Constructor University Bremen

Natural Science Laboratory
Electrical Engineering Module I

Fall Semester 2024

Lab Experiment 5 – Filter

Appendix Experiment 6 – Operational Amplifier

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Place of execution : Teaching Lab 53
Date of execution : March. 21, 2024

1 Introduction

This experiment aimed to explore the behavior of passive RLC networks when subjected to a sinusoidal input signal of varying frequencies. The primary goal was to construct the circuit, measure its key properties, and analyze the obtained data to understand its performance and characteristics.

2 Theory

A filter is an electrical network designed to isolate a specific range of frequencies from an input signal while attenuating all other frequencies. In this experiment, only passive filters were used, with three different types constructed: low-pass, high-pass, band-pass and Notch filters. A passive filter consists of resistors, capacitors, and inductors without any active components such as transistors or operational amplifiers.

The key properties of a filter include:

1. **Frequency Response** – Describes how the output of the filter varies with different input frequencies while maintaining a constant input signal.
2. **Cutoff Frequency (Corner Frequency)** – The threshold frequency beyond which the filter significantly attenuates the signal. At this frequency, the output power is reduced to half of its passband value, meaning the output voltage is reduced to $\frac{1}{\sqrt{2}}$ of its passband value.
3. **Center Frequency** – In a band-pass filter, the center frequency f_{bw} is the geometric mean of the upper f_1 and lower f_2 cutoff frequencies, given by:

$$f_{bw} = \sqrt{f_1 * f_2}$$

4. **Bandwidth** – The range of frequencies that pass through a band-pass filter without significant attenuation, calculated as the difference between the upper and lower cutoff frequencies.
5. **Time Constant (τ)** – Represents the time taken for a capacitor in an RC circuit to charge to 63.2% of its full capacity or discharge to 36.8% of its initial voltage. It is determined by the product of resistance (R) and capacitance (C):

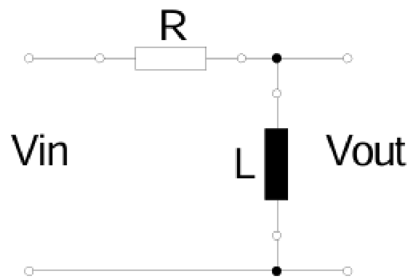
$$\tau = RC$$

6. **Angular Frequency (ω)** – A measure of the rate of change of phase in a sinusoidal function, defined as:

$$\omega = 2\pi f$$

High Pass Filters

A high-pass filter is a circuit designed to allow higher frequencies to pass through while attenuating lower frequencies. In this type of filter, the output signal experiences a phase shift that leads the input signal, meaning the phase shift is positive. High-pass filters can be constructed using either resistor-inductor (RL) or resistor-capacitor (RC) configurations. In this experiment, RC high-pass filter circuits were used to analyze their frequency response and behavior.



The amplitude ratio $\underline{A}(j\omega)$ for an RC combination:

$$\underline{A}(j\omega) = \frac{\underline{V}_{out}}{\underline{V}_{in}} = \frac{R}{R + \frac{1}{j\omega C}} + \frac{R}{1 + \frac{1}{j\omega RC}}$$

The magnitude and phase shift are given by:

$$|\underline{A}| = \frac{1}{\sqrt{1 + \left(\frac{1}{\omega RC}\right)^2}}$$

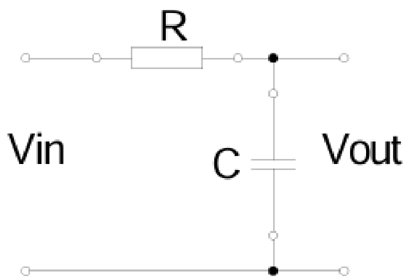
$$\varphi = arctan\left(\frac{1}{\omega RC}\right)$$

The Cutoff frequency

$$f_{-3dB} = \frac{1}{2\pi RC}$$

Low Pass Filters

A low-pass filter is a circuit that allows lower frequencies to pass through while attenuating higher frequencies. In this type of filter, the output signal lags the input signal, resulting in a negative phase shift. Low-pass filters can be constructed using various configurations, and in the case of an RC low-pass filter, the resistor and capacitor work together to determine the cutoff frequency and the filter's overall response.



The amplitude ratio $\underline{A}(j\omega)$:

$$\underline{A}(j\omega) = \frac{\underline{V}_{out}}{\underline{V}_{in}} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{1}{1 + j\omega RC}$$

The magnitude and phase shift are given by:

$$|\underline{A}| = \frac{1}{\sqrt{1 + (\omega RC)^2}}$$

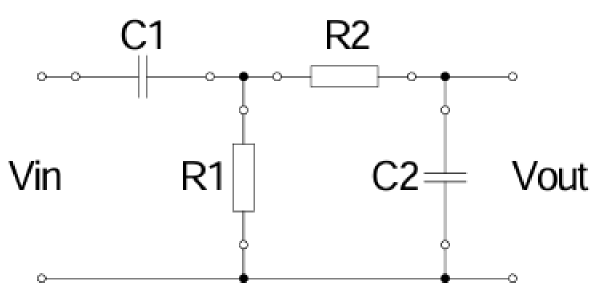
$$\varphi = -arctan(\omega RC)$$

The Cutoff frequency

$$f_{-3dB} = \frac{1}{2\pi RC}$$

Band Pass Filters

A band-pass filter is a circuit designed to allow frequencies within a specific range to pass while attenuating those outside this range. The simplest method to construct a band-pass filter is by combining a high-pass filter, which blocks low frequencies, with a low-pass filter, which blocks high frequencies. This combination effectively isolates the desired frequency band, making band-pass filters useful in applications such as signal processing and communications.



When combined, the overall transfer function of the band-pass filter is given by:

$$\underline{A}(j\omega)_{hi} * \underline{A}(j\omega)_{low} = \frac{\underline{V}_{out_{low}}}{\underline{V}_{in}} = \left|\underline{A}\right|_{hi} * \left|\underline{A}\right|_{low} * e^{j(\omega hi + \omega low)}$$

The cutoff frequency formula remains the same as before:

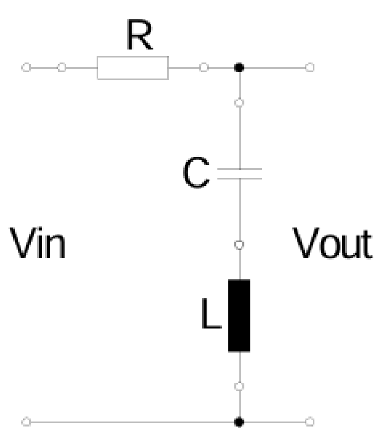
$$f_{-3dB} = \frac{1}{2\pi RC}$$

However, it must be applied separately for each stage of the filter—once for the high-pass section and once for the low-pass section—to determine the overall response of the band-pass filter.

