Final Report: Analogue Electronics: Feedback

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Report Module: Analogue Electronics: Feedback

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DECLARATION

I have read and understood the College and Department's statements and guidelines concerning plagiarism.

I declare that all material described in this report is all my own work except where explicitly and individually indicated in the text. This includes ideas described in the text, figures and computer programs.

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Abstract

The lab experiment examined the behavior of inverting amplifier in a feedback system. The feedback system has three parts to analysis: open loop configuration, closed loop configuration and stability. Each configuration was tested to collect data to deduce gain response and phase response against frequency. Ringing signal detection was involved for testing stability. Results showed that both configurations have low-pass property, and Gain-Bandwidth-Product were almost the same for both configurations. Also, involvement of feedback resistor in closed loop configuration stabilize the feedback system. Previous research ([2],[4],[7],[10],[11]) has provided theory related to the lab experiment and could prove results obtained from the lab experiment. These results have important implications for design of feedback system and further study in Analogue Electronics.

1.Introduction

The purpose of the lab experiment was to gain the understanding of basic amplifier concept, and how amplifiers could be limited by effects as slewing and clipping. Also, it was aimed to understand the Gain-Bandwidth-Product, and how this principle defined the tradeoff between the gain and the bandwidth of any amplifier. Likewise, it was aimed to understand the principle of stability, gain margin and phase margin, and how these could make an amplifier to become an oscillator.

The lab experiment was separated into three big tasks, task 1, task 2 and task3, then each part is divided into three or four smaller tasks for a structural and logical process. The task 1 aims to improve understanding of basic amplifier via analyze open loop configuration. The task 2 aims to discover the gain-bandwidth-product and the relationship between gain and the bandwidth of amplifier in closed loop configuration. The task 3 aims to have a deep learning about the principle of stability, gain margin and phase margin, and the formation of oscillator from an amplifier.

The lab experiment was proceeded by both my partner Toby Katerbau and I, who are both second year undergraduate students in Electronics and Electrical Department in UCL, in the lab room on 6^{th} floor of Robert Building in 22^{nd} October 2019. The lab experiment required hardware equipment as oscilloscope, power supply, signal generator and an amplifier board; while the Matlab was required for software aspect.

The report will start with detailed theory explanation which support the lab experiment, then the structure for the lab experiment and tasks will be stated, followed by the methods and results with fully comments and analysis. Finally, conclusion will be deduced.

2.The Underlying Theory and Preparatory Exercise

Before the lab experiment was started, there were theories, principles and behaviors of amplifiers which were crucial to define and understand.

2.1 Principles of feedback: open loop and closed loop

Considering the principles of feedback generally, the term ‘feedback’ means that some portion of the output is returned ‘back’ to the input to stimulate and regulate the final output ("Closed-loop Systems", 2017). Two kinds of feedback will be discussed, the first one is Positive Feedback and the second one is negative feedback. For positive feedback, it occurs if the original input signal and feedback signal are in phase with each other, the output will be tended to increase. For negative feedback, it occurs if the original input signal and feedback signal are out of phase, the output will be tended to reduce. Since negative feedback is more likely to stabilize the gain of the amplifiers and has a much more stable operating point than positive feedback, more applications of negative feedback are implemented in electronics field. ("Difference between Negative feedback and Positive feedback", 2019)

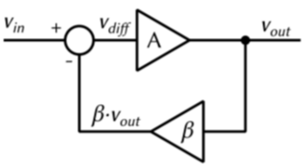


Figure.1 A generalized system employing negative feedback

As it is shown in Figure.1, the general system outcoming negative feedback which contains two operational amplifiers, one of the operational amplifiers with gain A is in the general system and parallels to the other operational amplifier with gain β. The summation block receives a positive input and a negative input and determines the output v_{diff}, the summation block can also define the operational amplifier with gain A as non-inverting amplifier or inverting amplifier. Then the output of summation block v_{diff} is being amplified by open-loop gain of A and become the output of the general system v_{out}. The feedback is generated by the operational amplifier with gain β which feeds a portion of the output v_{out} back to the input. The expression for the gain is shown below.

$$v_{out} = A v_{diff} \tag{1}$$

$$v_{diff} = v_{in} - \beta v_{out} \tag{2}$$

$$v_{out} = A(v_{in} - \beta v_{out}) \tag{3}$$

$$\frac{v_{out}}{v_{in}} = A - \frac{A\beta}{v_{in}} = \frac{A}{1 + A\beta} \tag{4}$$

From expression (4), it could be deduced that if A is sufficiently large, the expression is actually dominated by $1/\beta$ as '1' in the denominator can be ignored:

$$\frac{v_{out}}{v_{in}} = \frac{A}{A\beta} = \frac{1}{\beta} \tag{5}$$

Therefore, it is concluded that the open loop gain of a system with a differential input can be modified, by feeding a fraction, $1/\beta$ of the output back to the input. Furthermore, if the open loop gain is sufficiently high, the closed loop gain is clearly determined by the feedback fraction $1/\beta$.

2.2 Amplifier gain in open loop systems and closed loop systems

In this section, an inverting amplifier is considered as practical context to demonstrate how feedback employs to amplifiers, as it is shown in Figure.2:

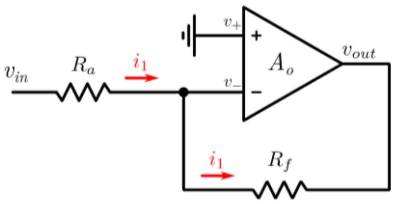


Figure.2 Simple Inverting amplifier circuit for an amplifier with open loop gain A_o

The inverting amplifier circuit diagram consists two resistors, R_a and R_f and an amplifier with a gain of A_o. The input v_{in} is being amplified by the amplifier with a gain of A_o, and some of the output v_{out} is being returned to the input through the resistor, R_f. Based on the assumption of ideal amplifier that there is no current flows into the inverting input (however, in reality there will be a very small current flow into the inverting input), therefore a single current i_1 which is generated by the input v_{in} will flow through R_a and R_f. Also, the input differential voltage v_+ and v_- are used to determine the value of the output v_{out}. Due to the grounded situation for v_+, $v_+ = 0V$, therefore:

$$v_{out} = -A_o\, v_- \tag{6}$$

This leads to a transformation of the circuit from Figure.2 to Figure.3 as a potential divider as it is shown below.

