Electronic Circuits

ELEC 301

Mini-Project 4

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Part A – An Active Filter

1. The values of C and A_M

The transfer function of the circuit is given: $H(s) = AM * \frac{1/(RC)^2}{S^2 + S(3-AM)/(RC) + 1/(RC)^2}$. All the zeros of a low-pass Butterworth filter are at ω = ∞. The denominator of the H(s) shows the Butterworth filter is a second-order filter. From ELEC 202 notes [1], the denominator is this standard form:

$$\text{Denominator} = s^2 + 2*\omega*\zeta*s + \omega^2$$

Where the ω is the undamped frequency, and the ζ is the damping factor.

From the given transfer function and the standard form, the expression of ω and ζ are known:

$$\omega = 1/(RC)$$
$$\zeta = (3 - A_M) / 2$$

The 3dB frequency is 10 kHz; the resistance of R is 10 kΩ. The value of C can be calculated:

$$2*\pi*10000 \text{ rad/s} = 1 / (10000*C)$$
$$\boxed{\mathbf{C = 1.592\ nF}}$$

According to the table of Normalized Butterworth Polynomials in ELEC 301 chapter 21 note [2] , the normalized polynomial is $s^2 + 1.414s + 1$ for a 2^{nd} -order Butterworth filter. The second term is $2*\omega*\zeta*s$ with ω = 1 (normalized). Therefore, the A_M can be calculated:

$$2*[\ (3 - A_M) / 2\ ] = 1.414$$
$$\boxed{\mathbf{A_M = 1.586}}$$

It is given that R1 + R2 = 10 kΩ, and AM = 1 + R2/R1. The values of R1 and R2 can be calculated:

$$R1 = 6.305\ k\Omega$$
$$R2 = 3.695\ k\Omega$$

The designed circuit is below:

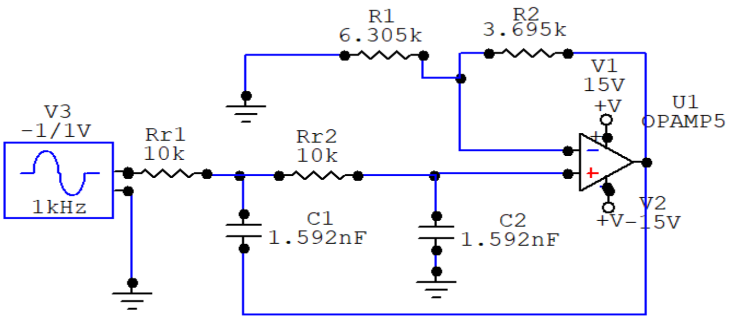

Figure 1. The designed circuit

The Bode and Phasor plots are obtained:

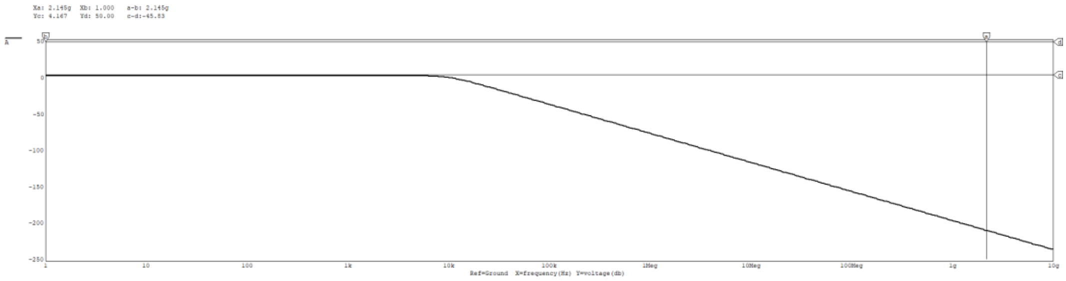

Figure 2. The Bode plot of the designed circuit

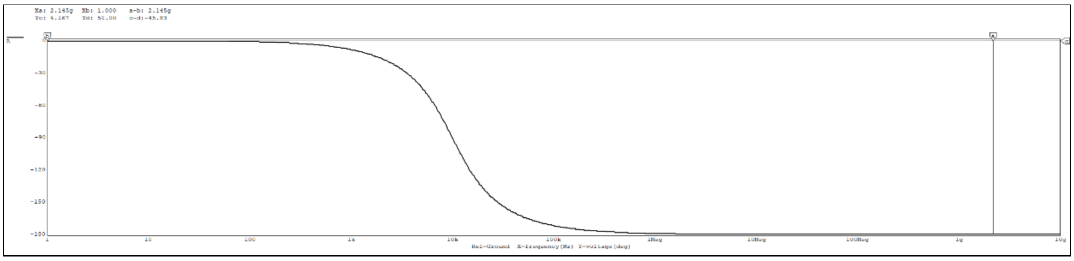

Figure 3. The Phasor plot of the designed circuit

Since this Butterworth filer is 2nd-order, the two poles are sitting on a circle of a radius ω = 62832 rad/s, and they space $\pi/2$ apart as shown below in **Figure 4.(a)**:

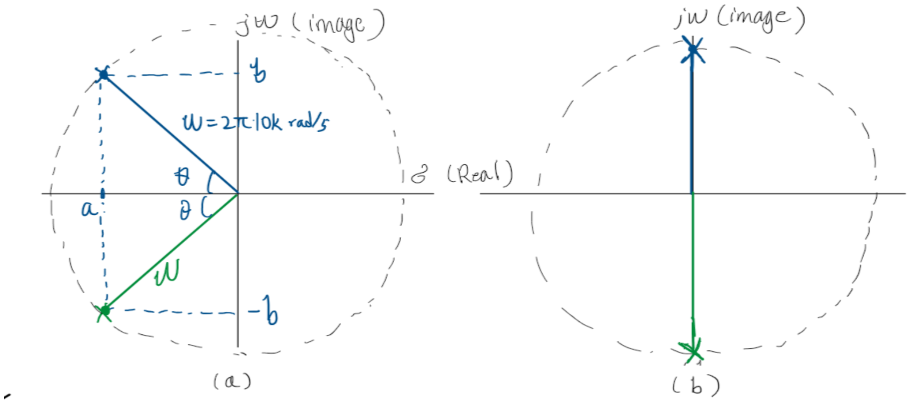

Figure 4. The pole locations on s-plane

2. The oscillating A_M

It is known that $A_M = 1 + R2/R1$. To increase A_M R2 is increased and R1 is decreased to keep R1 + R2 = 10 kΩ. After several adjustments and tests, it is found that the circuit starts to oscillate when $\boxed{\textbf{R1 = 3.305 k}\Omega}$ and $\boxed{\textbf{R2 = 6.695 k}\Omega}$. The output of the circuit is below:

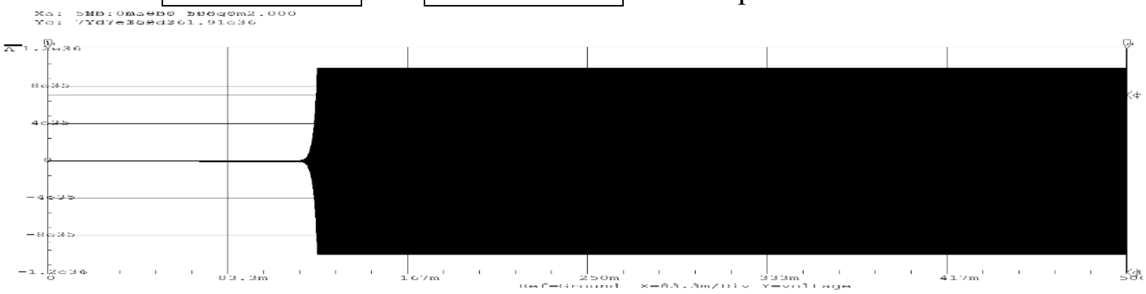

Figure 5. The starting oscillation output of the circuit

The new A_M is expected to be 3.00 because when A_M is 3.00, the 1st-order term of the denominator ($2*\omega*\zeta*s$) is 0 since $\zeta = (3 - A_M) / 2$. When the 1st-order term is 0, the denominator becomes $s^2 + \omega^2 = 0$, and the roots for s only have imaginary part. Thus, the poles are both located at the jω-axis, and the output starts to oscillate. The actual new A_M is then calculated: 1 + 6.695 kΩ / 3.305 kΩ ≈ $\boxed{\mathbf{3.00}}$, which satisfies the expectation. Therefore, the new pole locations are at the jω-axis which is the imaginary axis, as shown in **Figure 4 (b)**. The oscillation frequency is measured by the oscillator in *Circuitmaker*.

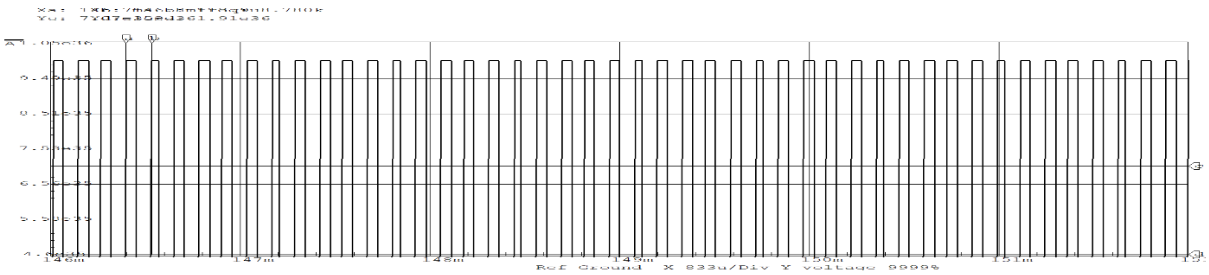

Figure 6. The zoomed in version of the oscillation part in Figure 5

As shown in **Figure 6**, the frequency is measured by calculating the inverse of the period. As a result, the oscillation frequency = $\boxed{\textbf{9.230 kHz}}$.

It is discovered that the poles move along circle (s-plane) from the real-axis to the imaginary-axis as A_M increases, as shown in **Figure 7**. The reason is the greater AM, the smaller the coefficient of the 's' term because $\zeta = (3 - A_M) / 2$. The roots of s are in the form of (a ± bj). The smaller coefficient of the 's' term will cause a smaller 'a'. The smaller 'a' will move the poles close to the jω-axis along the root locus. Therefore, when AM = 3, the poles are on the jω-axis. If AM is greater than 3, the poles will locate at the right-hand side of the plane, which will lead to the circuit unstable.

