Evan Bonner
South East Technological University
Measurement Systems lab report
August 2025

Operational Amplifiers

Aim
To investigate the action and characteristics of operational amplifiers.

Theory
An operational amplifier is a high gain amplifier with differential inputs. The 741 op amp has a high open-loop gain ($A_o \approx 2 \times 10^5$), high input impedance ($Z_i \approx 10^6 \Omega$) and low output impedance ($Z_o \approx 100\Omega$). The fundamental operation is described by

$$V_o = A_o(V^+ - V^-)$$

where V^+ is the non-inverting input,V^- is the inverting input, andV_o is the output voltage. Due to the very high open-loop gain, even a small differential input voltage causes the output to saturate near the supply rails. To achieve stable and predictable behaviour, negative feedback is commonly appliied which reduces the effective gain and increases the linear operating region.
For a non-inverting amplifier, the closed-loop gain is defined by:

$$A_v = 1 + \frac{R_f}{R_g}$$

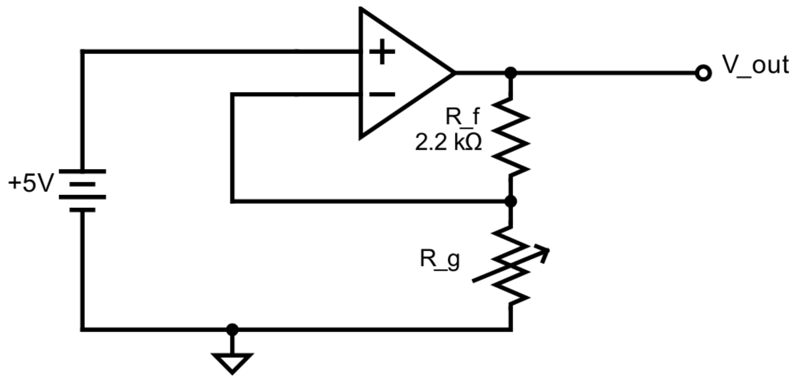
where R_f is the feedback resistor and R_g is the resistor to ground. The gain bandwidth product of an op amp limits the maximum frequency at which a given gain can be maintained, as

$$GBW = A_v \times \text{Bandwidth}$$

This governs the tradeoff between amplication and frequency response. An op amp can be provided with a null offset to ensure that zero input corresponds to zero output.

PART 2

Circuit Diagram



Method

The circuit was assembled as shown in the diagram above, with the input voltage as $5V$. R_g was set to 500Ω. Measurements were recorded for V_{out} and V_{-}. These measurements were repeated for values of R_g as 500Ω, 1kΩ, 2kΩ, 5kΩ, 10kΩ, 20kΩ, and 50kΩ. The gain of the amplifier was calculated using the formula