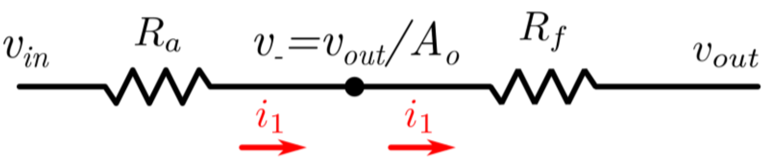


Figure.3: Considering Figure.2 as a potential devider

Therefore, i_1 can be expressed as:

$$i1 = \frac{v_{in} - \frac{v_{out}}{A_O}}{R_a} = \frac{\frac{v_{out}}{A_O} - v_{out}}{R_f} \tag{7}$$

Rearranging equation 7:

$$\frac{R_f}{R_a} = \frac{\frac{v_{out}}{A_O} - v_{out}}{v_{in} - \frac{v_{out}}{A_O}} \tag{8}$$

Rearranging equation 8:

$$\frac{v_{out}}{v_{in}} = [-\frac{R_a}{R_f}(\frac{1}{A_o} + 1) - \frac{1}{A_o}]^{-1} \tag{9}$$

The equation 9 shows the general equation for closed loop gain of the inverting amplifier for any value of input resistor, R_a, feedback resistor, R_f and amplifier gain (open loop gain) A_o.

2.3 Phase difference and how to measure it.

Phase difference is the difference in phase angle between two sinusoids or phasor that have the same frequency ((“Collins English Dictionary", 2019)). Normally the phase difference is calculated by either the time delay or angle between two sinusoids. In this experiment, the oscilloscope has function which can measure the phase difference and generate the result directly.

2.4 Stability in system: Transfer amplifier to oscillator

An oscillator is a combinational device that could generate continuous indefinite oscillations. For a transfer amplifier, the oscillations only appear in an unstable state in feedback system, which means that the feedback system cannot access to a stable state due to the dissatisfaction of the transfer function. For instance, using the example of negative feedback in Figure.1 and equation 4 for the closed loop gain. The equation tends to unstable when the denominator, $(1+A\beta)$ tends 0 as the system will be in an undefined state. Therefore, the formation of the oscillations in feedback system will determine the value of the product of A and β, which should be -1, or being expressed as $1\angle{-180°}$ in complex math. The phase shift is normally announced by both active and passive components. In the case of feedback system and oscillator, the 180° phase shift is mainly caused by passive components which are resistors and capacitors, because they are accurate and almost drift free. ((Mancini, 2017))

When $A\beta$ approaches to -1, the closed loop gain and the output voltage tends to infinity. However, based on the principle of amplifier, the output voltage cannot exceed the power rail and the increment of the output voltage will eventually stop. This leads to the change of open loop gain, A, in order to achieve $A\beta = -1$ and increasing the closed loop gain. At that stage, the system could either become stable and lock up as the non-linearity in saturation or cut-off; or produce highly distorted oscillation (usually quasi square waves) as the system will saturate and being held in saturation for a long period until the system become linear and approach to the opposite power rail; or produce sine wave as the system remains linear and reverses direction, approaching to the opposite power rail.((Mancini, 2017))

The oscillator which the lab experiment is testing is shown as Figure.4:

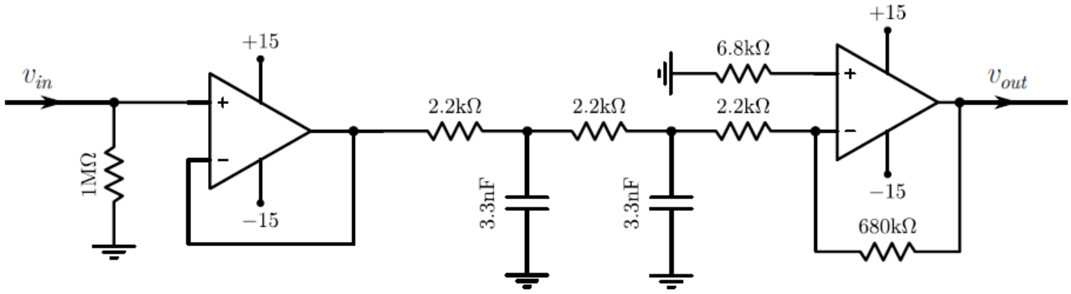


Figure.4: Schematic of the amplifier board

The circuit contains a buffer to eliminate the interference and a Resistance-Capacitance (RC) Oscillator (consist of resistors, capacitors and feedback system), which the characteristic will be due to the equations shown below:

$$X_C = \frac{1}{2\pi f C}, \; R = R \tag{10}$$

$$Z = \sqrt{R^2 + (X_C)^2} \tag{11}$$

$$\phi = \tan^{-1}\frac{X_C}{R} \tag{12}$$

From equations 10 and 12, it can be deduced that the phase shift of the circuit can be affected by the input frequency. Also depends on the number of sets of resistors and capacitors, the phase shift could increase even further if there are more sets of resistors and capacitors. For each set of resistors, the maximum phase shift is 90° (("The RC Oscillator Circuit", 2019))

2.5 Q-factor and time constants in the content of resonant systems

In general, resonance occurs when a system will oscillate at a higher amplitude when a certain frequency is applied and has least damping. In electronics and electrical field, the resonance presents at certain frequency called resonant frequency, when the impedance of each elements in circuit has cancelled each other out. This means that the impedance of the circuit between input and output is close to 0. (("Electrical resonance", 2019)) Similarly, for an oscillator system, certain frequency is needed from the input signal in order to form resonance which will cause oscillation with no driving and no damping force. The frequency is called natural frequency. (("Forced Oscillations and Resonance – College Physics", 2019))

Q-factor is one of the most important figures to show the characteristic of a resonant system. Q-factor is defined as a dimensionless parameter that indicates the energy loss in a resonant system and is associated with bandwidth of the resonant system due to the central frequency in the bandwidth. Particularly in electronic circuits, energy losses are strongly related to the passive components, i.e. resistors and capacitors. (("Quality Factor |

Q Factor Formula | Electronics Notes", 2019)) The mathematically expression for Q-factor is shown as equation 13:

$$Q = \frac{f_r}{\Delta f} = \frac{\omega_r}{\Delta\omega} \tag{12}$$

Where f_r is the resonant frequency; Δf is the -3dB bandwidth; ω_r is the angular resonant frequency; and $\Delta\omega$ is the angular -3dB bandwidth.

It can be deduced from the equation 12 generally that at the resonant frequency, as Q-factor become larger, the bandwidth will become narrower and will obtain a higher amplitude of response. Applying the characteristics into electronic circuits, increasing of the Q-factor will lead to a greater response of the circuit at resonant frequency. Also, the circuit will become more sensitive with smaller range of frequency with resonant frequency and less reactive to the frequency outside the range.