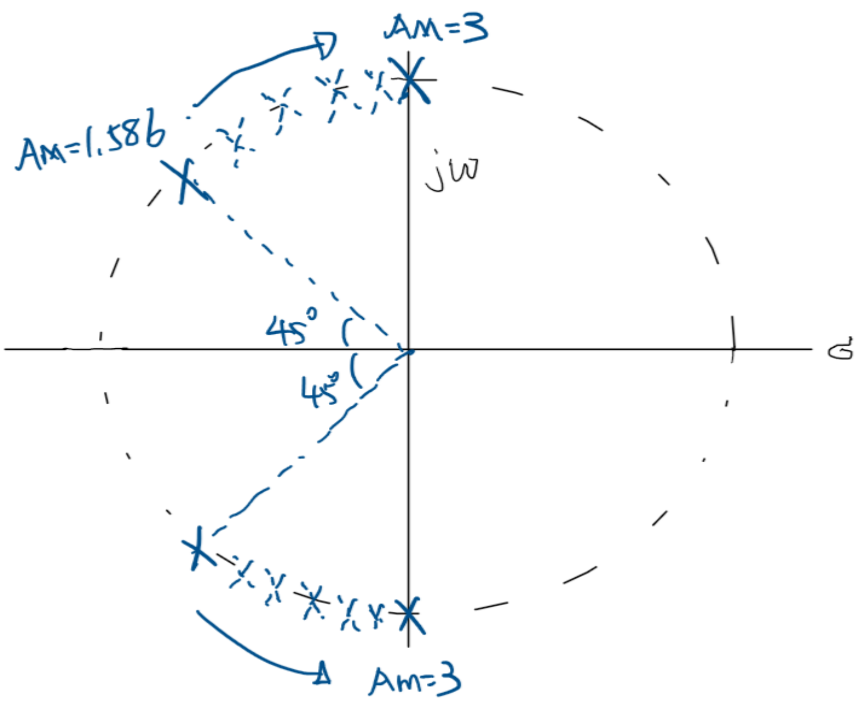

Figure 7. The routine of the poles as the A_M increases.

Part B – A Phase Shift Oscillator

When the 29R = 29 kΩ, the oscillation is decaying. Therefore, the 29R is slightly adjusted to form a non-decaying oscillation. The final resistance is **29.1 kΩ**. The reason will be discussed in the following.

The designed circuit is below:

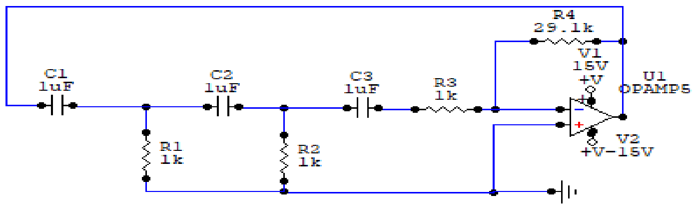

Figure 8. The circuit of the phase-shift oscillator.

The original values of R (1 kΩ) and C (1 μF):

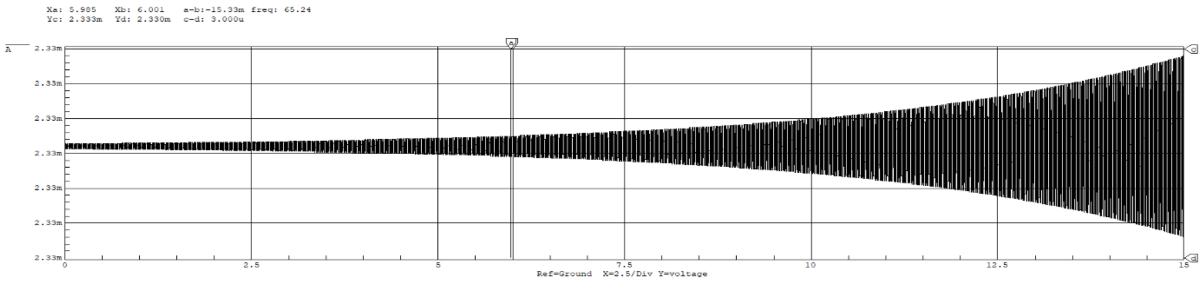

Figure 9. The oscillation of the circuit with the original R and C.

The oscillation frequency is measured by putting the a-b vertical lines on the adjacent peaks (in the zoomed in figure). The measured frequency can be then directly obtained by the oscilloscope, which is **65.24 Hz**.

According to the ELEC 301 chapter 22 note [2], the frequency can be calculated using these formula: $\omega = 1 / (\sqrt{6}RC)$ or $f = 1 / (2\pi\sqrt{6}RC)$. Then the calculated frequency is obtained:

$$f_{cal} = 1 / (2\pi * \sqrt{6} * 1000 * 1u) = \boxed{64.97\text{ Hz}}$$

The values of R and C are then increased by factors of 2. Now R = 2 kΩ and C = 2 μF.

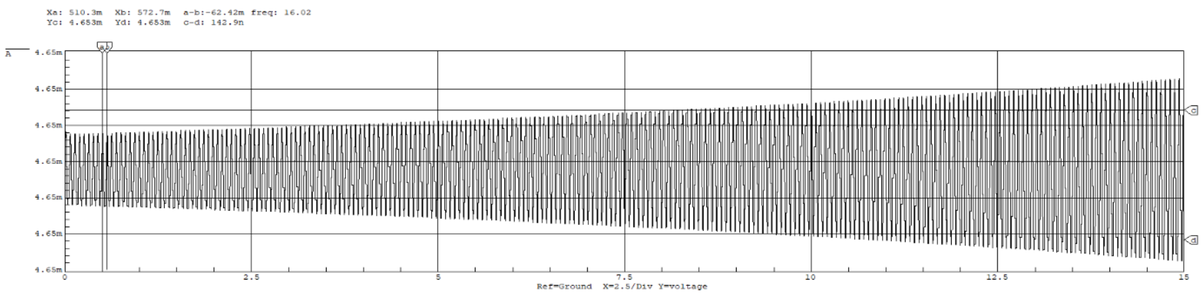

Figure 10. The oscillation of the circuit with the doubled R and C.

The frequency can be measured using the same method above. The measured frequency is **16.02 HZ**.

