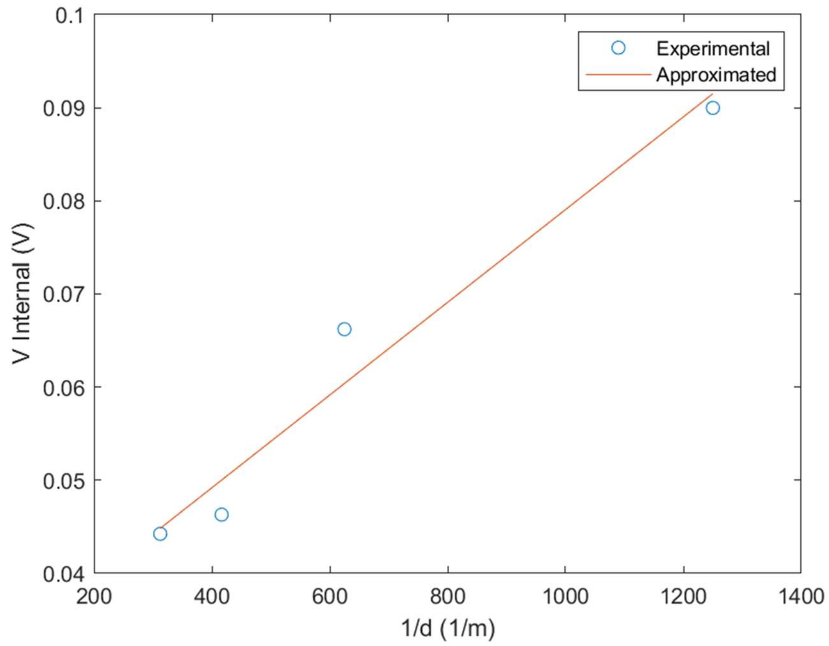

Figure 8. Experimental Data & Approximated Linear Function

Combining Eq. 6 and Eq. 7 gives a linear functional relationship between V_{int} and 1/d, which is shown in Eq. 8:

$$\frac{V_{int}}{V_{ext}}C_{int} = \frac{\varepsilon_0 A}{d} + C_{cable} \qquad (Eq.8)$$

Rearrange Eq. 8:

$$V_{int} = \frac{V_{ext}\varepsilon_0 A}{C_{int}} \times \frac{1}{d} + \frac{C_{cable}V_{ext}}{C_{int}} \qquad (Eq.9)$$

Knowing the coefficients from polyfits(), ε_0 and C_{cable} can be calculated:

$$\begin{cases} \varepsilon_0 = 6.575 \times 10^{-12}\, m^{-3}kg^{-1}\, s^4\, A^2 \\ C_{cable} = 1.464 \times 10^{-10}\, F \end{cases}$$

As the standard ε_0 is 8.854×10^{-12} $m^{-3}kg^{-1}s^4A^2$, an error of 2.279×10^{-12} $m^{-3}kg^{-1}s^4A^2$ is acceptable.

3. Lab 3

The equation to be proven:

$$\beta = \left(\frac{V_s - V_c}{V_s - V_b}\right)\frac{R_b}{R_c} \qquad (Eq.10)$$

The symbols in Eq. 10 are illustrated in Figure 9 below. β represents the current gain of the transistor:

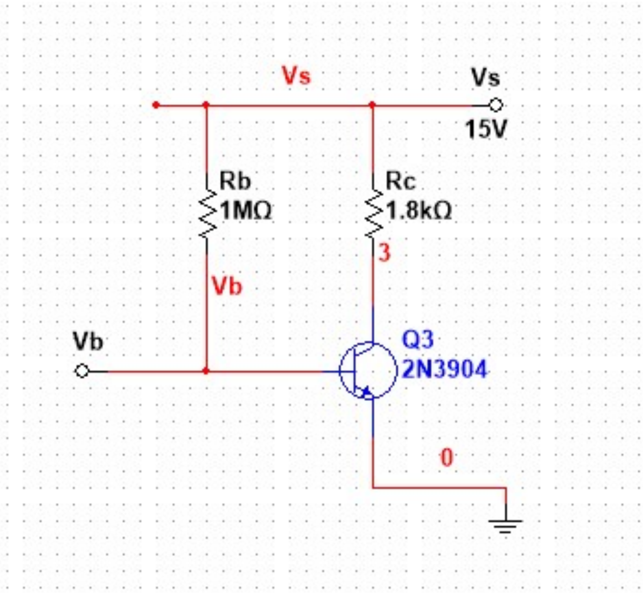

Figure 9. A Common Emitter Amplifier Circuit [2]