Time constant (τ), is the time required for a decay system which continue to decay at the initial rate such as step decrease, to the value of 36.8% of initial value; or the time required for an increasing system such as step increase to achieve 63.2% of the final value.(("Time constant", 2019)) Therefore, the less the time constant (τ) is, the quicker it is for the system to response. Applying the characteristics into the electronic circuits, considering the circuit as it is shown in the Figure.4 above, it is a complex RC circuit. Therefore, the time constant (τ) equals to the product of resistance and capacitance value of the circuit as it is the time period when the current though the capacities circuit decrease to 36.8% of its initial value. (("Time Constant | Electrical4U", 2019))

2.6 Preparatory Exercise

Question 1: Refer back to the amplifier in Figure.2, assuming it has an open loop gain A_o = 200, answer the following questions:

1. *For resistor value $R_f = R_a = 10k\Omega$, what gain does the amplifier achieve?*
2. *For resistor value $R_f = 1M\Omega$ and $R_a = 10k\Omega$, what gain does the amplifier achieve?*
3. *What can you conclude about the amplifier from these two results? Is it possible to achieve gain higher than A_o.*

Solutions:

1. From equation.9, $\frac{v_{out}}{v_{in}} = [-\frac{R_a}{R_f}(\frac{1}{A_o} + 1) - \frac{1}{A_o}]^{-1}$, we can deduce that after R_f, R_a and A_o have substituted in. $\frac{v_{out}}{v_{in}} = [-\frac{10k}{10k}(\frac{1}{200} + 1) - \frac{1}{200}]^{-1}$

$$\frac{v_{out}}{v_{in}} = -0.99$$

2. After substituting R_f, R_a and A_o in the equation.9: $\frac{v_{out}}{v_{in}} = [-\frac{10k}{1M}(\frac{1}{200} + 1) - \frac{1}{200}]^{-1}$

$$\frac{v_{out}}{v_{in}} = -66.45$$

3. With the same R_a, as R_f increases, the magnitude of gain increases. When $\frac{R_a}{R_f} = \frac{1}{\infty}$, the result of the fraction tends to zero and the gain is the largest which equal to A_o. Therefore, the gain will not be greater than A_o.

Question 2: Consider the non-inverting amplifier in Figure.5, applying the same methods from the previous section, derive an expression for v_{out}/v_{in}. What happens to this expression as $A_o \rightarrow \infty$?

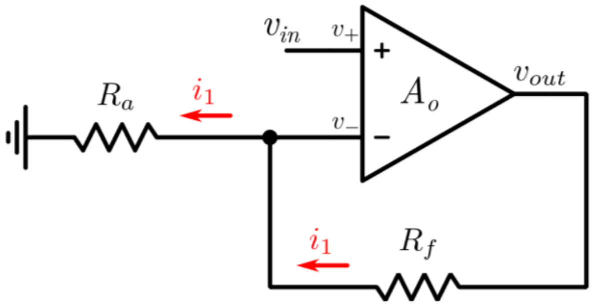


Figure.5: Non-inverting amp.

Solution:

$$v_{out} = [v_{in} - v_{out}(\frac{R_a}{R_f + R_a})]A_o$$

$$v_{out}[1 + (\frac{R_a}{R_f + R_a})A_o] = A_o\, v_{in}$$

Therefore:

$$\frac{v_{out}}{v_{in}} = \frac{A_0}{[1 + (\frac{R_a}{R_f + R_a})A_o]}$$

As $A_o \rightarrow \infty$:

$$\frac{v_{out}}{v_{in}} = \frac{R_f + R_a}{R_a}$$

3.The Tasks

Task1: Open Loop Characterization and Non-Linear Behavior

This task is separated into 4 parts, in order to analysis the open loop as shown in Figure.6

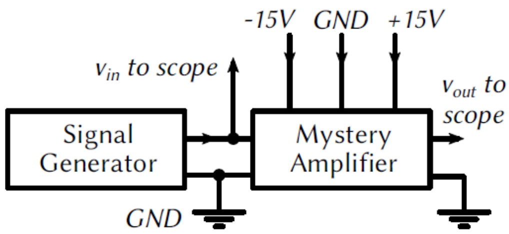


Figure.6: Connections for open loop tests

Task1.1:

The first task required us to connect the amplifier as shown in Figure.6, with input being generated by the signal generator, and both input output should be connected to the scope to be shown on the oscilloscope. Then it is required to make a phase measurement on the oscilloscope.

After connecting the amplifier as shown in Figure.6 and finishing all the setup, the phase measurement had been done by using the phase measure function in the oscilloscope.

Task1.2:

The second task required to discover the gain and the phase of the amplifier by sweeping the input frequency from 10Hz to 50kHz with a small input voltage (e.g. 100mV$_{p\text{-}p}$). After the data is collected, it is also required to display the results as a Bode plot.

Due to the requirement of using large range of input frequency from 10Hz to 50kHz and Bode plot, the data were collected using 1,2,5,10 rule to get a roughly log-spaced set of frequency. After the circuit was setup with 100mV$_{p\text{-}p}$ sinusoidal wave input voltage and set the frequency to 10Hz from the Signal Generator. Since V_{in} and V_{out} were both connected to the scope in Channel 1 and Channel 2 respectively already, two waves were shown on the oscilloscope. Measuring the peak to peak value of input and output from the oscilloscope, then using the 'measure' function in the oscilloscope to verify the phase difference. Then gain was calculated using Vout/Vin, and transfer in decibel (dB). Afterall, all the data were used to plot Bode Plot for both Gain and Phase using Matlab (Appendix A1).

Frequency (Hz)	Vin (mV)	Vout (V)	Gain (dB)	Phase (degree)
10	135.73	11.172	38.31	172.50
20	143.08	10.976	37.70	173.09
50	143.08	10.62	37.41	178.02
100	145.53	11.074	37.63	174.50
200	148.47	11.123	37.49	170.28
500	138.67	11.025	38.01	180.99
1000	150.43	10.927	37.22	171.16
2000	138.18	10.878	37.92	163.96
5000	138.18	10.192	37.36	126.29
10000	139.65	5.92	32.55	78.06
20000	144.06	1.754	21.71	17.76
50000	150.43	0.2558	4.61	-26.39