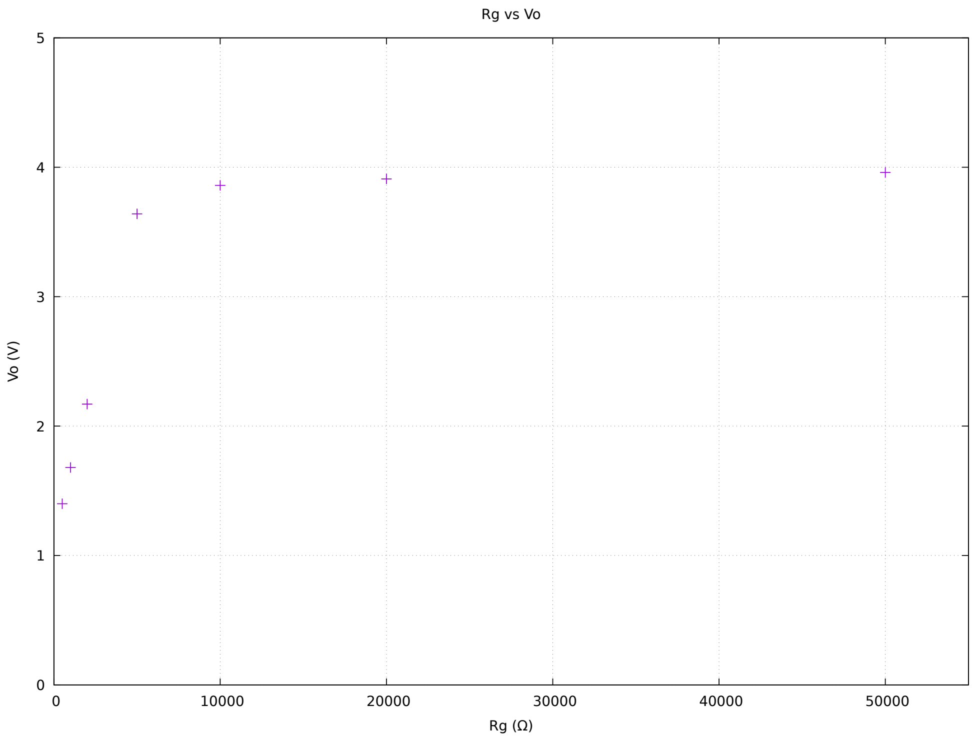
$$A_v = \frac{V_{out}}{V_{-}}$$

while the expected gain was calculated using the resistor values:

$$A_v = 1 + \frac{R_f}{R_g}$$

Results

Rg (kΩ)	V_{out} (V)	V_{-} (V)	Measured gain	Expected gain A_v
0.5	1.4	0.27	5.19	5.40
1	1.68	0.53	3.17	3.20
2	2.17	1.06	2.05	2.10
5	3.64	2.56	1.42	1.44
10	3.86	3.15	1.23	1.22
20	3.91	3.49	1.12	1.11
50	3.96	3.74	1.06	1.04

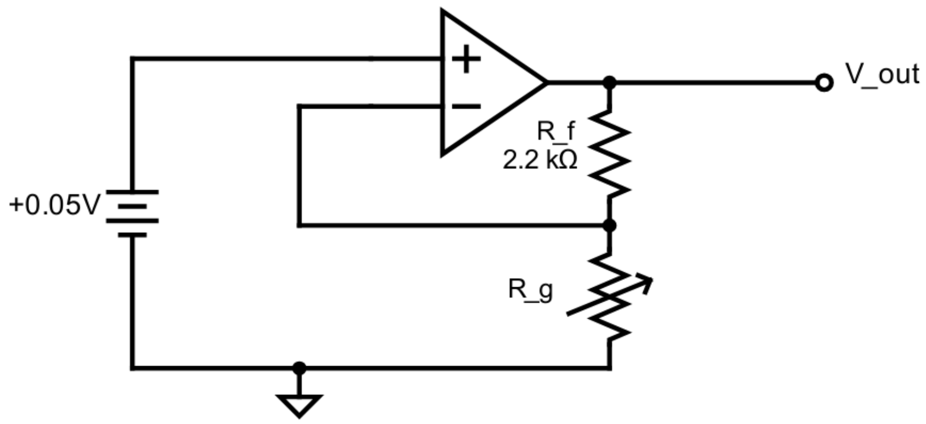


Discussion

As the resistance of R_g increased, the gain approached 1. This is expected, as the gain equation in terms of the resistors is $\frac{R_f}{R_g} + 1$, so as R_g approaches infinity the gain goes to 1. With a gain of 1, the output voltage should match the input voltage of 5 V. However, this was not the case in the measurements, which saturated at 4 V. I believe the supply voltage V_{cc} was incorrectly set to 5 V for this part, as a maximum output of $V_{cc} - 1$ V is seen in the subsequent experiments, which use a correct V_{cc} of 12 V. Regardless, the measurements taken are consistent and still demonstrate the desired behaviour. The measured gain followed the expected gain, with the highest margin of error being 3.89%, and averaging 1.75%. The small discrepancies between the measured and expected gain could be due to a lack of offset nulling on the op amp, and small tolerance differences in the components used.