The derivation of this equation is as follows:

$$\beta = \frac{I_c}{I_b} \qquad (Eq.11)$$

Assume that V_{BE} is above about 0.5 V to forward bias base-emitter junction, without exceeding the saturation voltage:

$$\begin{cases} I_c = \dfrac{V_s - V_c}{R_c} \\ I_b = \dfrac{V_s - V_b}{R_b} \end{cases} \qquad (Eq.12)$$

Substituting Eq. 12 to Eq. 11 gives Eq. 10.

4. Lab 4

4.1. Pre-lab workout

The pre-lab workout involves calculating the overall gain of a two-stage amplifier circuit, assuming that β is 300 for all three transistors. The process is shown below.

Firstly, a clearly labelled circuit diagram to aid the analysis, as shown in Figure 10.

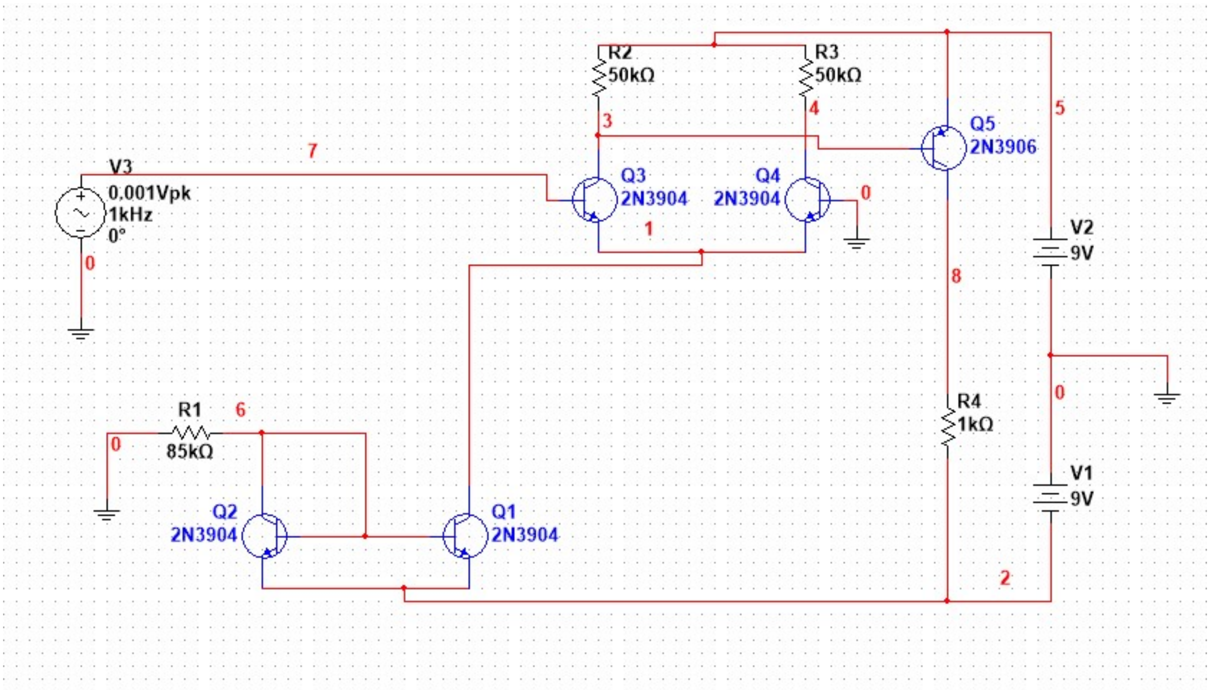

Figure 10. Two-stage Amplifier Design

Secondly, the current flowing into the transistor Q1 (IC-Q1) collector terminal needs to be calculated. As Q1 is part of a current mirror, there is a procedure to follow.