Table 1: Results for Task1.2

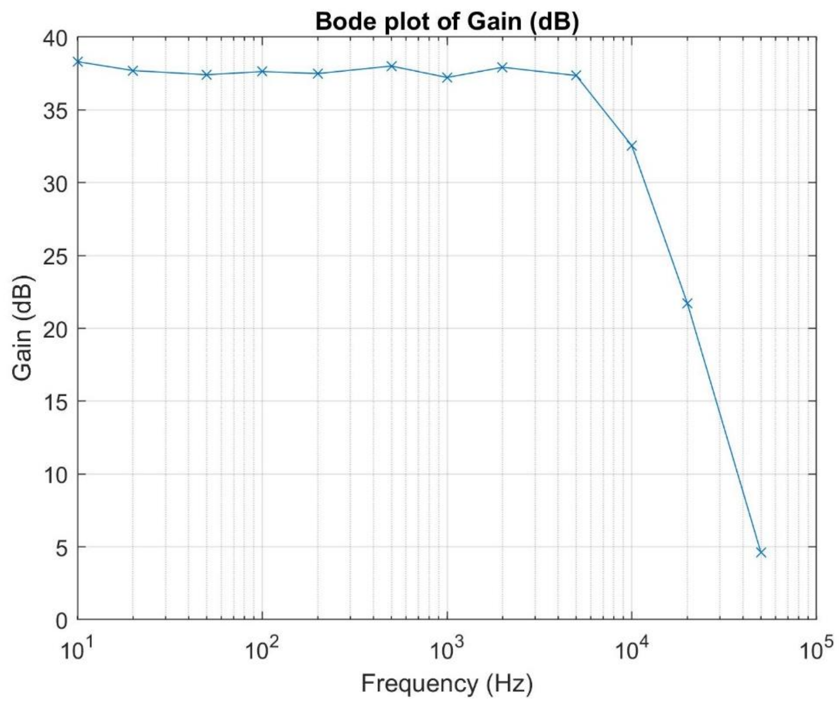


Figure.7: Bode Plot of Gain for Task 1.2

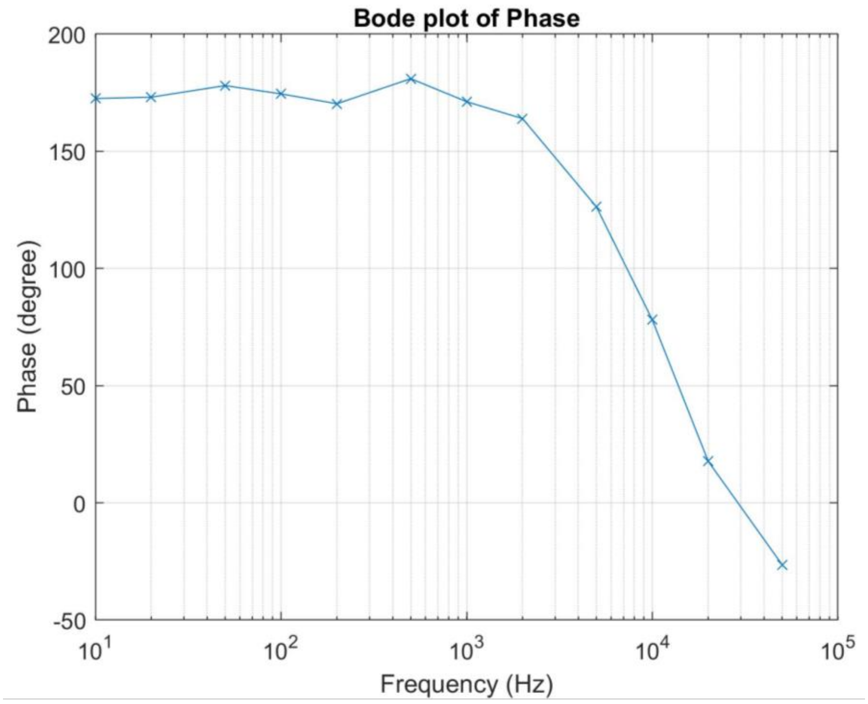


Figure.8: Bode Plot of Phase for Task 1.2

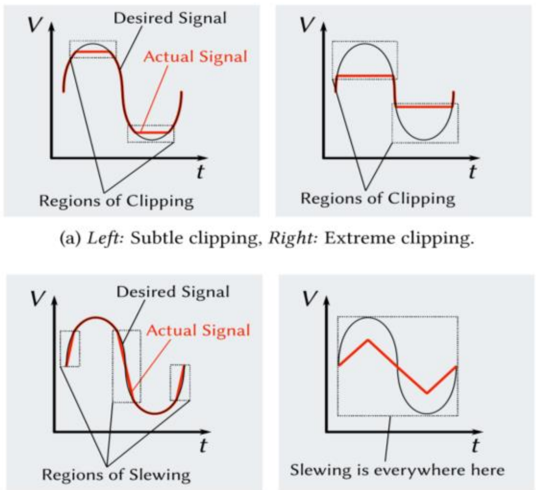
The Table.1 shows the table of results from the Task1.2 and Figure.7 and 8 show the Bode plot of Gain and Phase generated from the results.

Based on the results and the graph, the mystery amplifier shows a low pass filter property as gain stays above 35dB until at 10000Hz where the gain starts to drop dramatically. Also, the open loop gain of the mystery amplifier can be defined around 38 dB and the initial phase shift of the mystery amplifier is around 180°. Due to the equations 10 and 12 mentioned before, the maximum phase shift for each set of resistor and capacitor is 90°, therefore, it can be deduced that two sets of resistor and capacitor may be inside the mystery amplifier.

Task 1.3:

The third part of the task required to find out the maximum value of Vin that outcomes an undistorted Vout signal using the same frequency range as previous task. Record the voltage down and notice the nature of the distortion (clipping or slewing). Plot the 'distortion-point' voltages and the type of distortion (clipping or slewing).

As it is shown previously, 1,2,5,19 rule was used to determine a roughly log-spaced set of frequency. Adjusting the input voltage Vin from the signal generator until distortion showed (clipping when flat wave occurred at the peak of the wave, slewing when the sinusoidal wave become less curly and sharp at the peak. As shown in Figure.9). To ensure the 'distortion-point' voltage, double check Vin by increasing or decreasing the input to a point where it is the boundary between normal wave and distorted wave. Finally, the amplitude of 'distortion-point' voltage against frequency was plotted which also indicated type of distortion using Matlab (Appendix A2).



(a) *Left:* Subtle clipping, *Right:* Extreme clipping.

(b) *Left:* Subtle slewing, *Right:* Extreme slewing.

Figure.9: Illustrations of clipping and slewing, compare the red and black lines

Frequency (Hz)	Vin (V)	Nature of Distortion
10	0.294	Clipping
20	0.298	Clipping
50	0.305	Clipping
100	0.295	Clipping
200	0.283	Clipping
500	0.285	Clipping
1000	0.295	Clipping
2000	0.295	Clipping
5000	0.316	Clipping
10000	0.420	Slewing
20000	0.630	Slewing
50000	1.130	Slewing