PART 3

Circuit Diagram



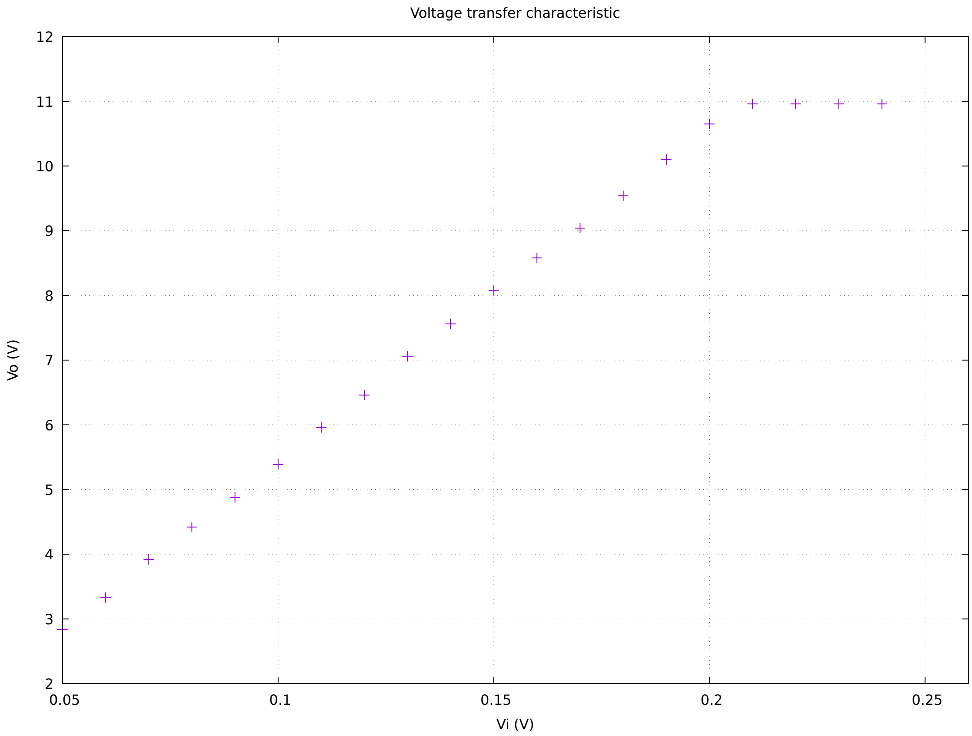
Method

The circuit was assembled as shown above. The input voltage of the circuit set to 50 mV DC. The value of R_g was varied until the value ofV_{out} = 5 V, so that the gain of the amplifier was 40 dB. This gain saturated too quickly, so a reduced gain of roughly 35 dB was chosen instead. A range of measurements were taken for V_{in} and V_{out} to show the linear and saturation regions of the amp.

Data

V_{in} (V)	V_{out} (V)	Gain (dB)
0.05	2.84	35.09
0.06	3.33	34.89
0.07	3.92	34.96
0.08	4.42	34.85
0.09	4.88	34.68
0.1	5.39	34.63
0.11	5.96	34.68
0.12	6.46	34.62
0.13	7.06	34.70
0.14	7.56	34.65

V_{in} (V)	V_{out} (V)	Gain (dB)
0.15	8.08	34.63
0.16	8.58	34.59
0.17	9.04	34.51
0.18	9.54	34.49
0.19	10.1	34.51
0.2	10.65	34.53
0.21	10.96	34.35
0.22	10.96	33.95
0.23	10.96	33.56
0.24	10.96	33.19

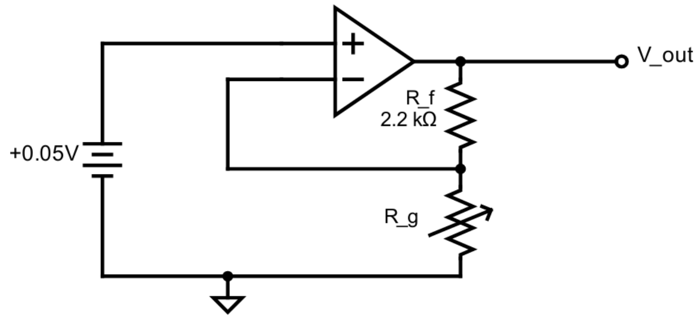


Discussion

The results are as expected. The produced graph clearly shows the op amps positive linear region, followed by saturation around $V_i > 0.2$. The measured gain drops slightly as the output approaches saturation, which is likely due to the op amp's inability to deliver a linear output as it approaches it's supply voltage.