The frequency can also be calculated using the formula above:

$$f_{cal} = 1 / (2\pi * \sqrt{6} * 2000 * 2u) = \boxed{\textbf{16.24 Hz}}$$

Then the values of R and C are decreased by a factor of 2. Now R = 0.5 kΩ and C = 0.5 μF. The oscillation plot is obtained.

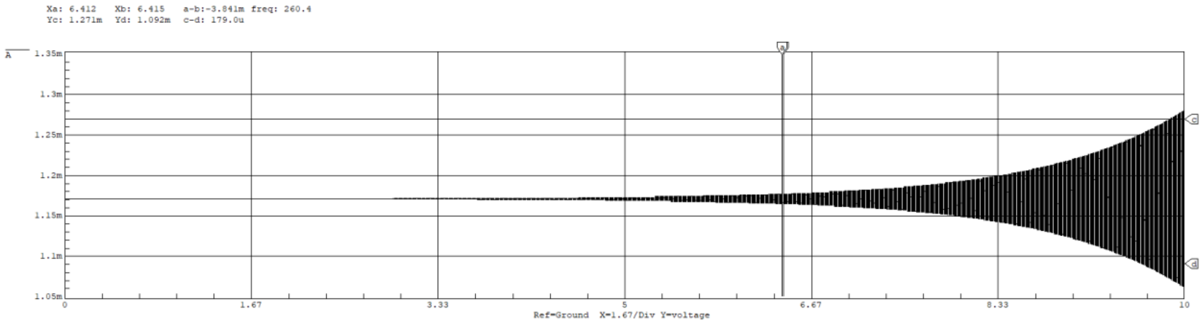

Figure 11. The oscillation of the circuit with the halfed R and C

The oscillation frequency is measured using the same method above, which is **260.4 Hz**.
The frequency is also calculated:

$$f_{cal} = 1 / (2\pi * \sqrt{6} * 500 * 0.5u) = \boxed{\textbf{259.90 Hz}}$$

Report

This sine-wave oscillator consists of one op-amp and a feedback network containing 3 pairs of RC which determine the frequency and the amplitude of the oscillations. The transfer function of the circuit is Af = A(jω) / (1+ A(jω) β(jω)). When the denominator is 0, the gain Af is infinite. The oscillator circuit have the poles on the jω-axis. Therefore, the denominator is of the form ($s^2 + \omega_o^2$). Thus, the roots are s = ±jω, and σ = 0. At a specific frequency, Aβ = -1, so the Af = ∞. Thus, the circuit has a finite output with a zero input. Meanwhile, at this frequency, the feedback network provides a -180° phase shift to the output gain with the unity magnitude.

We call the 29R resistor the feedback resistor (R_{fb}). R_{fb} is utilized to sustain the oscillation, which has a resistance of 29*R. The oscillation should neither grow nor decay when the R_{fb} is exactly 29R and the amplifier is ideal. However, in the experiment, the oscillation is decaying when R_{fb} is 29R because the amplifier used in the lab is non-ideal. The turn-on transient and the thermal electrical noise provide the start signal for the oscillation [3]. In the experiment, R_{fb} is slight increased to make sure the amplitude of the oscillation will grow instead of remaining the same or decaying (the amplitude is decaying when R_{fb} = 29k in the test).

Assuming the amplifier is ideal, and the oscillation frequency is calculated by this formula [3]:

$$f = \frac{1}{2\pi\sqrt{R2R3(C1C2+C1C3+C2C3)+R1R3(C1C2+C1C3)+R1R2C1C3}}$$

$$f_{orginal} = \boxed{\textbf{64.968 Hz}} \approx 64.97\text{ Hz}$$

$$f_{doubled} = \boxed{\textbf{16.24 Hz}} \approx 16.24\text{ Hz}$$

$$f_{halfed} = \boxed{\textbf{259.89 Hz}} \approx 259.90\text{ Hz}$$

As shown above, the calculated values by the *f* and the formula in handout are almost the same.

The calculated and measured frequencies are listed in a table below:

Table 1. The calculated and measured oscillation frequencies

R,C	Original	Doubled	Halfed
Calculated, Hz	64.97	16.24	259.9
Measured, Hz	65.24	16.02	260.4
Discrepancy	0.41%	1.37%	0.19%

As shown in **Table 1**, the discrepancies are increased with the increase of the values of R and C. These tiny errors may be caused by non-ideal Op-Amp. Even though some errors exist, the results are still reasonable because these errors are insignificant. Since the measured values are comparable to the values calculated by the formula in the lecture notes, the formula is the course notes can be used to calculate the oscillating frequency.

Part C – A Feedback Circuit

The circuit is wired up as the following:

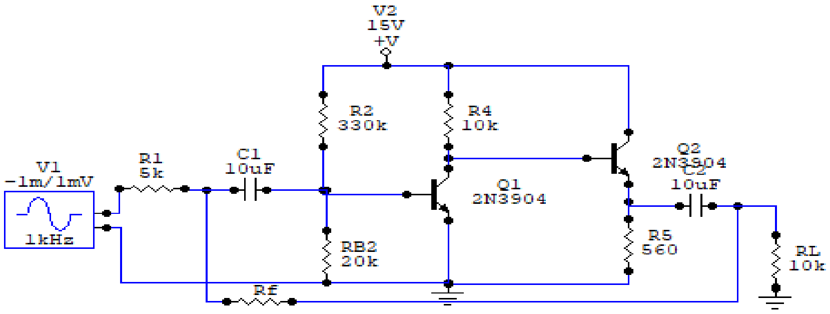

Figure 12. The feedback circuit

The resistance of R_{B2} is various to make sure the amplifier has the largest open-loop gain at 1kHz. The outputs corresponding to the various R_{B2} are listed:

Table 2. The resistances of R_{B2} and the corresponding output

R_{B2}, kΩ	10	12	14	16	18	**20**	21
V_o, μV	6.40	134.2	191.3	197.2	198.1	**199.0**	49.67

As Table 2 shown, when the resistance of R_{B2} is $\boxed{\textbf{20 k}\Omega}$, the amplifier has the largest gain.