Notch Filters

A Notch Filter (also known as a Band-Stop Filter or Band-Rejection Filter) is a type of filter that allows most frequencies to pass through unchanged, but significantly attenuates frequencies within a specific range. This filter functions as the opposite of a band-pass filter. It is typically built using an RLC combination (resistor, inductor, and capacitor), as shown in the circuit diagram on the left.

The magnitude A(jω) and phase shift φ are derived from the voltage divider formula. Since this design differs from that of a band-pass filter, new calculations are required. Additionally, it is possible to design a band-pass filter from this circuit by simply using the voltage drop across the resistor as the output.



The amplitude ratio $\underline{A}(j\omega)$:

$$\underline{A}(j\omega) = \frac{\underline{V}_{out}}{\underline{V}_{in}} = \frac{j\left(\omega L - \frac{1}{\omega C}\right)}{R + j\left(\omega L - \frac{1}{\omega C}\right)} = \frac{1}{1 - j\left(\frac{R}{\omega L - \frac{1}{\omega C}}\right)}$$

The magnitude and phase shift are given by:

$$|\underline{A}| = \frac{1}{\sqrt{1 + \left(\frac{R}{\omega L - \frac{1}{\omega C}}\right)^2}}$$

$$\varphi = arctan\left(\frac{R}{\omega L - \frac{1}{\omega C}}\right)$$

The Center frequency

$$f_{cf} = \frac{1}{2\pi\sqrt{LC}} \quad eq.1$$

The Cutoff frequency

$$\omega_{low} = \frac{-RC \pm \sqrt{(RC)^2 + 4LC}}{2LC} \quad eq.2$$

$$\omega_{high} = \frac{RC \pm \sqrt{(RC)^2 + 4LC}}{2LC} \quad eq.3$$

Output Characteristics of a filter

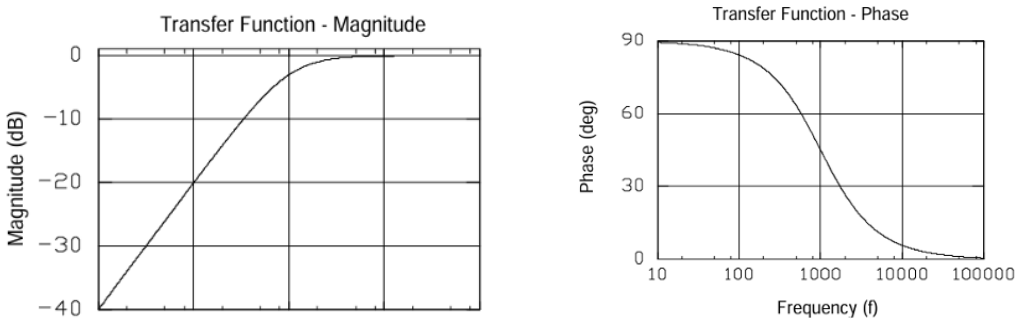
The frequency response is a key characteristic used to describe the behavior of a filter. It is analyzed by observing how the output signal changes as the input frequency varies. The amplitude of the output signal is measured across a broad frequency range, often spanning multiple decades. The output-to-input voltage ratio is then calculated and expressed in decibels (dB) using the following formula:

$$A = 20 * log10\left(\frac{V_{out}}{V_{in}}\right)$$

In addition to measuring amplitude, another important characteristic of the filter is the phase shift (φ) between the input and output signals, with the input signal taken as the reference. If the phase shift is positive, it indicates that the output signal leads the input signal. Conversely, if the phase shift is negative, the output signal lags the input signal.

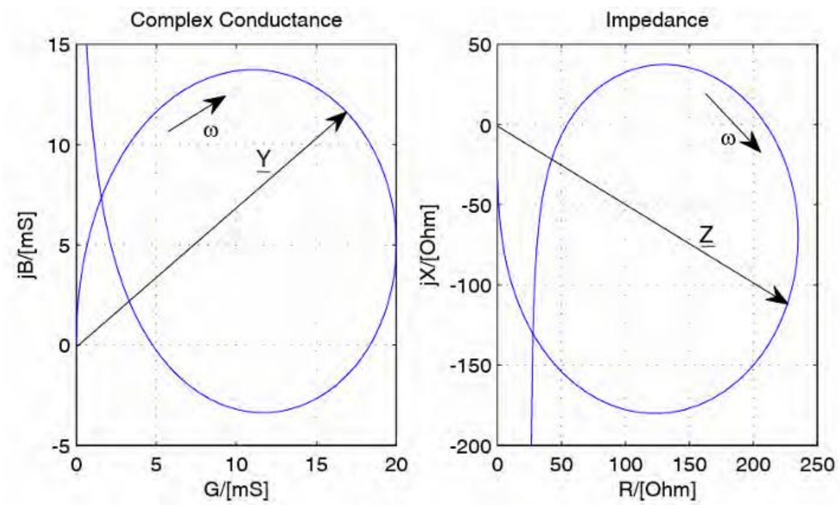
Bode Plot

A magnitude Bode plot is a graphical representation of the magnitude (in dB) plotted against frequency on a logarithmic scale. Similarly, a phase Bode plot shows the phase shift as a function of frequency, also using a logarithmic scale for the frequency axis. These plots provide a comprehensive view of how a filter's amplitude and phase change across different frequencies. Below are examples of typical Bode plots:



Nyquist Plot

A Nyquist plot is a parametric representation of a system's frequency response. In this plot, the real part of the transfer function is shown on the X-axis, while the imaginary part is plotted on the Y-axis. The frequency is varied as a parameter, producing a curve that represents the system's behavior at each frequency. Below is an example of a Nyquist plot:



3 Experimental Part 1 – Hi - Pass

Workbench No.8

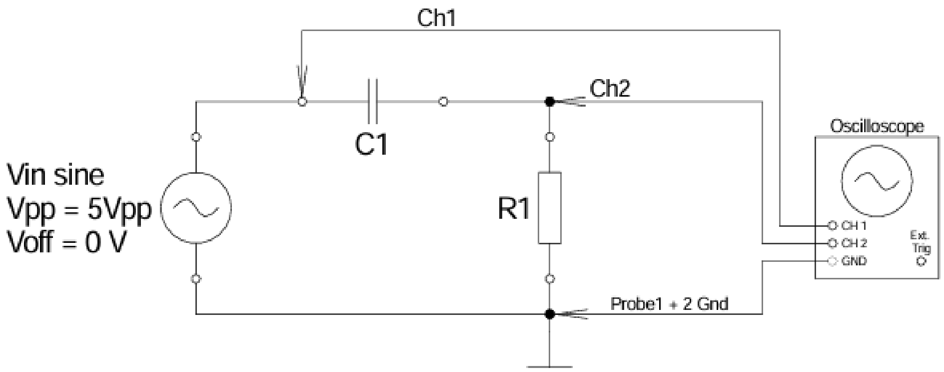
Used tools and Instruments:

- Signal Generator
- TENMA Multimeter
- BNC Cable
- Oscilloscope

- 1 x10 k-Ohm 1x22 k-Ohm and 1x8.2 k-Ohm Resistors
- Breadboard
- 1 x 1.5nF and 1 x 100nF Capacitors

The goal of this task is to determine the properties of a high-pass filter and analyze its characteristics over a range of frequencies. The results should be displayed using a Bode plot.

The following High-pass filter circuit was assembled. The signal generator was connected to the setup via a BNC-to-Kleps cable. Channel 1 (Ch1) of the oscilloscope was used to display the input signal, while Channel 2 (Ch2) was used to monitor the output signal.



$$C_1 = 1.5n\,\mathrm{F} \text{ and } R_1 = 22\,\mathrm{k\Omega}$$

The frequency of the signal generator was varied from 50 Hz to 100 kHz. During this range, the amplitude of both the input and output signals, as well as the phase shift between them, were measured. The measured values are summarized in Table.

I/P Frequency (khz)	I/p Amplitude (V)pp	o/p Amplitude (V)pp	Phase shift(degree)
0.05	10.3	0.128	105
0.1	10.3	0.234	90.9
0.2	10.2	0.452	88
0.5	10.3	1.09	82.9
1	10.8	2.6	83.8
2	10.8	4.4	69.6
5	10.8	7.6	48
10	10.8	9.4	30
20	10.8	10	16
50	10.8	10.6	7.2
100	10.8	10.8	1.7

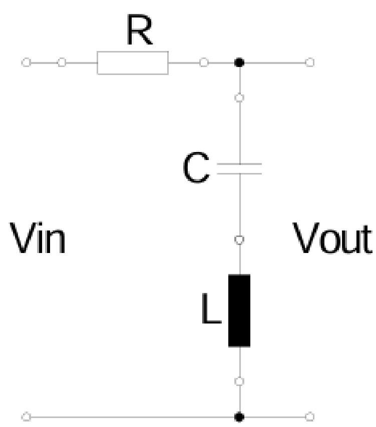
Table 1. Measured Amplitudes and phase shift for High - Pass

4 Experimental Part 2 – Notch Filter

The task is to determine the properties of a notch filter and analyze its characteristics over a range of frequencies. The results should be presented using both a Bode plot and a Nyquist plot.

A notch filter was built using a 1.5kΩ resistor, a 15nF capacitor, and a 10mH inductor. The signal generator was connected via the BNC-to-Kleps cable to the input, using a sine wave signal with a 5V amplitude and no offset. The oscilloscope was used to measure the input signal (Ch1), the output signal (Ch2), and the phase shift. Ch1 served as the reference signal.

Test Circuit



To calculate cutoff frequencies the following values were given:

Capacitor (F)	Inductor (H)	Resistor (Ω)
0.000000015	0.01	1500

Table 2. Given Element values

According eq.2 and eq.3 the cutoff frequencies were calculated where negative values can be ignored:

Fr cut_low (hz) (+ve)	Fr cut_high (hz) (+ve)	Fr cut_low (hz) (-ve)	Fr cut_high (hz) (-ve)
5708.535	29581.7774	-29581.7774	-5708.535938

Table 3. Calculated cutoff frequencies

Calculating Centre Frequency:

$$f_{cf} = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2 * \pi * \sqrt{0.01 * 0.000000015}} = 12995.536\ hz$$

Experimentally measured value for $f_{cf} = 13120\ Hz$ which is very close to the theoretical one.

A table was created for V_{in}, V_{out}, and φ. The frequency was varied from 10 kHz to 100 kHz. The table includes the cutoff values, as well as the calculated and measured center frequencies. Five additional values were inserted between each of the two cutoff frequencies (calculated) and the center frequency (measured experimentally).

I/P Frequency (khz)	I/p Amplitude (V)pp	O/p Amplitude (V)pp	Phase shift(degree)
1	10.2	10	-7.56
5.7	10	7.04	-43.4
7	10	5.84	-52.9
8	9.92	4.8	-60
9	9.92	3.84	-64
10	9.92	2.27	-70.3
11	9.92	1.84	-76.1
12.995	9.92	0.24	38.3
13.12	10	0.228	35.7
15	10	1.58	75.2
18	10	3.38	67.9
20	10	4.4	63.6
23	10	5.52	55.5
25	10	6.16	52.2
29.5	10	7.12	43.1
50	10.1	9.04	26.3
100	10.2	10.1	11.7

Table 4. Measured Input Output Voltage amplitude and Phase shift

5 Evaluation Part 1 – Hi - Pass

The Bode magnitude and phase plots for the data measured in Part 1 were generated using Excel. The magnitude was calculated using the formula:

$$A = 20 * log10\left(\frac{V_{out}}{V_{in}}\right)$$

It was then plotted against the logarithmic scale of the angular frequency.