Part 4

Circuit Diagram



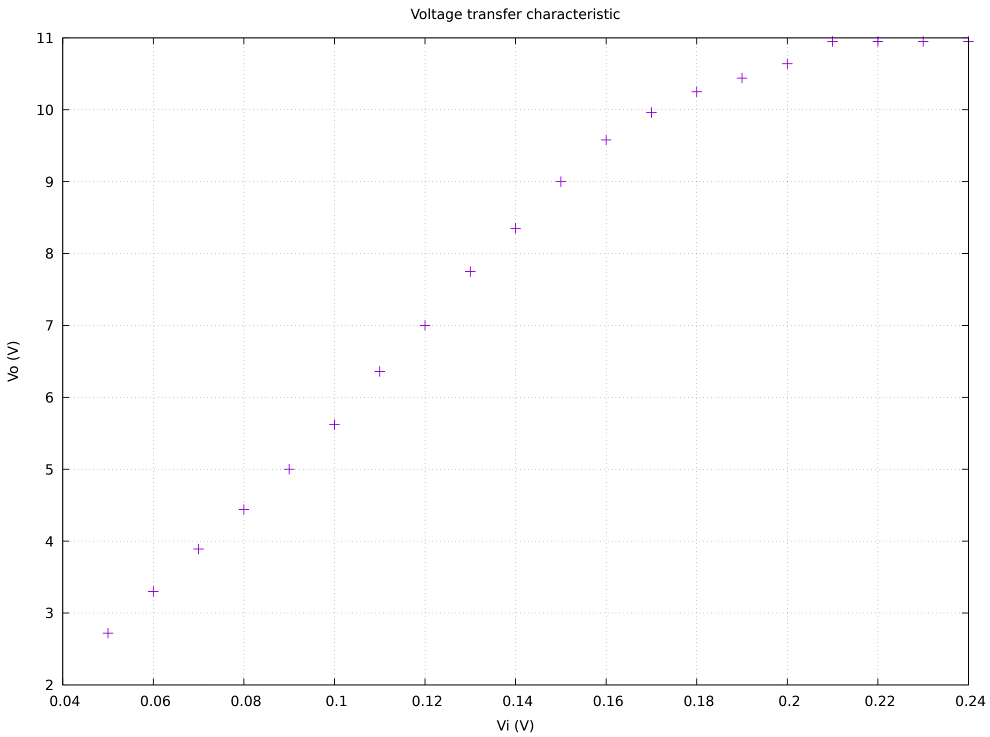
Method

The circuit was assembled as in part 3, but with a 10 kΩ potentiometer across the “offset null” pins of the amp, and the middle pin of the amp connected toV_{cc-}. While the input voltage was zero, the potentiometer was adjusted untilV_{out} was measured to be zero. V_{in} was then set to 50 mV and and measurements were taken for V_{in} and V_{out}, as in part 3.

Data

V_{in} (V)	V_{out} (V)
0.05	2.72
0.06	3.3
0.07	3.89
0.08	4.44
0.09	5
0.1	5.62
0.11	6.36
0.12	7
0.13	7.75
0.14	8.35

V_{in} (V)	V_{out} (V)
0.15	9
0.16	9.58
0.17	9.96
0.18	10.25
0.19	10.44
0.2	10.64
0.21	10.95
0.22	10.95
0.23	10.95
0.24	10.95



Discussion

The result is similar to part 3 with the same graph but slightly offset on the Y axis. We did not take any measurements at $V_i \le 0$, but we would expect to see the line of the linear region intersect the point (0, 0), and we would not expect to see this for the graph in part 3.

Part 5

Method

The gain of the amp was set to 100dB. The power supply was replaced with an AC power supply generating a sine wave. V_{in} was set to 50 mV. For a range of values between 50 Hz and 100 kHz, measurements were taken for V_{out} and A_v (the gain) of the circuit. The bandwidth of the amp was then determined for each measurement. This was then all repeated with the gain of the amplifier set to 10dB.

