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Non-ideal Characteristics of an Operational Amplifier

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Abstract

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The aim of this thesis was to provide the reader with detailed theoretical background of the operational amplifier. It also presents the non-ideal characteristics of an op-amp, open and closed loop configuration, and inverting and non-inverting circuits. The objective of the thesis was to design PCB test boards of sample op-amps and demonstrate their functionality as well as to measure non-ideal characteristics, such as input offset voltage, input bias current, gain bandwidth product, and slew rate.

This study selected three samples of op-amps in such a way that they can be distinguished from their non-ideal parameter values. The schematic and PCB were designed in KiCad to measure non-ideal characteristics. The non-ideal parameter values of the samples were analysed in Multisim and measured through the PCB board at the electronics laboratory at Metropolia University of Applied Sciences. The measured values were compared to the datasheet values, and the achieved result was satisfactory.

The design PCB can be used in the laboratory project for an analog electronics course to distinguish sample op-amps. The limitation of this thesis was the inability to measure the slew rate of OPA134 because of its high value.

Keywords: Input offset voltage, input bias current, GBP, slew rate

The originality of this thesis has been checked using Turnitin Originality Check service.

Contents

List of Abbreviations

A_{vol}:	Open Loop Voltage Gain
A_v:	Voltage Gain
CMMR:	Common mode Rejection Ratio
dB:	decibel
DC:	Direct Current
DUT:	Device Under Test
f_C:	Cut-off frequency
I_B:	Bias Current
IC:	Integrated Circuit
I_{in}:	Current through input resistor
I_f:	Current through feedback resistor
I_{os}:	Input Offset Current
Op-amp:	Operational Amplifier
PCB:	Printed Circuit Board
P_o:	Output Power
R_f:	Feedback Resistor

R_i: Input Resistor

RTR: Rail to Rail

SR: Slew Rate

$+V_{cc}$: Positive Supply Voltage

$-V_{cc}$: Negative Supply Voltage

V_f: Voltage across feedback resistor

V_{in}: Input Voltage

V_{io}: Input Offset Voltage

V_o: Output Voltage

Z_n: Load

1 Introduction

The operational amplifier, commonly known as the “op-amp,” is a fundamental component in the realm of analog electronics. Initially, the op-amp was designed using vacuum tubes to execute mathematical operations such as summation, subtraction, differentiation, and integration. Today, op-amps are widely used in various tasks, including signal conditioning, filtering, analog-to-digital and digital-to-analog converters

The thesis aims to provide the reader with detailed theoretical background of the operational amplifier. This study also analyzes the non-ideal characteristics of an op-amp, such as input offset voltage, input bias current, gain, gain bandwidth, slew rate, common mode rejection ratio, and rail-to-rail output. Furthermore, the thesis explores the open-loop and closed-loop configurations. The thesis also explores the inverting and non-inverting circuit configuration of the operational amplifier. The objective of the thesis is to design PCB test boards for three op-amps and demonstrate their functionality, as well as measure non-ideal characteristics, such as input offset voltage, input bias current, gain bandwidth product, and slew rate.

This thesis can be used as learning material by the electronics engineering students for their analog electronics course. The designed PCB test boards of selected op-amps can be used in the laboratory projects of the analog electronics course to distinguish between the sample op-amps.

2 Operational Amplifier

An operational amplifier, commonly referred to as an op-amp, is a direct-coupled high-gain differential amplifier with high input impedance and low output impedance. The operational amplifier has become a fundamental tool for handling circuit design problems. The op-amp's range of usefulness has extended from linear to non-linear and digital areas. The op-amp was initially conceived to perform arithmetic operations; however, it has wide applications such as signal amplification, wave shaping, servo and process control, analog instrumentation, and system design. The non-linear applications of op-amps are voltage compensation, logarithmic amplifiers, A/D and D/A converters, and non-linear function generators. The circuit symbol of an op-amp is presented in Figure 1 and is generally characterized by differential inputs and typically a single-ended output. [1,32.]

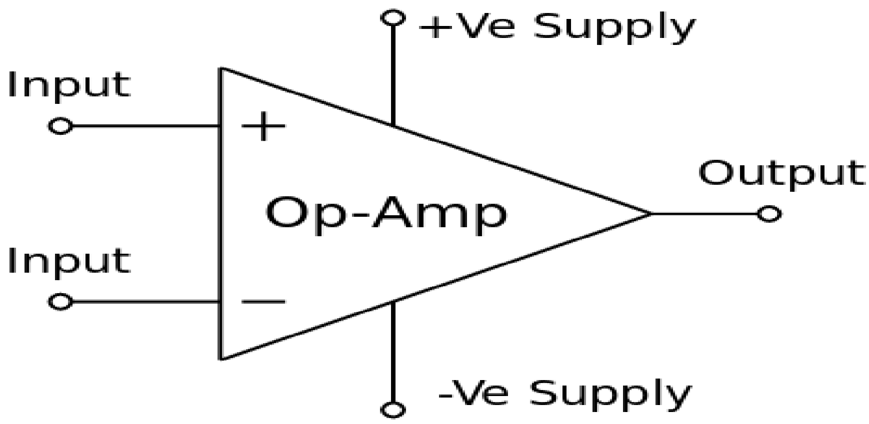

Figure 1. Circuit symbol of operational amplifier [2].