Magnitude A (dB)	Frequency (Hz)
-38.1125451	50
-32.8724273	100
-27.0692347	200
-19.5082145	500
-12.3690082	1000
-7.79942158	2000
-3.05220326	5000
-1.20591804	10000
-0.66847511	20000
-0.1623578	50000
0	100000

Table 5. Values for experimentally calculated Magnitude and Frequency

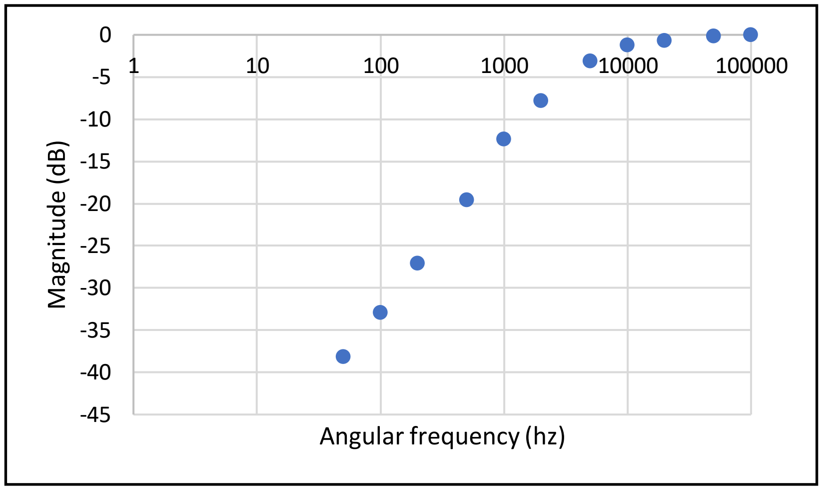


Figure 1. Bode Plot of Magnitude VS angular frequency logarithmic scale.

Same plot was constructed for Phase shift:

Frequency (HZ)	Phase Shift(degree)
50	105
100	90.9
200	88
500	82.9
1000	83.8
2000	69.6
5000	48
10000	30
20000	16
50000	7.2
100000	1.7

Table 6. Measured Phase Shift and Frequency

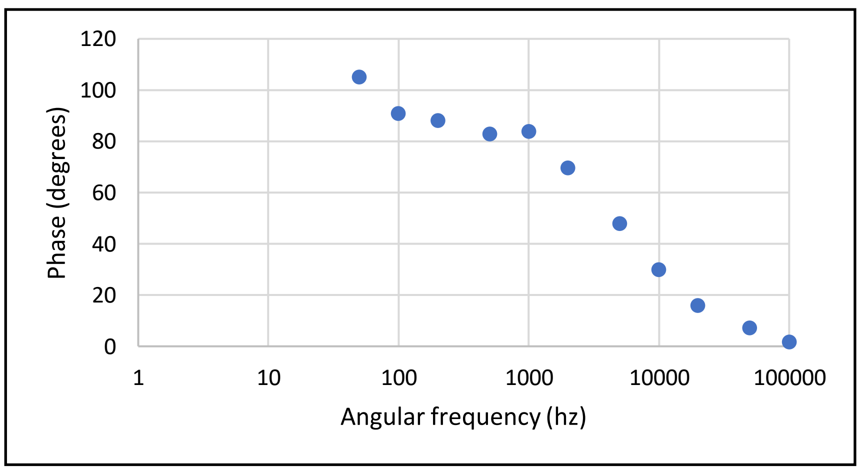


Figure 2. Bode Plot of Phase VS angular frequency logarithmic scale.

To compare measured Bode plot to Theoretical one the following formulas were used:

$$|\underline{A}| = \frac{1}{\sqrt{1 + (\omega RC)^2}} - to\ calculate\ the\ magnitude$$

$$\varphi = -arctan(\omega RC) - to\ determine\ the\ Phase\ Shift$$

$$A = 20 * log10(|\underline{A}|) - to\ calculate\ magintude\ in\ Decibels$$

After the calculations the following theoretical table were made:

I/P Frequency (hz)	Magnitude (dB)	Phase Shift (degrees)
50	-39.68	89.41
100	-33.67	88.83
200	-27.66	87.7
500	-19.78	84.29
1000	-13.94	78.69
2000	-8.6	68.2
5000	-3.36	47.73
10000	-1.3	30.51
20000	-0.45	17.1
50000	-0.14	6.84
100000	-0.07	3.44

Table 6. Theoretically calculated Magnitude (dB) and Phase shift

According to these data the comparison plot between experimental and theoretical values were made using logarithmic scale:

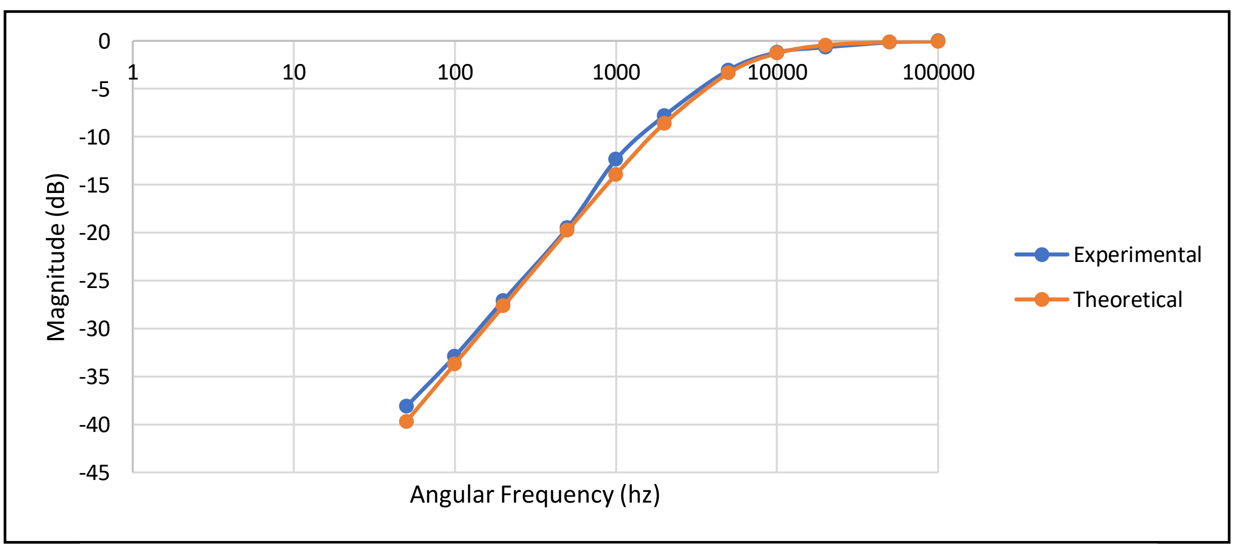


Figure 3. Comparison Bode Plot of Magnitude VS angular frequency logarithmic scale.