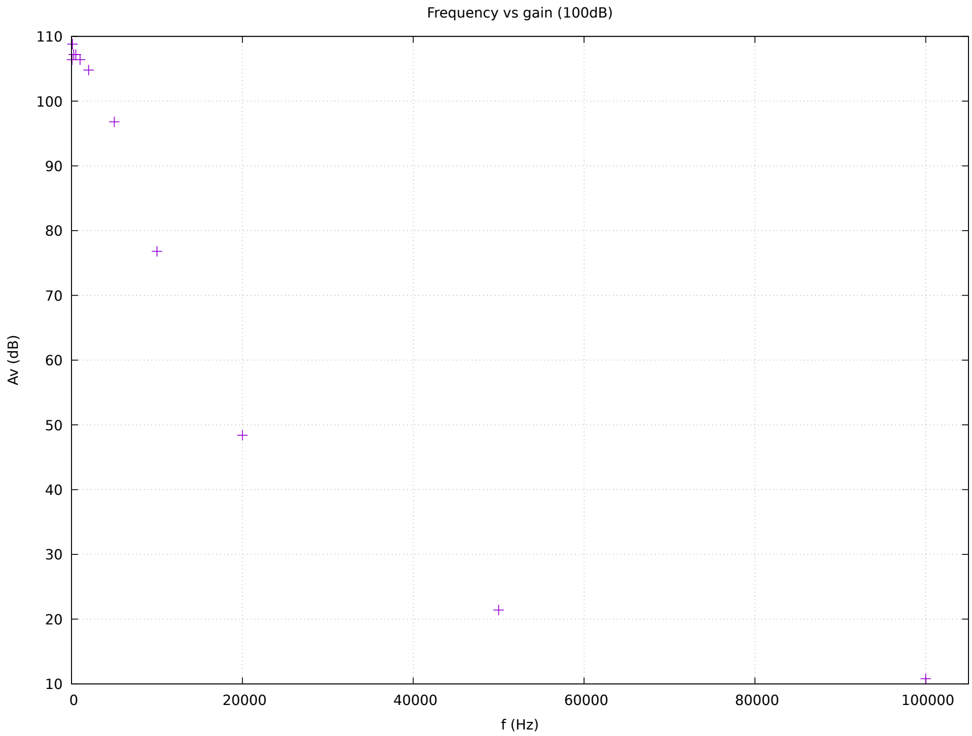
Data

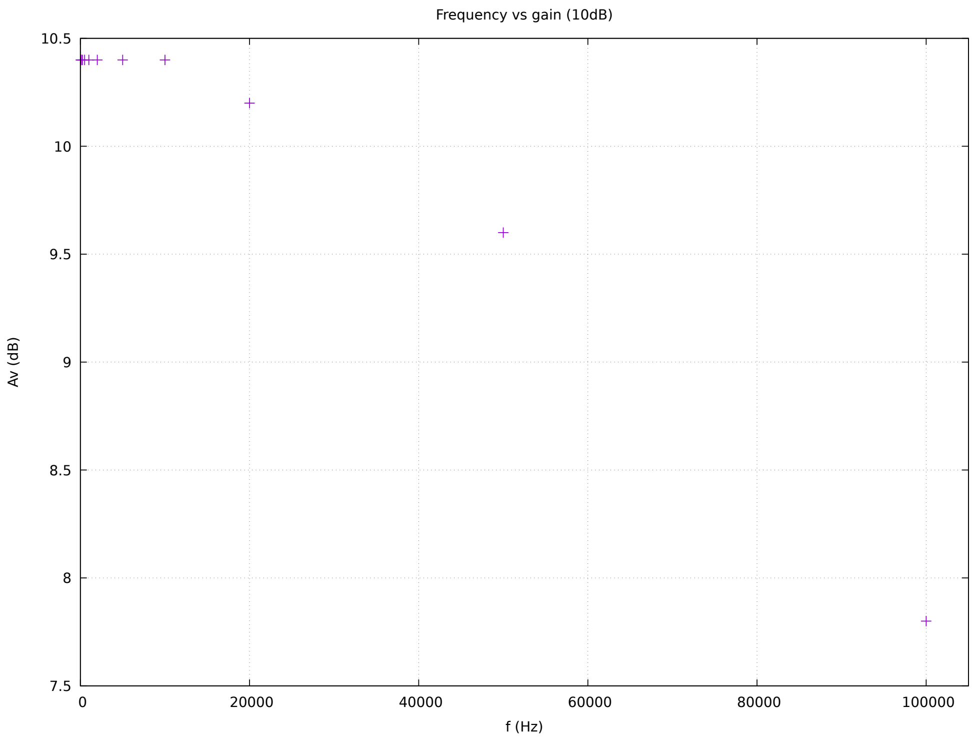
100dB

f (Hz)	V_o (V)	A_v (dB)	Bandwidth
50.00	5.32	106.40	9398.50
100.00	5.44	108.80	9191.18
250.00	5.36	107.20	9328.36
500.00	5.36	107.20	9328.36
1000.00	5.32	106.40	9398.50
2000.00	5.24	104.80	9541.98
5000.00	4.84	96.80	10330.58
10000.00	3.84	76.80	13020.83
20000.00	2.42	48.40	20661.16
50000.00	1.07	21.40	46728.97
100000.00	0.54	10.80	92592.59

10dB

f (Hz)	V_o (V)	A_v (dB)	Bandwidth
50.00	0.52	10.40	96153.85
100.00	0.52	10.40	96153.85
250.00	0.52	10.40	96153.85
500.00	0.52	10.40	96153.85
1000.00	0.52	10.40	96153.85