Table.2: Results for Task1.3

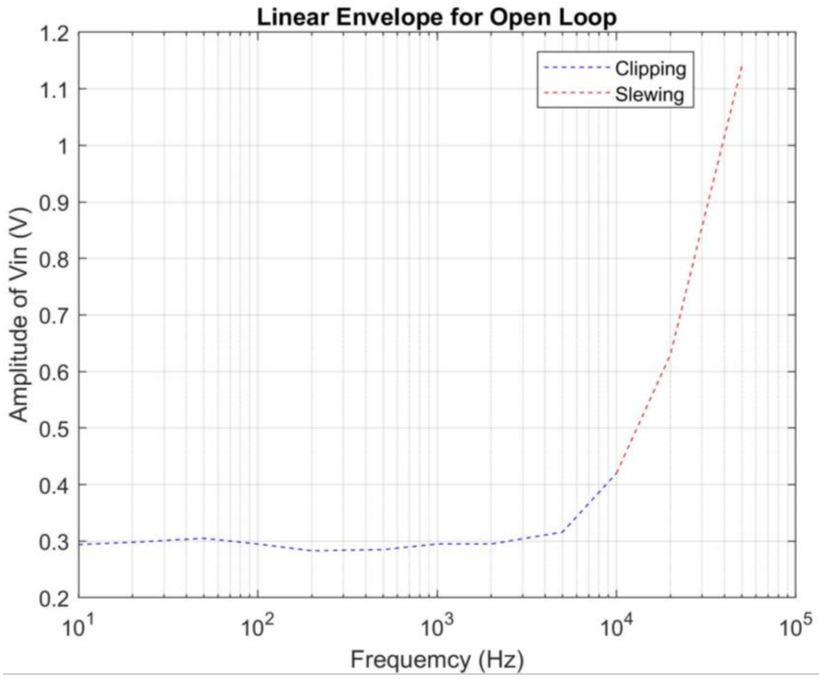


Figure.10: Linear Envelope for Open Loop Configuration

Clipping depends on the maximum output voltage or current from the amplifier. If the output exceeds the maximum output, the input signal cannot be amplified even further, therefore, causing a flat peak in sinusoidal wave. Slewing depends on frequency, as the amplifier cannot follow up with the fast change of voltage in input due to the high frequency. Both Table.2 and Figure.10 shows that clipping appears in low frequency, slewing appears in high frequency and in this case the clipping and slewing 'switching' point is above 5kHz and below 10kHz. Also, the gain between 5kHz and 10kHz starts to drop significantly as shown in Figure.8, therefore, the peak of slewing cannot reach the desired peak output. Overall, the results show the effect of increasing frequency and the type of distortion changes from clipping to slewing.

Task 1.4:

The final part of this task required to use a fixed input frequency and amplitude of 1kHz and 150 mV_{p-p} and then at the output of the amplifier, the switchable load is connected. By connecting an ohmmeter across the switchable load and find out the resistance value. Adjusting the potentiometer in order to change the output load and note down the gain and nature of distortion for each value of load resistance. Finally verify the maximum output current limit of the amplifier from previous results.

At the beginning, the fixed frequency was set to 1kHz and fixed amplitude of 150 mV_{p-p} input, the connect to the amplifier then switchable load. The range of switchable load is from 180Ω to 1164Ω. Therefore, it was decided to use the resistance from 200Ω to 1000Ω with 100Ω intervals between each resistance. With screw driver, the switchable load was adjusted. Afterall, all the data was collected, the maximum output current limit was calculated using the maximum output voltage and resistance at the distortion 'switching' point.

Resistance (Ω)	Vin (V)	Vout (V)	Gain	Nature of Distortion
200	0.179	9.114	50.92	Clipping
300	0.175	13.23	75.6	Clipping

350	0.176	14.11	60.17	Clipping
400	0.176	16.121	91.60	None
500	0.175	16.02	91.54	None
600	0.176	16.121	91.60	None
700	0.180	16.219	90.11	None
800	0.175	16.219	92.68	None
900	0.180	16.219	90.11	None
1000	0.178	16.17	90.84	None

Table.3: Results for task 1.4

From the table, the 'switching' point is between the resistance value of 300Ω and 400Ω, therefore, measurement of 350Ω was inserted in to the table. The maximum output current limit was calculated as:

$$I_{max} = \frac{V_{out}}{R} = \frac{16.121 - 14.11}{400 - 350} = 0.0402 \text{ A}$$

The term 'None' occurs in Table.3 in 'Nature of Distortion' column as during the lab experiment, there was no distortion showed up no matter how large the input voltage Vin it was put in. The maximum output current limit calculated was not precise as it was only an estimation and the relationship between output voltage and resistance are not linear. By narrowing down the intervals between 350Ω and 400Ω would improve the precision.

Task2: Feedback and The Gain-Bandwidth-Product

This task is separated into 3 parts. The objectives of this task are to identify the amplifier in a closed loop configuration and to make comparison with the results from previous task which is about the open loop configuration. In this task, input resistor R_a and feedback resistor R_f are added by using the switchable feedback resistor board. Figure.11 shows the circuit diagram for this task:

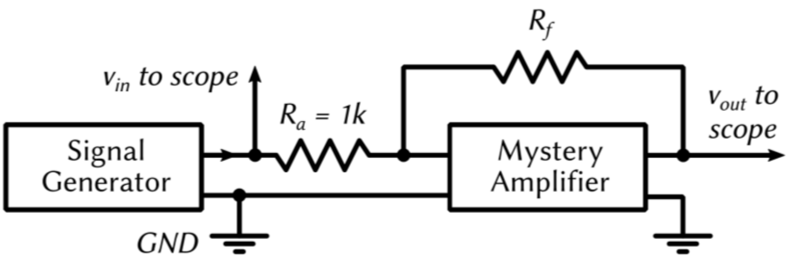


Figure.11: Closed loop setup

Task 2.1:

This first task required us to setup the circuit as shown in Figure.11. Then, it was asked to repeat the process which had been done in Task 1.2 and Task 1.3. For the testing, the input resistor R_a to 1kΩ and feedback resistor to 100Ω. Similarly, after all the data has collected, plot bode plots and linear envelopes.

Based on the requirement, the circuit built on as shown in Figure.11, similar method was used as before and data had been collected using the 1,2,5,10 rule again. Finally, Bode plots and linear envelope which were generated by Matlab (Appendix A3).

Frequency(Hz)	Vin (mV)	Vout (V)	Gain (dB)	Phase (degree)
10	117.6	5.74	33.77	179.44
20	119.56	5.78	33.69	179.46

50	113.68	5.12	33.07	174.49
100	116.13	5.60	33.66	171.79
200	115	5.8	34.05	175.64
500	115	5.6	33.75	174.18
1000	113.65	5.33	33.42	175.18
2000	113.68	5.46	33.63	168.54
5000	112.84	5.34	34.13	150.08
10000	114.66	5.28	33.26	101.29
20000	120.05	2.60	26.71	44.36
50000	116.13	1.31	21.04	-28.66

Table.4 Results for Task 2.1 Bode plots

Frequency (Hz)	Vin (V)	Nature of Distortion
10	0.245	Clipping
20	0.256	Clipping
50	0.247	Clipping
100	0.244	Clipping
200	0.253	Clipping
500	0.245	Clipping
1000	0.242	Clipping
2000	0.248	Clipping
5000	0.323	Clipping
10000	0.648	Slewing
20000	1.68	Slewing
50000	3.58	Slewing