1. Calculate the reference current flowing through R1: $I_{R1} = \frac{0-(-9+V_{BE})}{R1} = \frac{8.5}{R1}$.

2. Assume that V_{BE} is identical for both Q2 and Q1, and β is large, then ($I_{C\text{-}Q1}$) is roughly equal to I_{R1}, which is 1×10^{-4} A.

Thirdly, the current flowing out of the collector of Q5 ($I_{C\text{-}Q5}$) needs to be calculated. For testing purpose, power supply V3 is set to have a DC component of 0V. As

$$\frac{I_{C-Q3}}{I_{C-Q4}} = exp\left[\frac{V_{BE-Q3}-V_{BE-Q4}}{V_T}\right],$$

and that $V_{BE\text{-}Q3}$ and $V_{RE\text{-}Q4}$ equal to zero, it can be determined that $I_{C\text{-}Q3} = I_{C\text{-}Q4} = 0.5\times I_{C\text{-}Q1} = 5\times10^{-5}$ A. As the collector current flowing into Q3 consists of currents flowing from R2 and the base of Q5:

$$I_{C-Q3} = I_{R2} + I_{B-Q5} = \frac{0.5}{R_2} + \frac{I_{C-Q5}}{\beta} \qquad (Eq.13)$$

Rearranging Eq. 13 gives the value of $I_{C\text{-}Q5}$: 12 mA.

Fourthly, the half-wave small-signal voltage gain of the differential stage and its input/output impedances need to be calculated.

Gain: $$A_3 = \frac{v_{C-Q3}}{v_3} = \frac{1}{2}g_m R_2 = \frac{1}{2}\frac{I_{C-Q3}}{V_T}R_2 = 50$$

Input Impedance: $$r_{IN} = \frac{v_3}{i_{B3}} = 2\frac{\beta}{g_m} = 300\ k\Omega$$

Output Impedance: $$r_{OUT3} = 50\ k\Omega$$

Fifthly, the second stage common emitter amplifier's gain and input/output impedances need to be calculated.

Gain: $$A_5 = \frac{v_{C-Q5}}{v_{B-Q5}} = -g_m R_4 = -\frac{I_{C-Q5}}{V_{T-Q5}}R_4 = -\frac{12\ mA}{25\ mV}\times 1000\Omega = -480$$

Input Impedance: $$r_{IN5} = \frac{\beta}{g_m} = \frac{300}{12/25} = 625\Omega$$

Output Impedance: $$r_{OUT5} = R_4 = 1\ k\Omega$$

Lastly, the overall response of the two-stage amplifier:

Gain: $$\frac{v_{OUT}}{v_{IN}} = A_3 A_5 \frac{r_{IN3}}{r_{IN3}+r_{OUT3}} = -296$$

Input Impedance: $$r_{IN} = r_{IN3} = 300\ k\Omega$$

Output Impedance: $$r_{OUT} = r_{OUT5} = 1\ k\Omega$$

4.2. Results and Discussion

The purpose of this section is to compare the characteristics of a two-stage amplifier with or without negative feedback and an equivalent op-amp.

Firstly, a DC sweep was conducted on the circuits, as shown in Figure 11, Figure 12 and Figure 13.