1. d.c bias values

The d.c operating points are measured by the DC multimeter in the *Circuitmaker*.

Table 3. The d.c operating points of the transistors

Parameters	I_C, mA	I_B, mA	I_E, mA	V_C, V	V_B, V	V_E, V
Q1	1.295	0.0108	1.305	1.900	0.654	0.000
Q2	2.190	0.0154	2.205	15.00	1.900	1.235

The transistor parameters are calculated (processes are in the Appendix):

Table 4. The transistor parameters.

	g_m	h_{fe}	r_π, kΩ
Q1	0.0504	116.57	2.315
Q2	0.0876	142.21	1.623

2. Open-loop frequency response

When measuring the open-loop frequency response from 10 mHz to 100 MHz, $R_f = \infty$. The Bode plot is obtained.

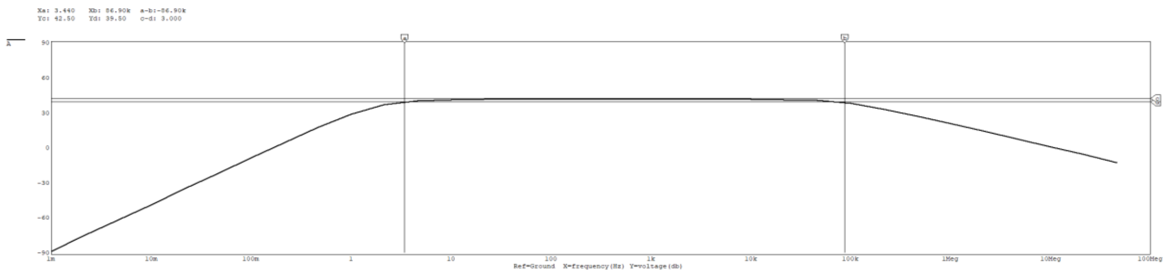

Figure 13. The Bode plot of the open-loop circuit

The lower and upper 3-dB frequency are also measured in the plot. **ω_{L3dB} = 3.44 Hz** and **ω_{H3dB} = 86.90 kHz**. The mid-band gain is **-42.11 dB** or **-127.5 V/V**. They are negative because this amplifier has negative feedback.

To measure the input resistance at 1 kHz, the same method in mini-project 2 is used here [3]. The Oscilloscope probe is located at the left node of C1 in **Figure 12**. The peak to peak voltage and peak to peak current are measured: V_{in} = 676.7 µV ; I_{in} = 264.2 nA. Therefore, the measured input impedance is equal to $R_{in} = V_{in}/I_{in}$ = **2.561 kΩ.** To measure the output impedance at 1 kHz, the input generator is shorted, and the RL is removed. Another generator is moved to the load terminals with a small resistor in series to measure the current. The peak to peak voltage and peak to peak current are measured: V_{out} = 0.002V ; I_{out} = 33.50 µA. Therefore, the measured output impedance is equal to $R_{out} = V_{out} / I_{out}$ = **59.70 Ω.**

Closed-loop Response

The feedback resistor is parallel to the both input and output terminals. Therefore, this network is in the shunt-shunt topology, and the 'y' parameters will be used. After a 100 kΩ R_f is connected in the circuit, the equivalent circuit is obtained:

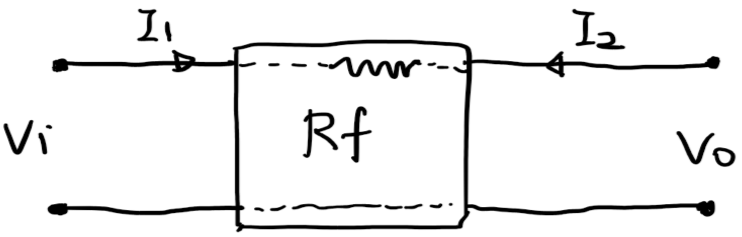

Figure 14. The equivalent circuit

From ELEC 301 notes P19.10 [2], the 'y' parameters can be calculated using the method in the notes. Among them, 'y_{12}' is the feedback gain, β. 'y_{21}' is too small so it is neglected. The 'y' parameters are calculated (processes are in the Appendix): 'y11' = 'y22' = 0.00001, and 'y12' = β = -0.00001.

Since the circuit is shunt-shunt, the gain is obtained by a I-V amplifier. The open-loop voltage gain is from the above which is -127.5 V/V.

$$A = Vo / Ii = Vo / (Vi/Rs) = Rs*(Vo/Vi) = 5k\Omega * (-127.5\ V/V) = -637500\ V/A$$

From the Lecture note P18.8 [2], the closed loop gain is calculated:

$$A_f = A / (1+A*\beta) = -86440.7\ V/A$$

To convert it into V/V, the A_f is divided by Rs, which $\boxed{\mathbf{A_f = -17.288\ V/V}}$.