2000.00	0.52	10.40	96153.85
5000.00	0.52	10.40	96153.85
10000.00	0.52	10.40	96153.85
20000.00	0.51	10.20	98039.22
50000.00	0.48	9.60	104166.67
100000.00	0.39	7.80	128205.13





Discussion

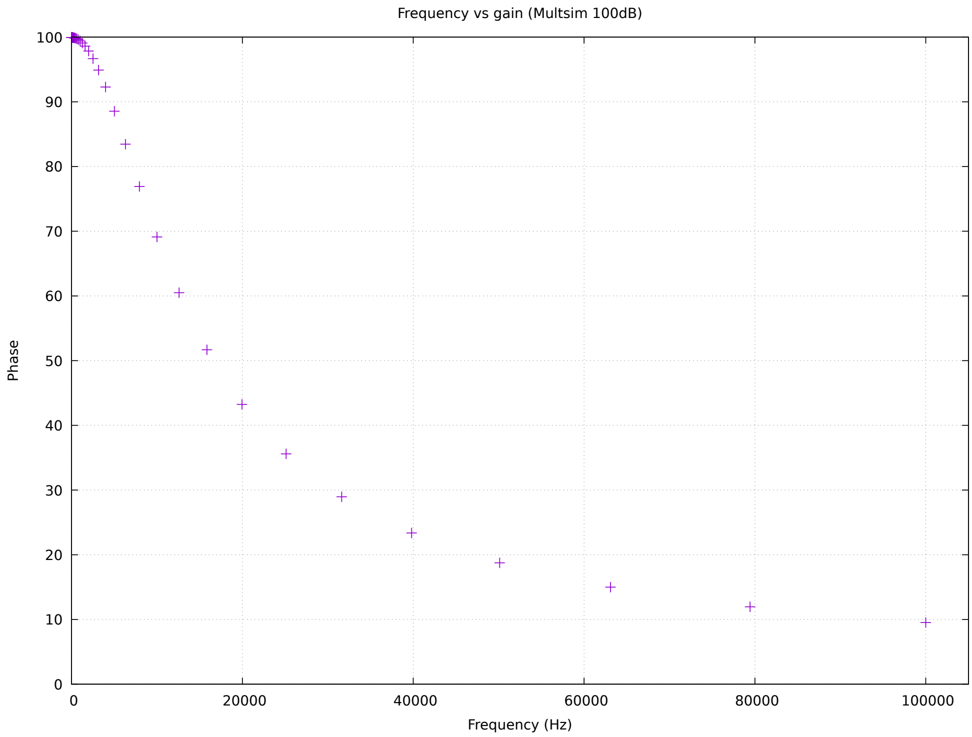
The maximum gain of an op amp decreases as the frequency increases. This is reproduced in the above graphs. The 100dB circuit shows a large dropoff in gain almost immediately, as the maximum gain falls below 100dB at a relatively low frequency. The 10dB circuit is able to maintain it's gain at much higher frequencies due to it being much lower than 100dB.