Table.5 Result for Task 2.1 linear envelope

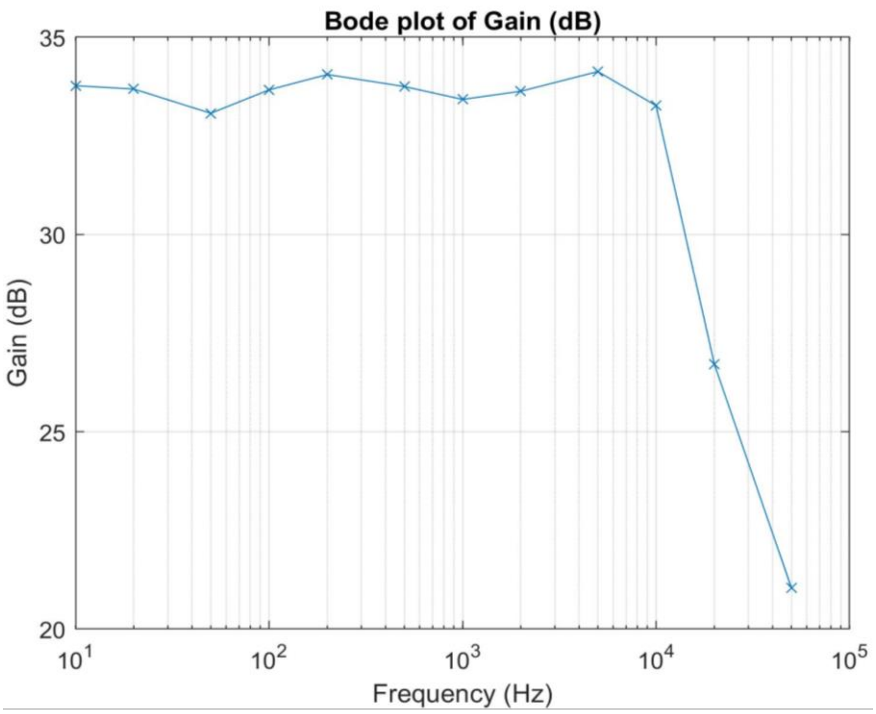


Figure.12: Bode Plot of Gain for Task 2.2

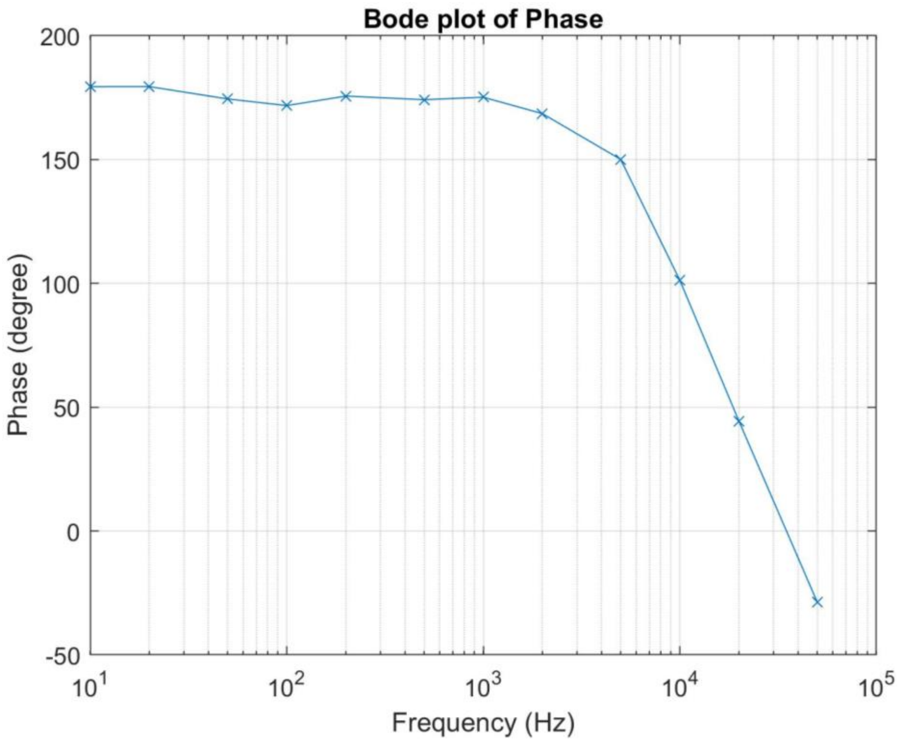


Figure.13: Bode Plot of Phase for Task 2.2

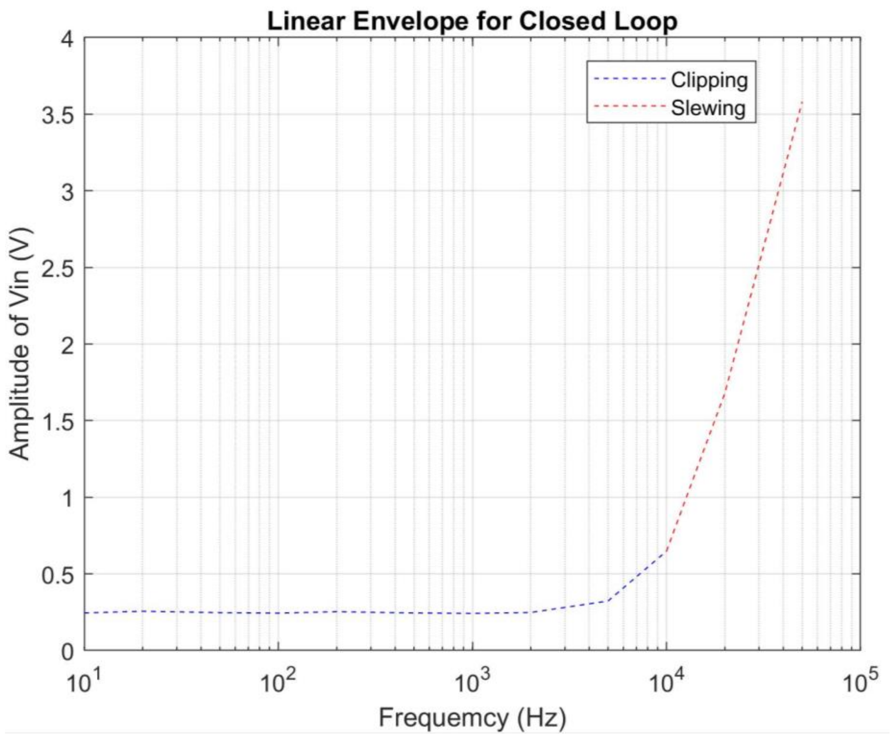


Figure.14: Linear Envelope for Closed Loop Configuration

Based on the Table.5 and Figure.12 and 13, the closed loop configuration shows a low pass filter property as gain stays above 32dB until the frequency reaches 10000Hz where the gain starts to drop enormously. Also, it can also conclude that the maximum phase shift of the circuit is around 180°. Table.6 and Figure.14 shows that in low frequency, the nature of distortion of the circuit is clipping, while in high frequency especially in above the range between 5kHz and 10kHz, the nature of distortion of the circuit is slewing. The comparison between open loop configuration and closed loop configuration will be notified and discussed in Task 2.2.