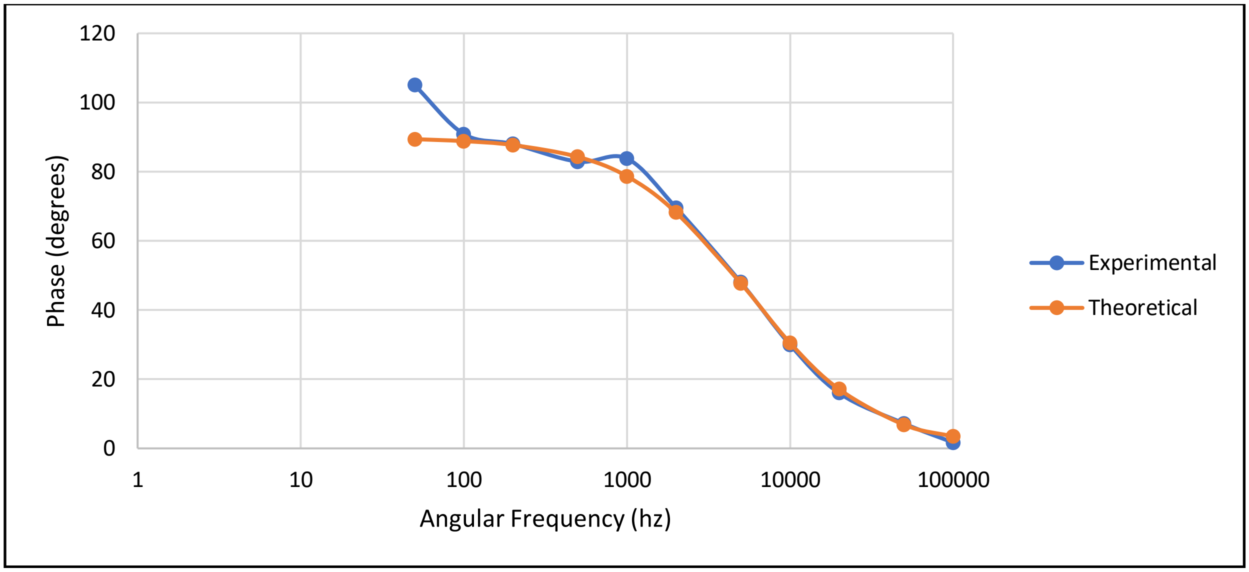


Figure 4. Comparison Bode Plot of Phase VS angular frequency logarithmic scale.

The plotted results revealed a slight difference between the theoretical and measured curves. This discrepancy can largely be attributed to errors encountered while recording measurements from the oscilloscope. However, despite this minor variation, the overall trends in both graphs were closely aligned and remained comparable.

To calculate theoretical -3dB frequency the following formula were used:

$$f_{-3dB} = \frac{1}{2\pi RC} = \frac{1}{2 * \pi * 22000 * 0.0000000015} = 4822.8771\ Hz$$

$$\omega_{-3dB} = 2\pi f_{-3dB} = 2\pi * 7073.55 = 2 * 3.14 * 4822.8771 = 30303.0303\ (rads^{-1})$$

The −3dB frequency was determined by identifying the nearest frequency point from the measured data that corresponds to a −3dB gain, and this frequency was then recorded as:

$$\omega_{-3dB} = 4 * 10^4\ rads^{-2}$$

Hence:

$$f_{-3dB} = \frac{\omega_{-3dB}}{2\pi} = \frac{40000}{2 * 3.14} = 6369.42\ Hz$$

It is important to note that there was a significant discrepancy between the theoretical −3dB frequency and the one obtained from the plot of the measured data. This difference can be attributed to the fact that the angular frequency extracted from the plot was only an approximation, not the exact value. The precise value could not be determined because the measured frequencies were not continuous.

Similarly, the theoretical phase shift at the ω_{-3dB} was calculated using the appropriate formula:

$$\varphi = arctan\left(\frac{1}{\omega_{-3dB}RC}\right) \approx 37.1°$$

Again, by taking the closest approximation from the plot, the phase shift at ω_{-3dB} was found to be around 30°. The discrepancy arises because an approximate value was used, as the data set had limited resolution and did not provide continuous frequency measurements.

However, both the frequency at −3dB and its corresponding phase shift, as measured from the graphs, were found to be very close to the theoretical values. This agreement holds after considering the fact that approximate values were taken due to the limitations of the data set.

Furthermore, the gradient of |A| per decade was determined by selecting two points from the graph, and the measured value was found to be:
From 100 Hz to 1kHz: $f_2 = 10 * f_1$

$$gradient\ |\underline{A}| = \frac{A_{dB}(f_2) - A_{dB}(f_1)}{log_{10}\left(\frac{f_2}{f_1}\right)} = A_{dB}(f_2) - A_{dB}(f_1) = (-12.37) - (-32.872) =$$
$$= 20.502\ dB/decade$$

The behavior of the high-pass filter was analyzed in three frequency regimes, based on both experimental and theoretical data:

1. Amplitude Ratio (in dB):

   a) $f \ll f_{-3dB}$ (Low frequencies, far below cutoff):
   The amplitude ratio approaches very low values, with the experimental data showing approximately −50 dB. This indicates significant attenuation of low-frequency signals.
   Theoretical expectation: −∞ dB.

   b) $f \gg f_{-3dB}$ (High frequencies, far above cutoff):
   The amplitude ratio approaches 0 dB, as observed in the experimental data. This confirms that high-frequency signals pass through the filter with minimal attenuation.
   Theoretical expectation: 0 dB.

   c) $f = f_{-3dB}$ (Cutoff frequency):
   The amplitude ratio is −3 dB, which corresponds to the theoretical half-power point. The experimental data shows this transition occurring near 3 Hz.
   Theoretical expectation: −3 dB.

2. Phase Shift:

   a) $f \ll f_{-3dB}$ (Low frequencies, far below cutoff):
   The phase shift approaches +90° in the experimental data, indicating that the output leads the input by nearly 90° at very low frequencies.
   Theoretical expectation: +90°.

   b) $f \gg f_{-3dB}$ (High frequencies, far above cutoff):
   The phase shift approaches 0°, showing that the output and input are in phase at very high frequencies.
   Theoretical expectation: 0°.

   c) $f = f_{-3dB}$ (Cutoff frequency):
   The phase shift is +45°, which is expected at the cutoff frequency. The experimental data confirms this midpoint transition.
   Theoretical expectation: +45°.

The experimental results show a close alignment with the theoretical predictions for an RC high-pass filter. The cutoff frequency f_{-3dB} is estimated to be approximately 33 Hz, where the amplitude ratio reaches −3 dB and the phase shift is +45°. Minor discrepancies between the experimental and theoretical values are likely due to measurement tolerances or the non-idealities of the components used.