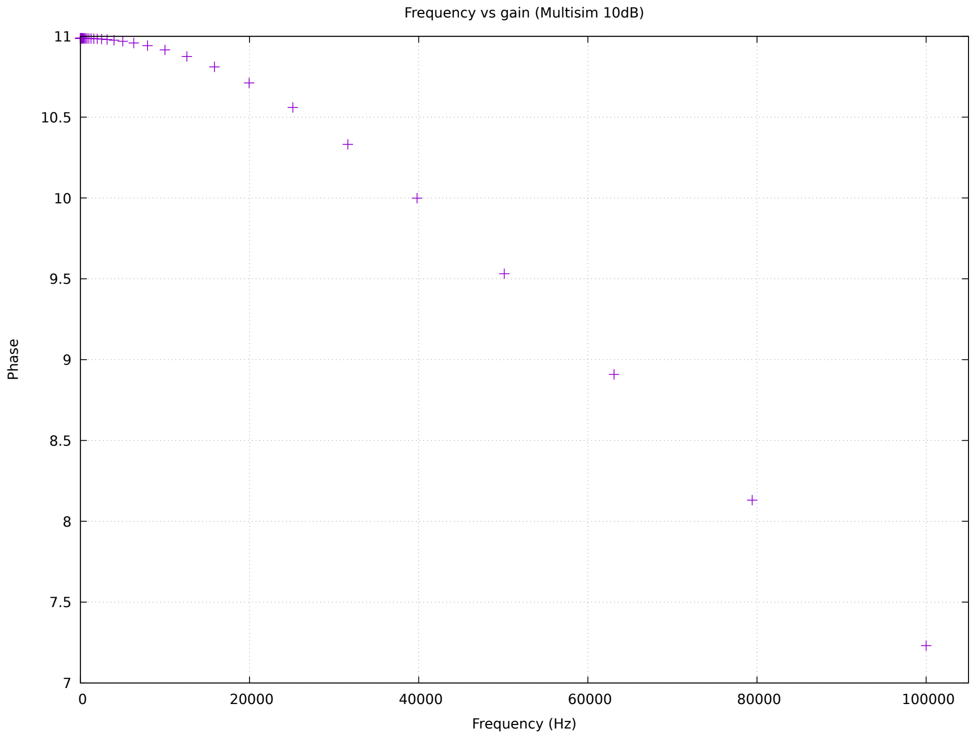
Part 6

Method

A 40dB gain amplifier circuit was constructed in Multisim. The op amp parameters set $A_{vol} = 10\text{k}$, $BW = 1\text{MHz}$, $R_I = 10\text{M}\Omega$, and $R_O = 100\Omega$. V_{cc+} and V_{cc-} were set to 12V and -12V respectively. An AC sweep was used to generate a graph of frequency vs gain. This was repeated for a circuit with a 10dB gain.

Data





Discussion

The graphs from Multisim closely resemble the graphs produced in part 5, albeit with many more data points. The 10dB graph matches almost exactly to the 10dB graph in part 5. The 100dB graph rolls off a bit slower than in part 5, following more of a smoother curve.

Conclusion

The experiments successfully demonstrated the fundamental characteristics and behavior of operational amplifiers. The experiments confirmed that applying negative feedback allows for stable and predictable circuit behavior. Slight discrepancies in measurements were attributed to factors like a lack of offset nulling (for part 3) and component tolerances. The voltage transfer characteristic experiments clearly showed the op amp's linear operating region and subsequent saturation as the output approached the supply voltage. Also, the experiments on gain versus frequency showed the inverse relationship between the two, showing that gain decreases as frequency increases, which is consistent with the gain bandwidth product. The results from the Multisim simulations also validated the experimental findings.