Task 2.2:

This task required us to compare the difference between the Bode plots of the open loop configuration and closed loop configuration.

This task could be done by comparing the two Bode plots of Gain and Phase and spotting the difference.

Firstly, for Bode plots of gain, by comparing two graphs, it could be observed that both plots have similar pattern, but the closed loop configuration average gain is slightly lower than open loop configuration average gain, with average gain 32.01dB compare to 33.16dB and increasing of bandwidth which could be deduced from the -3dB point. This might because of the involvement feedback system into the open loop configuration. Also, from the bode plots of linear envelope, it could be obtained that both graphs had similar pattern but the input voltage for distortion in closed loop configuration is higher than the input voltage in open loop configuration in all frequency.

As it is mentioned in the theory, as the amplitude response (gain) increases the bandwidth will be narrower, vice versa. The results did show a growth of bandwidth (at -3dB point), when there was a decline of gain in closed loop configuration. Therefore, the experimental result matches the theoretical conclusion.

Task 2.3:

The final part of this task required us to compute the Gain-Bandwidth-Product (GBWP) of both two configurations.

The method to calculate GBWP was simply multiplying the average gain and the bandwidth where the average gain should be the gain above -3dB point and the bandwidth should be taken from -3dB point. Therefore:

GBWP for open loop configuration:37.67dB * 7.5kHz = 282525 dBHz

GBWP for closed loop configuration: 30.64dB * 10.3kHz = 315592 dBHz

Both GBWP are almost equal which obey the theory that the GBWP is independent to the gain, which means that the bandwidth is negative proportional to the gain since GBWP is always constant in theory.

Task3: Feedback and stability

This task is separated into 3 parts. The intention of this is to investigate the stability of the mystery amplifier and check the condition that can make the mystery amplifier become unstable by employing more feedback.

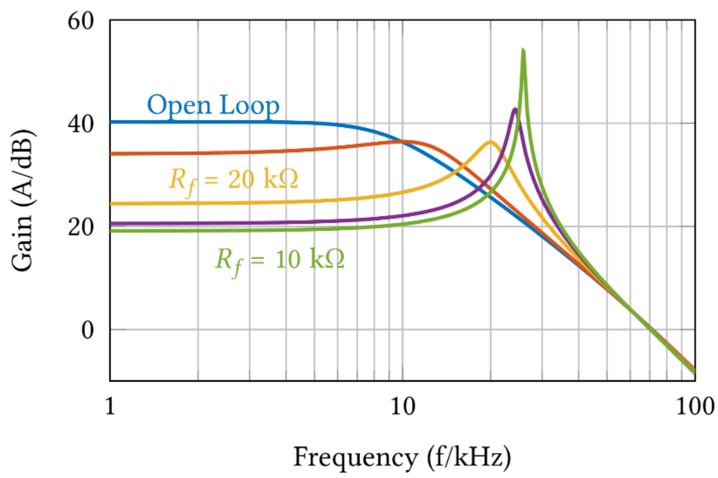


Figure.15: Bode plots for reducing values of R_f (increasing value of β

From the Figure.15 above, Bode plots for the mystery amplifier with different values of R_f could be observed. As the feedback resistor R_f reduces, the gain shows a sharp peak close to the -3dB point which would be expected in open loop curve. The sharp peaks demonstrate resonant response, the frequency where the peak occurred will be called resonant frequency, f_{res}. At the peak frequency, the amplifier will ring if an impulse involves; likewise, if the peak is sufficiently sharp, the amplifier may spontaneously oscillate.

Task 3.1:

The first part of task required to set the signal generator to a low frequency and amplitude, then to find the value of R_f when the spontaneous oscillation appears in the output of the mystery amplifier. Afterall, it is asked to deduce the frequency of the spontaneous oscillation.

First, it was set that the input signal as 1Hz sine wave and $1V_{p\text{-}p}$. Then signal generator is connected to the mystery amplifier. Sweeping the feedback resistor from large value to low value, until spontaneous oscillation occurred. Shorten the time domain range to determine the frequency of the spontaneous oscillation. The oscillation being generated should be at high frequency and is independent to the input signal from the signal generator.

At the end, the spontaneous oscillation occurred when R_f was in the range of 0Ω - 12kΩ and the frequency of the spontaneous oscillation was in the range 19kHz to 25kHz, respectively.

The results show that as the feedback resistance increases, the frequency of the spontaneous oscillation increases. This is because as feedback resistance increases, the resonant frequency decreases and the peak get smoother, which upsurges the stability of the system. As more stable the system is, the higher frequency there will as spontaneous oscillation. Figure.15 and the results had shown the relationship between feedback resistance, spontaneous frequency and stability.

Task 3.2:

The second part of the task required us to sweep R_f values between 1MΩ and 5kΩ and deduce the gain at low frequency, the resonant frequency f_{res} and the gain at f_{res}. Also, as

R_f gets higher, there may be no peak at all, so for some value of R_f, f_{res} may not be identified.

At the beginning, the test was started at 5kΩ, and increases the resistance from low to high. The resonant frequency was found out by changing the input frequency and finding the highest output voltage, then Vin and Vout at resonant frequency were recorded down in order to find the gain. Finally, the frequency was changed to 1Hz and the Vin and Vout were recorded down in order to find the gain at low frequency.

Resistance (kΩ)	Resonant Frequency (kHz)	Low Frequency Vout (V_{p-p})	Resonant Frequency Vout (V_{p-p})	Low Frequency Gain	High Frequency Gain
5	13.5	0.578	0.846	14.83	20.17
10	12.2	0.736	5.157	18.07	35.42
15	11.5	0.984	6.036	19.94	35.93
20	11	1.377	3.437	23.27	30.83
30	10.7	2.168	4.519	26.31	33.18
40	10.6	2.530	4.621	28.57	33.59
50	10.4	2.963	5.117	30.13	34.18
75	10.2	4.423	5.227	32.91	34.44
100	10	4.569	5.936	33.49	35.82
125	9.8	5.282	6.093	34.32	36.45
150	9.6	6.058	6.561	35.73	36.28
200	6.3	6.421	6.865	36.15	36.81
300	4.6	7.106	7.271	37.08	37.36
400	No Peaking	7.537	N/A	37.92	N/A

Table.6: Results for Task 3.2

From table.6, as the value of R_f increases from 5kΩ to 400kΩ, there was no peaking for the at the output for the gain. Therefore, no more further data being collected from the resistance higher than 400kΩ needed for this lab experiment.

As it is shown from the results in table.6, as the feedback resistance rises, the difference between Low Frequency Gain and High Frequency diminishes. This relationship demonstrates that the system become more stable as the Gain between low frequency and high frequency are getting closer, thus the peak become smoother. Also, the sharp peak is less likely to appear as the feedback resistance enlarges, this means the resonance will disappear gradually, which proves the improvement of the stability even further.