5 Evaluation Part 2 – Notch Filter

To draw the Bode Magnitude and phase plot from the values we measured we used the same formula:

$$A = 20 * log10\left(\frac{V_{out}}{V_{in}}\right)$$

It was then plotted against the logarithmic scale of the angular frequency. After few steps the following table and plots were made:

I/P Frequency (hz)	Magnitude A (db)	log10(frequency) 10^4	Phase shift(degree)
1000	-0.172	3	-7.56
5700	-3.04855	3.755875	-43.4
7000	-4.67174	3.845098	-52.9
8000	-6.30541	3.90309	-60
9000	-8.24361	3.954243	-64
10000	-12.8097	4	-70.3
11000	-14.6339	4.041393	-76.1
12995	-32.326	4.113776	38.3
13120	-32.8413	4.117934	35.7
15000	-16.0269	4.176091	75.2
18000	-9.42167	4.255273	67.9
20000	-7.13095	4.30103	63.6
23000	-5.16122	4.361728	55.5
25000	-4.20839	4.39794	52.2
29500	-2.9504	4.469822	43.1
50000	-0.96306	4.69897	26.3
100000	-0.08558	5	11.7

Table 7. Measured and calculated Magnitude A(dB) and Phase shift for different frequencies.

The following Plots were made:

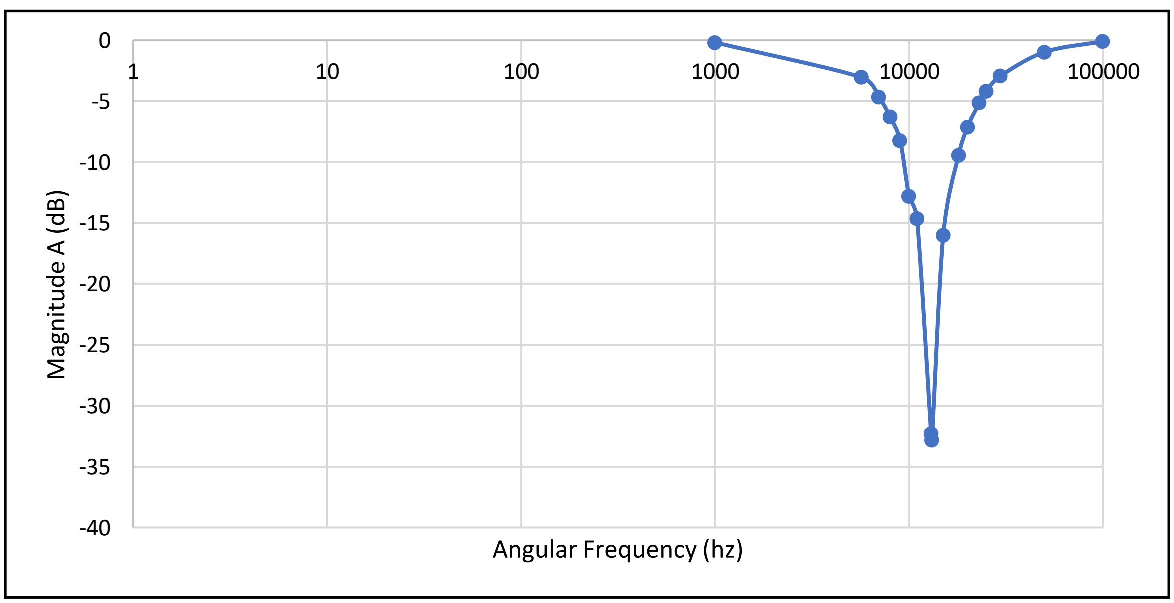


Figure 5. Bode Plot for Notch Filter Magnitude A (dB) VS Angular frequency.

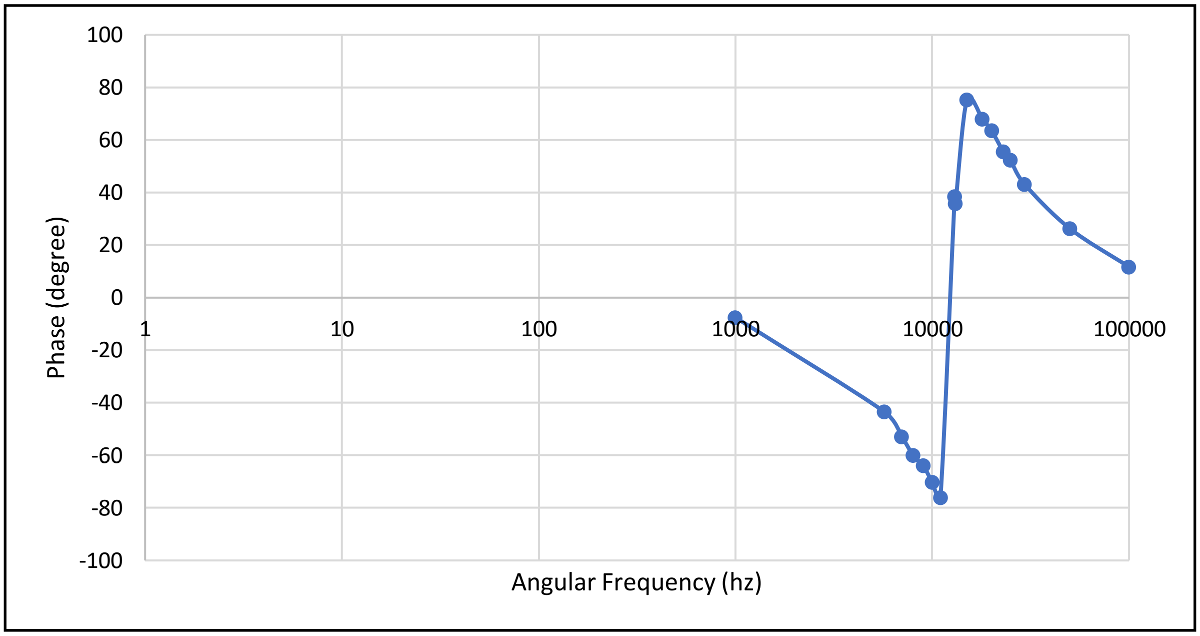


Figure 6. Bode Plot for Notch Filter Phase Shift (dB) VS Angular frequency.