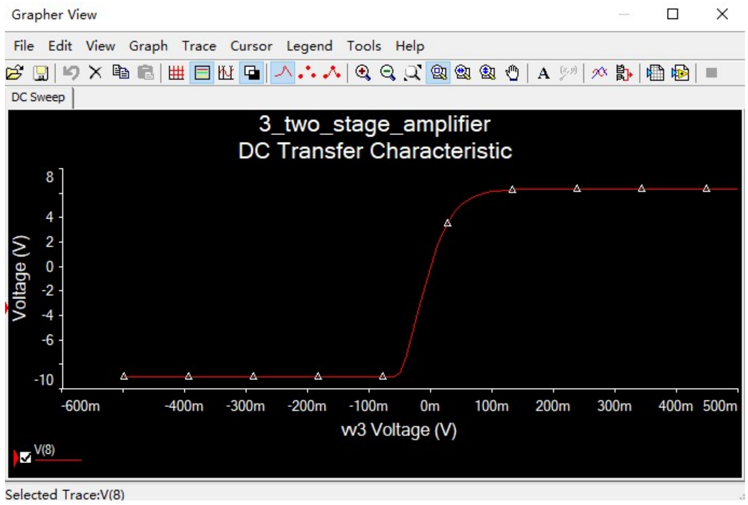

Figure 11. DC Analysis of the Amplifier without Feedback

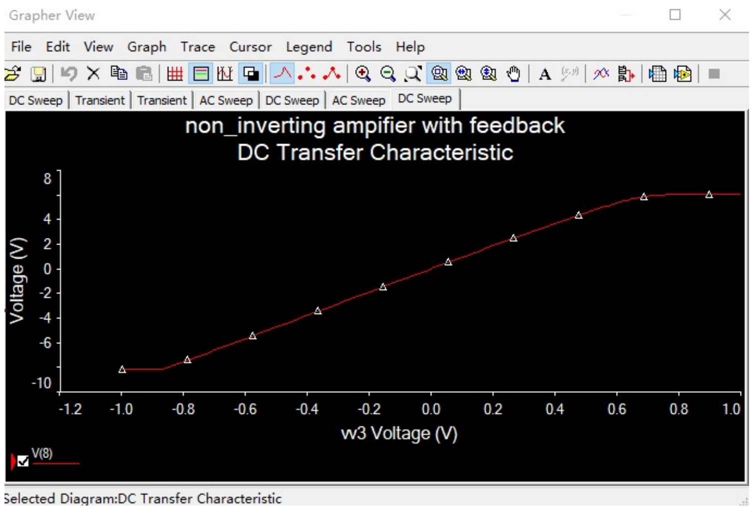

Figure 12. DC Analysis of the Amplifier with Feedback

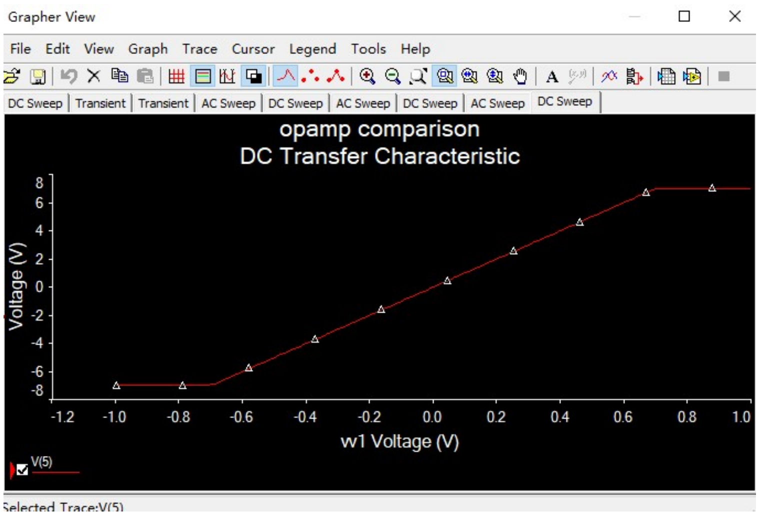

Figure 13. DC Analysis of the Equivalent Op-amp

From the above figures, it can be observed that the operational input range of the amplifier with the feedback loop and the equivalent op-amp is approximately four times larger than the amplifier without the feedback loop. This is the expected behaviour as negative feedback should increase the stability of the system.

Secondly and finally, an AC sweep analysis was performed for the three circuits. The results are shown in Figure 14, Figure 15, and Figure 16.