Task 3.3

The final part of this task required to set the input signal to a square wave at low frequency. Then sweeping the feedback resistance, discover the response at the output where the ringing should be generated by the mystery amplifier at the output as shown in Figure.16:

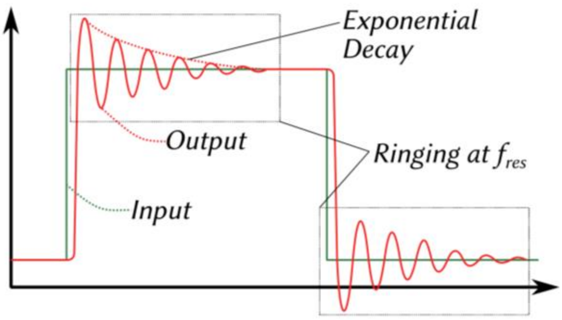


Figure.16: Step Inputs generating ringing

At the end, determine the relationship between changes of ringing and changes of R_f.

First, set the signal generator from sine wave to square wave, set the input frequency to 1kHz and amplitude to $0.5V_{p-p}$ and connect the signal generator to the mystery amplifier. Then R_f was changed in order to discover its relationship to the changes of ringing. Amplitude of ringing were recorded down.

Feedback Resistance (kΩ)	Ringing Amplitude (V)
1	12.443
2	12.302
5	12.110
10	7.723
12	5.414

Table.7: Results for Task 3.3

The recording of Ringing Frequency and Ringing Amplitude stopped when value of feedback resistance reached 12kΩ, as the spontaneous oscillation only occurs below 12kΩ. As the feedback resistance increased, the output displayed in oscillator become more similar to the output which is shown in Figure.16. Also, from Table.7, the Ringing Amplitude showed a negative proportional property to the Feedback Resistance while as Feedback resistance stepped up, the Ringing Amplitude shrunk.

This is because the ringing shows at output is undesirable, the appearance of ringing indicate the instability of the feedback system. At high frequency the feedback resistor in small value provides enough close-loop gain to stabilize the amplifier and avoid ringing ((Bendaoud & Marino, 2004)). However, at low frequency, the feedback resistor should reach sufficient resistance in order to stabilize the system. The reduction of the amplitude of ringing deduces that the ringing is disappearing which means the system become stable and the result also prove the theory. Therefore, at low frequency, the boost of the feedback resistance will increase the stability of the feedback system.

4. Conclusion

During the lab experiment, the open loop configuration and the closed loop configuration was analyzed in task1 and task 2, respectively by the gain and phase response of the amplifier. Also, the nature of distortion for two configurations were discovered, however, in order to improve accuracy for the changing point between two natures, more data should be collected by smaller the intervals between two sets of data for further and clear analysis. In task 2, for closed loop configuration, the gain-bandwidth-products were also deduced, but there was still some error occurred due to the estimation of data from the figure. However, the error was quite acceptable, and the error could be reduced by taking more recording at -3dB point, furthermore the content of the gain-bandwidth-product had demonstrated successfully.

In task 3, the feedback property and the stability were tested. Ringing signal detection which could show the stability of the feedback system was challenge, as the frequency of input signal was set too low due to the previous experiment, the time consumption was enormous to find the ringing signal. After some research had been done, the frequency of input signal was adjusted to 1kHz for better formation and observation of Ringing signal. The task was also successful as the results meets the conclusion from the theory.

At the end, recalling all the process had been done and the result in the lab experiment, basic concepts of amplifier were more solidifier. Also, gain-bandwidth-product and the relationship between gain and bandwidth of amplifier were clearer. Likewise, principle of stability, gain margin and phase margin were discovered with more details. Furthermore, the formation of oscillator from amplifier were leant. Therefore, the aims and objectives of the lab experiment had achieved, thus the lab experiment was successful.

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Appendices:

A. Matlab Coding

Appendix A1:

```
Freq = [10 20 50 100 200 500 1000 2000 5000 10000 20000 50000];
vin = [135.73 143.08 143.08 145.53 148.47 138.67 150.43 138.18 138.18 139.65 144.06 150.43]*10^-3;
vout = [11.172 10.976 10.62 11.074 11.123 11.025 10.927 10.878 10.192 5.92 1.754 0.2558];
phase = [172.50 173.09 178.02 174.5 170.28 180.99 171.16 163.96 126.29 78.06 17.76 -26.39];
Gain = vout./vin;
GaindB = 20.*(log10(Gain));
figure;
semilogx(Freq,GaindB,'x-');
grid on
xlabel('Frequency (Hz)');
ylabel('Gain (dB)');
title('Bode plot of Gain (dB)');
figure;
semilogx(Freq,phase,'x-');
grid on
xlabel('Frequency (Hz)');
ylabel('Phase (degree)');
title('Bode plot of Phase');
```

Appendix A2:

```
FreqC = [10 20 50 100 200 500 1000 2000 5000 10000];
FreqS = [10000 20000 50000];
VinC = [0.294 0.298 0.305 0.295 0.283 0.285 0.295 0.295 0.316 0.42];
VinS = [0.42 0.63 1.14];
figure;
semilogx(FreqC, VinC, 'b--');
hold on;
semilogx(FreqS, VinS, 'r--');
grid on;
xlabel('Freqeuemcy (Hz)');
ylabel('Amplitude of Vin (V)');
title('"Distortion-point" voltage and type of Distortion');
legend('Clipping','Slewing');

```

Appendix A3:

```
Freq = [10 20 50 100 200 500 1000 2000 5000 10000 20000 50000];
vin = [117.6 119.56 113.68 116.13 115 115 113.65 113.68 112.84 114.66 120.05 116.13]*10^-3;
vout = [5.74 5.78 5.12 5.60 5.8 5.6 5.33 5.46 5.74 5.28 2.60 1.31];
phase = [179.44 179.46 174.49 171.79 175.64 174.18 175.18 168.54 150.08 101.29 44.36 -28.66];
Gain = vout./vin;
GaindB = 20.*(log10(Gain));
figure;
semilogx(Freq,GaindB,'x-');
grid on
xlabel('Frequency (Hz)');
ylabel('Gain (dB)');
title('Bode plot of Gain (dB)');
figure;
semilogx(Freq,phase,'x-');
grid on
xlabel('Frequency (Hz)');
ylabel('Phase (degree)');
title('Bode plot of Phase');
```

```
FreqC = [10 20 50 100 200 500 1000 2000 5000 10000];
FreqS = [10000 20000 50000];
VinC = [0.245 0.256 0.247 0.244 0.253 0.245 0.242 0.248 0.323 0.648];
VinS = [0.648 1.68 3.58];
figure;
semilogx(FreqC, VinC, 'b--');
hold on;
semilogx(FreqS, VinS, 'r--');
grid on;
xlabel('Freqeuemcy (Hz)');
ylabel('Amplitude of Vin (V)');
title('Linear Envelope for Closed Loop');
legend('Clipping','Slewing');
```