The ω_{Lf} and ω_{Hf} are then calculated using the formulate from Lecture notes chapter17 [2]:

$$\omega_{Hf} = \omega_{H3dB} * (1+A\beta) = 86.90k * [1+(-637500)*(-0.00001)] = \boxed{\mathbf{640.888\ kHz}}$$

$$\omega_{Lf} = \omega_{L3dB} / (1+A\beta) = 3.44 / [1+(-637500)*(-0.00001)] = \boxed{\mathbf{0.466\ Hz}}$$

The bode plot of the closed-loop circuit is obtained:

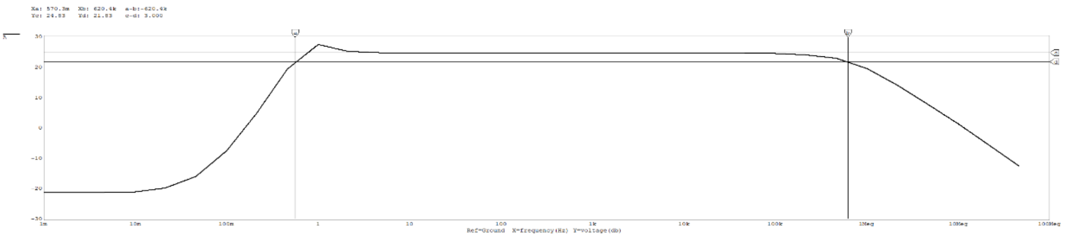

Figure 15. The Bode plot of the closed-loop circuit

The mid-band gain at 1 kHz is measured: **24.83dB** or **-17.20 V/V**. From the plot, the ω_{Lf} and ω_{Hf} are also measured, which are **0.57 Hz** and **620.4 kHz** respectively.

The open-loop Rin and Rout are measured before. The Rin and Rout of the closed loop circuit are calculated using the formula in Lecture note P18.6 [2] (Processes are in the Appendix). The **Rif = 347.25 Ω**, and **Rof = 8.095 Ω**.

To measure the input and output resistance, the same method for the open loop circuit is used. The peak to peak voltage and peak to peak current are measured: $V_{in} = 92.00\ \mu V$; $I_{in} = 372.2$ nA. Therefore, the measured input impedance is equal to $R_{inf} = V_{in}/I_{in} =$ **239.5 Ω**. For the output, the peak to peak voltage and peak to peak current are measured: $V_{out} = 0.002V$; $I_{out} = 241.7$ uA. Therefore, the measured output impedance is equal to $R_{outf} = V_{out}/I_{out} =$ **8.275 Ω**.

The measured and the calculated data of the closed-loop circuit is compared:

Table 5. The calculated and measured data of the closed-loop network.

	Mb-Gain V/V	ω_{H3dB}, kHz	ω_{L3dB}, Hz	R_{in}, Ω	R_{out}, Ω
Calculated	-17.288	640.888	0.466	347.25	8.095
Measured	-17.20	620.400	0.570	247.18	8.275

As shown in **Table 5**, the calculated values are comparable to the measured values. However, the calculated and the measured input resistances have a relatively large deviation. It may because the electric noise in the simulated circuit. In summary, the calculations are acceptable because the inaccuracies are very small.

3. Feedback factors of the closed loop

The R_f is various from 1 kΩ to 10 MΩ. The curves of the frequency responses of the closed loop for these R_f over 10mHz to 100MHz are plotted.

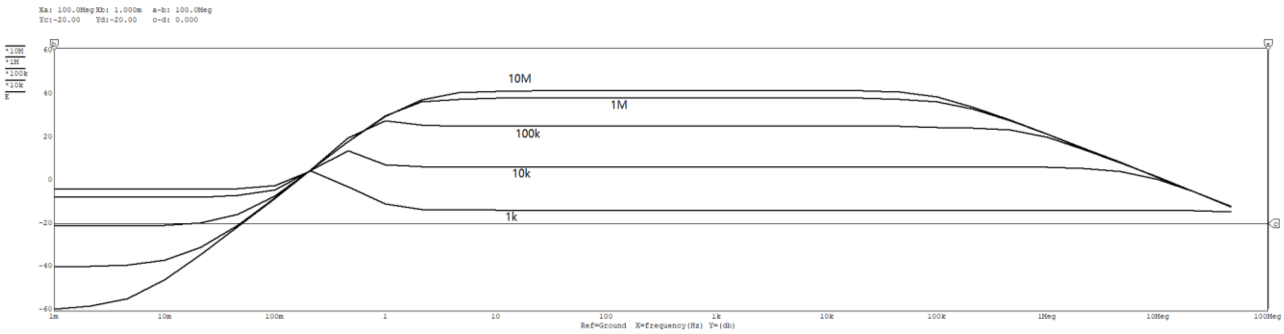

Figure 16. The Bode plots of the closed-loop circuit with various R_f

The mid-band gain in dB is measured:

Table 6. The frequency response of various R_f.

R_f, Ω	1 k	10k	100k	1M	10M
Gain, dB	-14.07	5.981	24.82	37.86	41.49

The feedback factor βs of each R_f can be calculated by the formula β = 'y12' = (-1 / R_f). The specific processes are on the Appendix. The magnitude of the mid-band gains, A_f (V/V) of each R_f are measured in the plot. Recall that the open loop gain, A, was obtained from part 2, which is -637500 V/A. The A_f (V/V) is converted to (V/A) by multiplying Rs. Then the measured β of each Rf can be calculated by the formula: $A_f = A / (1+A\beta)$. The processes are in the Appendix. The results are listed below:

Table 7. The measured and calculated feedback factors of various R_f.