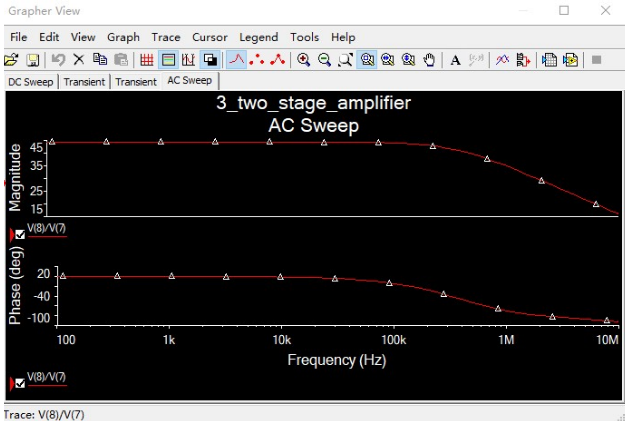

Figure 14. AC Sweep Analysis of the Amplifier without Feedback

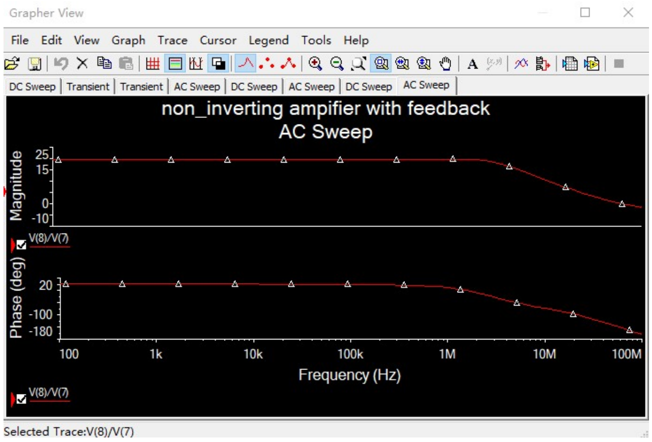

Figure 15. AC Sweep Analysis of the Amplifier with Feedback

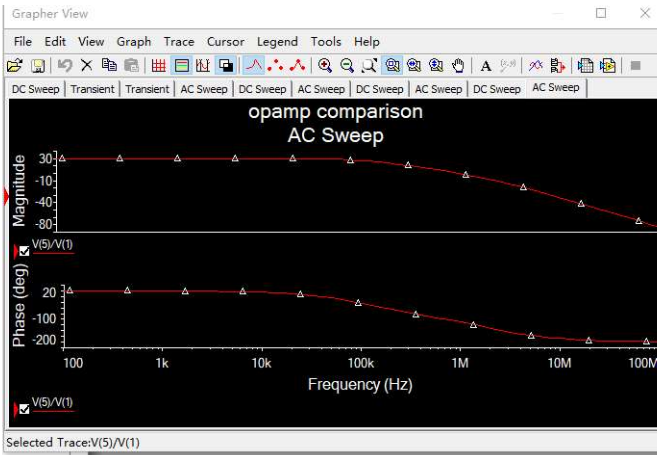

Figure 16. AC Sweep Analysis of the Equivalent Op-amp

It is shown in the above figures that the op-amp has a similar bandwidth of 100 Hz to around 100 kHz as the two-stage amplifier without feedback. The two-stage amplifier with feedback has the widest bandwidth, ranging from 100 Hz to more than 1 MHz.

Reflection and conclusions

These experiments significantly improved my understanding of op-amp, capacitor, and transistor circuits. The experiment results align well with theories with acceptable margins. It is an efficient approach to learning and understanding the construction and the behaviour of the circuits mentioned before.

References

[1] TEXAS INSTRUMENTS. LM741 Operational Amplifier. Available at: https://www.ti.com/lit/ds/symlink/lm741.pdf [Accessed 05 May 2021].

Appendix

Relevant Multisim models, MATLAB scripts, and datasheets are available at: https://github.com/Yang-Li86/UoB_MREng_yr_2.git in the folder called "ECDE_Lab_Report".