To compare measured Bode plot to Theoretical one the following formulas were used:

$$|\underline{A}| = \frac{1}{\sqrt{1 + \left(\frac{R}{\omega L - \frac{1}{\omega C}}\right)^2}} - to\ calculate\ magintude$$

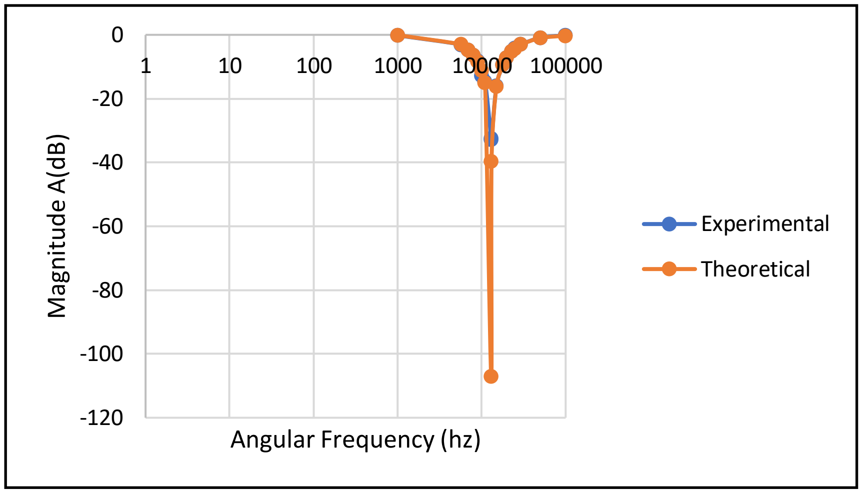
$$\varphi = arctan\left(\frac{R}{\omega L - \frac{1}{\omega C}}\right) - to\ calculate\ the\ Phase\ Shift$$

$$A = 20 * log10(|\underline{A}|) - to\ calculate\ magintude\ in\ Decibels$$

After the calculations the following theoretical table were made:

I/P Frequency (hz)	Magnitude A (dB)	Phase Shift (degree)
1000	-0.09	-8.09
5700	-3	-44.94
7000	-4.69	-54.35
8000	-6.35	-61.23
9000	-8.44	-67.76
10000	-11.14	-73.91
11000	-14.93	-79.67
12995	-107	90
13120	-39.64	89.4
15000	-16.2	81.09
18000	-9.38	70.15
20000	-7.22	64.17
23000	-5.22	56.74
25000	-4.33	53.61
29500	-3.03	45.12
50000	-1.01	27.11
100000	-0.25	13.65

Table 8. Theoretical values for Magnitude A(dB) and Phase shift.



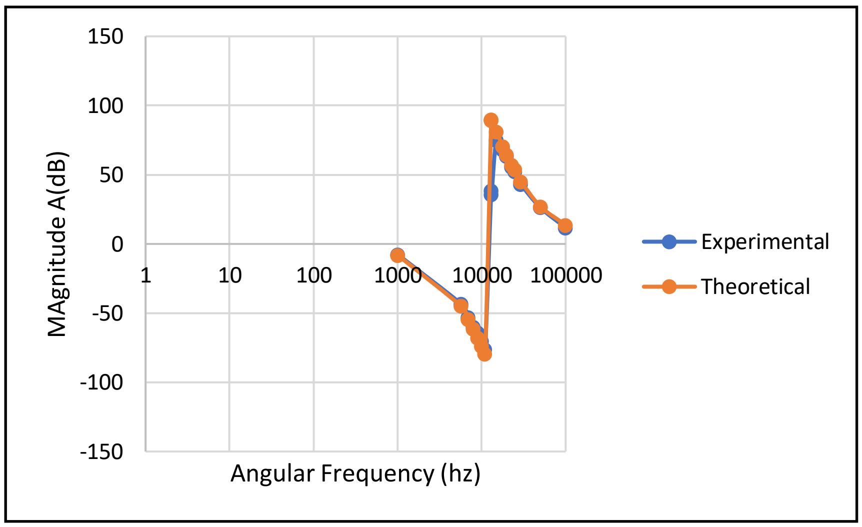


Figure 7. Comparison between Theoretical and Experimental values for Magnitude A(dB) and The Phase Shift

As observed from the plot, there was a slight discrepancy between the theoretical and measured curves. Similar to Part 1, this difference could be attributed to measurement errors when using the oscilloscope. However, overall, the graphs were largely consistent and closely matched each other.

To calculate the bandwidth, we used cutoff frequencies values from *Table.3* and using the following formula we determined bandwidth frequency:

$$f_{BW} = \omega_{high} - \omega_{low} = 29581.7774 - 5708.536 = 23873.2414\, Hz$$

To calculate phase at cutoffs we used calculated values for cutoff frequencies:

$$f_1 = 5708.536\, Hz \quad and \quad f_2 = 29581.7777\, Hz$$

And the following formula:

$$\varphi = arctan\left(\frac{R}{\omega L - \frac{1}{\omega C}}\right) where \quad \omega = 2\pi f$$

After calculations we get:

$$\varphi_{f_1} \approx -45° \; (phase\ lag) \quad and \quad \varphi_{f_2} \approx +45° \; (phase\ lead)$$

To plot a Nyquist plot we used transfer function:

$$H(\omega) = |\underline{A}| * e^{j(\varphi)} \quad where\ |\underline{A}| = \frac{1}{\sqrt{1 + \left(\frac{R}{\omega L - \frac{1}{\omega C}}\right)^2}}$$

Here, the real part is given by:

$$real(f) = |\underline{A}| \cos{(\varphi)}$$

And imaginary part is given by:

$$imaginary(f) = |\underline{A}| \sin{(\varphi)}$$

Using the values from *Table.7* the following table was made:

I/P Frequency (hz)	Acos(ϕ)	Asin(ϕ)
1000	0.9712	-0.1291
5700	0.5136	-0.484
7000	0.3712	-0.468
8000	0.2335	-0.4044
9000	0.17	-0.3486
10000	0.0775	-0.214
11000	0.0435	-0.1793
12995	0.0189	0.015
13120	0.0183	0.0131
15000	0.0395	0.1534
18000	0.1274	0.3126
20000	0.1949	0.3967
23000	0.3106	0.4556
25000	0.3735	0.4822
29500	0.5171	0.4841
50000	0.8041	0.398
100000	0.9705	0.2012

Table 8. Calculated real and imaginary parts of the transfer function.