R_f, Ω	A_f, V/V	A_f, V/A	$\beta_{measured}$	$\beta_{calculated}$	Deviation
10 M	-119.9	-599500	-9.943E-8	-1.000E-7	0.57%
1 M	-77.9	-389500	-9.988E-7	-1.000E-6	0.12%
100 k	-17.2	-86000	-1.006E-5	-1.000E-5	0.60%
10 k	-1.953	-9765	-1.008E-4	-1.000E-4	0.79%
1 k	-0.182	-910	-1.097E-3	-1.000E-3	8.84%

As shown in **Table 7**, the calculated βs are comparable to the measured βs. When the R_f is 1 kΩ, the deviation is relatively large. This may because the noise in the circuit is relatively large for the feedback resistor. Even though the deviation of R_f = 1 kΩ is greater than others, the errors are still tiny. Therefore, the calculated results are reasonable and acceptable.

4. Amount of feedback

The estimated amount of feedback is '1+Aβ', where A is the open loop gain which is -637500 V/A. The input R_{if} and output resistances R_{of} are measured using the same method before for Rf = 10kΩ, 100kΩ and 1MΩ.

Table 8. The measured input and output resistances of various R_f.

Rf, Ω	10k	100k	1M
Rif, Ω	26.47	240.29	1306.62
Rof, Ω	1.124	8.421	37.502

The relationship between R_{if}, R_{of} and the amount of feedback is:

$$R_{if} = \frac{Ri}{1+A\beta} \quad \text{and} \quad R_{of} = \frac{Ro}{1+A\beta}$$

The R_i is the input resistance of the open loop network, and R_o is the output resistance of the open loop network. They are calculated in part C.2: R_i = 2.561 kΩ and R_o = 59.70 Ω. The input and output resistances are both decreased by the amount of feedback because the circuit is shunt-shunt. The predicted amount of feedback (using the data in part 2 and part 3) can be calculated by the formula:

$$A_f = \frac{A}{1+A\beta}$$

The estimated and predicted amount of feedback is '1+Aβ' for each R_f is then calculated in the Appendix and they are listed below:

Table 9. The estimated and the predicted amount of feedback of various R_f.

R_f, Ω	Estimated	Predicted	Deviation
10k	74.93	65.284	12.87%
100k	8.875	7.413	16.47%
1M	1.776	1.637	7.83%

As shown in **Table 9**, the amount of feedback decreases as the resistance of R_f increases. It can be concluded that the amount of feedback and R_f have a negative relationship. In addition, the estimated values are higher than the predicted values. However, the inaccuracies are in a range of 5% ~ 15%. Therefore, the deviations are small and acceptable. The estimated and the predicted amount of feedback are reasonable.

5. De-sensitivity factor

According to the Lecture note chapter 17 [2], the de-sensitivity factor is (1+Aβ). To derive the factor:

$$\frac{dAf}{dA} = \frac{1}{(1 + A\beta)^{\wedge}2}$$

When $R_f = \infty$ (open loop), the $\beta = -1/R_f = 0$. Therefore, the de-sensitivity factor is $\boxed{\mathbf{1.00}}$ for $R_f = \infty$.

Then, the open loop gains for each Rc are measured in *Circuitmaker*. When R_f = 100 kΩ, the closed loop gain A_f are also measured. The measured gains are in V/V. To convert to V/A, the values are multiplied by Rs which is 5 kΩ. The data are listed below:

Table 10. The measured gain of various R_c.

R_c, Ω	9.9k	10k	10.1k
A_f, V/A	-86150	-86200	-86350
A, V/A	-634000	-637500	-643500

The de-sensitivity factor is then calculated:

$$(1+A\beta)_{9.9k\text{-}10k} = 1 / \sqrt{dAf/dA} = 1 / \sqrt{50/3500} = 8.366$$

$$(1+A\beta)_{10k\text{-}10.1k} = 1 / \sqrt{dAf/dA} = 1 / \sqrt{-150/-6000} = 6.325$$

$$\text{Average } (1+A\beta) = (8.366+6.325) / 2 = \boxed{\mathbf{7.346}}$$

Therefore, the calculated de-sensitivity factor of the amplifier is 5.000.

The predicted value is from the measurement of part 2 and 3 above. In part 2 and 3, the measured A is -637500 V/A, and the measured β is $-1.006*10^{-5}$ /Ω. The predicted factor is then calculated:

$$(1+A\beta) = 1 + (-637500)*(-1.006*10^{-5}) = \boxed{\mathbf{7.41}}$$

The calculated and the predicted values are listed below:

Table 11. The comparison of the de-sensitivity factors.

	calculated	predicted	deviation
De-sensitivity factor	7.346	7.41	0.871%

As shown in **Table 11**, the calculated and predicted de-sensitivity factors are highly similar. The small inaccuracy can be neglected. Therefore, the results are reasonable and acceptable.

In addition, as shown in **Table 7** and **Table 8**, the circuit with a small R_f has larger mind band gain. Thus, the feedback resistor can control the amplifier gain. The feedback resistor is connected to the output and the inverting input terminals, which forces the differential input voltage to zero. Then the circuit becomes closed loop and it has negative feedback. The negative feedback is utilized by the closed loop inverting amplifier to control the gain but with a cost of the reduction of the gain. The lower resistance improves the DC accuracy and reduces the thermal noise voltage. Therefore, smaller feedback resistance will have a larger amplifier gain [4].

Conclusion

In this mini project, the basic principle of an active filter is investigated. The values of the electrical components and the gain in a second-order Butterworth filter are calculated. The gain in which the circuit starts to oscillate are discover and measured. The bode plots of the oscillations are drawn to illustrate the phenomenon in the oscillation circuit. Moreover, a phase shift oscillator is studied. The oscillator uses op-amp implementation. The function and the values of the feedback resistor are discovered. The reason for why the feedback resistor is slightly larger than 29R is also explained. Then the oscillating frequency is measured and calculated. The deviation is analyzed. Finally, a shunt-shunt feedback circuit which consists of 2N3904s is studied. The parameters of the transistors are calculated. The measured and the calculated input and output resistances are compared. The open-loop and the closed-loop frequency responses are obtained. Furthermore, the resistance of the feedback resistor is varied. The corresponding amplitude responses and the feedback factors are measured and calculated. Also, the amount of feedback and the de-sensitivity factor of the amplifier are calculated and studied. In conclusion, the mini project provides the advanced knowledge of amplifier which is useful for the future career.

References

[1] ELEC 202 Lecture notes.

[2] ELEC 301 Lecture notes.

[3] *Mancini, Ron (2002). Op Amps For Everyone (PDF). Dallas, Texas: Texas Instruments. pp. 15–15, 15–16. SLOD006B.*

[4] https://www.researchgate.net/post/What-are-the-typical-value-of-resistors-for-gain-of-10-in-opamp

Appendix

C1: Transistor Parameters:

Q1:

$$g_m = \frac{I_C}{V_T} = \frac{1.259\,mA}{25\,mV} = 0.0504$$

$$\beta = h_{fe} = \frac{I_C}{I_B} = \frac{1.259\,mA}{0.0108\,mA} = 116.57$$

$$r_\pi = \frac{\beta}{g_m} = \frac{116.57}{0.0504} = 2.315\ k\Omega$$

Q2:

$$g_m = \frac{2.190\,mA}{25\,mV} = 0.0876$$

$$h_{fe} = \frac{2.190\,mA}{0.0154\,mA} = 142.21$$

$$r_\pi = \frac{142.21}{0.0876} = 1.623\ k\Omega$$

C2: Y parameters:

$$y_{11} = \frac{I_1}{V_1}\bigg|_{V_2=0} = \frac{1}{R_f} = \frac{1}{100k} = 0.0001$$

$$y_{12} = \frac{I_1}{V_2}\bigg|_{V_1=0} = \frac{-1}{R_f} = \frac{-1}{100k} = -0.0001$$

$$y_{22} = \frac{I_2}{V_2}\bigg|_{V_1=0} = \frac{1}{R_f} = 0.0001$$

C2: Input and Output resistance

since it is shunt-shunt

$$R_{if} = \frac{R_{in}}{1+A\beta} = \frac{2.561\ k}{1+(-637500)(-0.00001)} = 347.25\ \Omega$$

$$R_{of} = \frac{R_{out}}{1+A\beta} = \frac{59.70}{1+(-637500)(-0.00001)} = 8.095\ \Omega$$

C3: Calculated feedback factors.

$$\beta = \frac{-1}{R_f}: \Rightarrow R_f = [\,1k,\ 10k,\ 100k,\ 1M,\ 10M\,]$$

$$\text{calculated } \beta = \frac{-1}{R_f} = [\,-1\times10^{-3},\ -1\times10^{-4},\ -1\times10^{-5},\ -1\times10^{-6},\ -1\times10^{-7}\,]$$

when $R_f = 1K$, $A_f(\frac{V}{V}) = -0.182$, $A_f(\frac{V}{A}) = -0.182 \times R_S = -0.182 \times 5000 = -910$

similarly, the $A_f(\frac{V}{A})$ of other R_f are calculated.

$$\Rightarrow R_f = [\,1k,\ 10k,\ 100k,\ 1M,\ 10M\,]$$

$$\text{measured } A_f(\tfrac{V}{V}) = [-0.182,\ -1.953,\ -17.20,\ -77.9,\ -119.9]$$

$$A_f(\tfrac{V}{A}) = [-910,\ -9765,\ -86000,\ -389500,\ -599500]$$

measured β: $A_f = \frac{A}{1+A\beta}$. $\Rightarrow$ $\beta = \frac{A-A_f}{A \cdot A_f}$, $A = -637500 \ \frac{V}{A}$

when $R_f = 1k$, $\beta = \frac{-637500+910}{(-637500)(-910)} = -1.097 \times 10^{-3}$

similarly, the β of other R_f are calculated:

$\Rightarrow R_f = [1k, \ 10k, \ 100k, \ 1M, \ 10M]$, $\beta = \frac{-1}{R_f}$

measured: $\beta = [-1.097\times10^{-3}, -1.008\times10^{-4}, -1.006\times10^{-5}, -9.988\times10^{-7}, -9.943\times10^{-8}]$

C4: amount of feedback

Estimated:

$R_f = 10k$: $(1+A\beta)_{in} = \frac{R_i}{R_{if}} = \frac{2561}{26.47} = 96.75$
$(1+A\beta)_{out} = \frac{R_o}{R_{of}} = \frac{59.70}{1.124} = 53.11$
$\xrightarrow{ave} = 74.93$

$R_f = 100k$: $(1+A\beta)_{in} = \frac{2561}{240.29} = 10.66$
$(1+A\beta)_{out} = \frac{59.70}{8.421} = 7.089$
$\xrightarrow{ave} = 8.875$

$R_f = 1M$: $(1+A\beta)_{in} = \frac{2561}{1306.62} = 1.96$
$(1+A\beta)_{out} = \frac{59.70}{37.502} = 1.592$
$\xrightarrow{ave} = 1.776$.

Predicted: $A = -637500 \ V/A$, $A_f = \frac{A}{1+A\beta}$

from table 7.

$R_f = 10k$, $A_f = -9765$
$(1+A\beta) = \frac{A}{A_f} = 65.284$

$R_f = 100k$, $A_f = -86000$
$(1+A\beta) = \frac{A}{A_f} = 7.413$

$R_f = 1M$, $A_f = -389500$
$(1+A\beta) = A/A_f = 1.637$