According to these values the Nyquist plot was constructed:

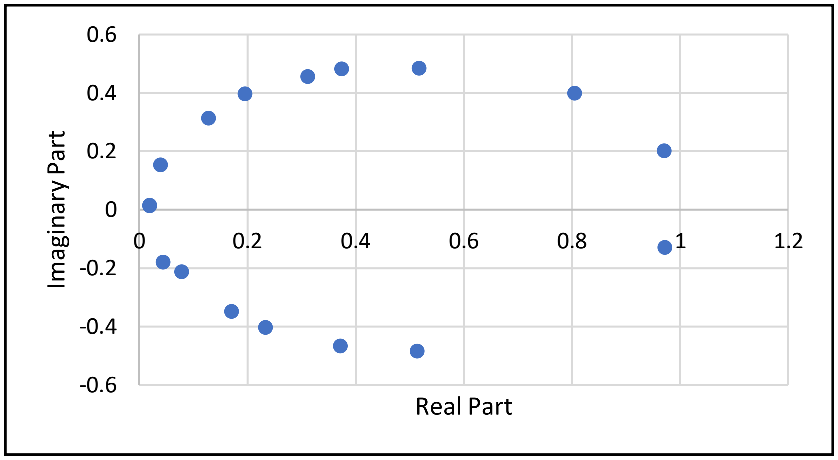


Figure 7. Nyquist plot for Notch Filter

6 Conclusion

Throughout this experiment, two different types of filters were constructed: a High-Pass Filter and a Notch Filter. Their frequency response characteristics were measured and compared with theoretical predictions.

In Task 1, an RC High-Pass Filter was designed. The Bode plot obtained from the measured values closely resembled the theoretical Bode plot derived from the transfer function. As expected, higher frequencies passed through with minimal attenuation, while lower frequencies were significantly attenuated. Minor discrepancies between the measured and theoretical plots were likely due to inherent errors in the oscilloscope and breadboard. Additionally, the differences in measured properties, such as the cutoff frequency and phase shift at that point, resulted from the use of approximated rather than exact values.

Similarly, in Task 2, a Notch Filter was implemented. Like in Task 1, the Bode plot obtained from the measured values aligned well with the theoretical transfer function. The expected behavior was observed, where a specific range of frequencies was attenuated while others were allowed to pass. The small differences between the measured and theoretical responses could again be attributed to instrumental limitations and approximations in measurement. Furthermore, the Nyquist plot was drawn, representing the real part of the transfer function on the x-axis and the imaginary part on the y-axis.

In conclusion, the experimental results for both filters closely followed theoretical predictions, demonstrating the expected behaviors of a High-Pass and a Notch Filter. The experiment was successful in verifying these properties and understanding their practical applications.

In this experiment, the frequency responses of the constructed High-Pass and Notch Filters were found to be in close agreement with their theoretical predictions, validating their expected behaviors. Although the results were largely successful, slight discrepancies between the measured and theoretical values were observed, stemming from several error sources. Tolerances in the components—resistors, capacitors, and inductors—caused variations in the cutoff and notch frequencies, while limitations of the instruments, such as oscilloscope resolution and the output impedance of the function generator, affected measurement accuracy. Additionally, parasitic elements like stray capacitance and inductance on the breadboard influenced the circuit's performance, particularly at higher frequencies. Theoretical calculations assumed ideal components, but real-world components exhibited parasitic behaviors that were not accounted for in the models. Furthermore, manual measurement techniques, such as determining phase shifts from the oscilloscope, introduced minor human errors. Despite these challenges, the experiment successfully validated the core principles of both filter types, demonstrating the significance of considering practical limitations when designing and analyzing electronic circuits. The strong correlation between theory and practice emphasizes the reliability of the fundamental concepts, while also highlighting the importance of meticulous experimental techniques to reduce errors.

7 References

- Lab Manual - http://uwp-raspi-lab.jacobs.jacobs
- Fundamental Of Electric Circuits – Sadiku
- https://testbook.com/electrical-engineering

8 Appendix

11.4.2

freq (Khz)	A_in (V)	A_out (V)	phase shift
1	0.5	0.52	179
2	0.5	0.52	178
5	0.5	0.52	178
10	0.5	0.52	176

20	0.512	0.52	177
50	0.512	0.504	172
100	0.512	0.504	164
200	0.512	0.48	148
500	0.512	0.316	103
1000	0.508	0.156	72.1
2000	0.508	0.064	51.8
5000	0.504	0.016	-23

R_1 = 10kΩ

R_1 = 22kΩ

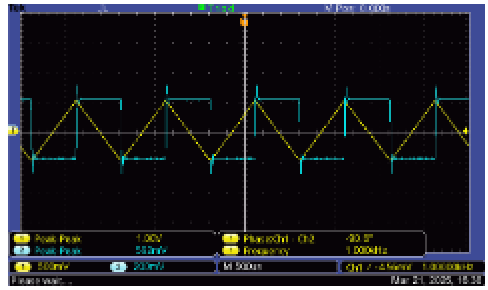
freq (Khz)	A_in (mV)	A_out (mV)	phase shift
1	508	232	178
2	508	232	178
5	508	232	177
10	508	232	178
20	508	232	177
50	508	232	174
100	508	232	169
200	508	232	158
500	512	208	122
1000	512	122	73.4
2000	512	44.8	23
5000	504	8.8	-47

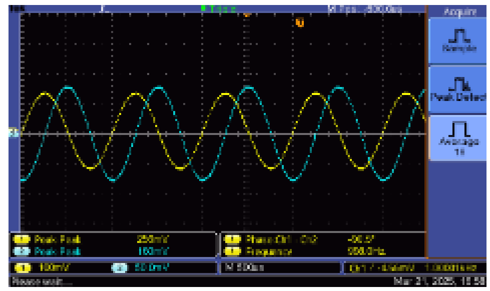
R_1 = 1kΩ

freq (Khz)	A_in (mV)	A_out (V)	phase shift
1	496	4.92	179
2	496	4.92	178
5	496	4.92	168
10	496	4.92	171
20	496	4.76	161
50	500	3.6	132
100	508	2.04	110
200	504	1.02	94.3
500	508	0.404	76.3
1000	512	0.188	57.7
2000	512	0.08	16.5
5000	520	0.028	-12.3

11.5

freq (hz)	A_in (mV)	A_out (mV)	phase shift
100	252	17.6	-83
200	252	33.6	-86.6
500	252	80	-89.8
1000	256	158	-90.7
2000	256	314	-90.7
5000	256	792	-93.4
10000	248	1620	-96.1





11.6

range = 200

I_Elabo (ma)	V_Tenma (V)	V- (V)	V+ (V)	Vout (V)
97.07	0.2103	5.066	4.402	-2.1532