An ideal op-amp is assumed to have infinite voltage gain and infinite bandwidth. In addition, an ideal op-amp has an infinite input impedance (open) so that it does not draw current from the source connected to its inputs. Finally, the output impedance is assumed to be zero, delivering output voltage without loss. In practice, the op-amps often fail to meet these ideal standards. There is no such device without limitations. An op-amp has both current and voltage limitations. The output current is limited by power dissipation, and the peak-to-peak output voltage is always slightly less than two supply voltages. The practical characteristics of op-amps are very high voltage gain, high but finite input impedance in the range of megaohms to gigaohms, and very low output impedance. There is always undesired noise generated within the op-amp that affects the quality of the signal. [3,603.]

A typical op-amp consists of three types of amplifier circuits: a differential amplifier, a voltage amplifier, and a push-pull amplifier, as shown in Figure 2. The input stage of the op-amp is a differential amplifier that amplifies the difference voltage between the two inputs. The second stage is the gain stage, which usually consists of a class A amplifier that provides voltage gain. There might be more voltage amplifier stages in some op-amps. The final stage is the output stage that consists of a push-pull amplifier. The output amplifier provides low output impedance to deliver full output voltage without a voltage drop. [3,604.]

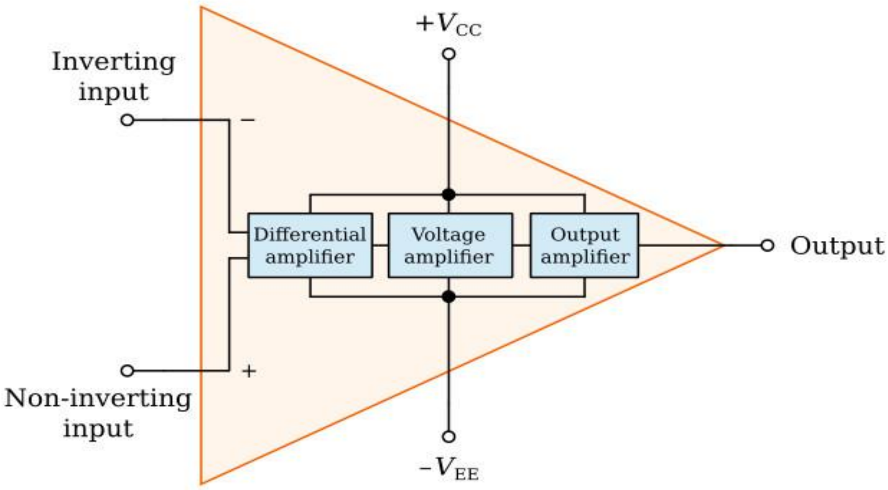

Figure 2. Block diagram of Op-amp [4].

2.1 Op-Amp in Open-loop Configuration

When the output terminal of the op-amp is not connected to the input terminal of the op-amp, then the op-amp is said to be in open-loop configuration. In other words, the feedback loop is open. In this configuration, the voltage gain is the overall voltage gain of the different stages inside the internal circuit of the op-amp. The voltage gain of the op-amp can be represented by A_{VOL}. In an open-loop configuration, the ideal value of A_{VOL} is ∞; however, in practice, its typical value is approximately 10^5. Figure 3 below shows an op-amp in open-loop configuration. [5,15.]

A_{VOL} = Voltage gain in open loop configuration

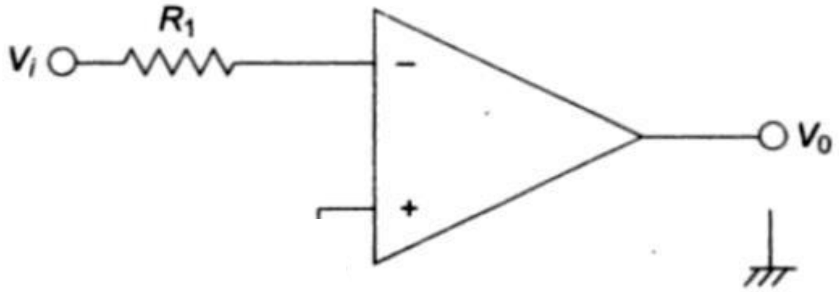

Figure 3. Op-amp in open-loop configuration [5].

2.2 Op-Amp in Closed-loop Configuration

When the output terminal of the op-amp is connected to its input terminal, the op-amp is said to be in a closed-loop configuration. The circuit shown in Figure 4 shows an op-amp in a closed-loop configuration. Here, the feedback loop is connected to the inverting input terminal, and the output will produce a phase shift of 180°. The closed-loop voltage gain (A_{VCL} or Av) is limited by the ratio of the feedback resistor and input resistor. [5,15.]

$$A_{VCL} = A_V = \frac{V_o}{V_i} = \frac{R_f}{R_1} \quad (1)$$

Where:

R_f = feedback resistor

R_1 = input resistor

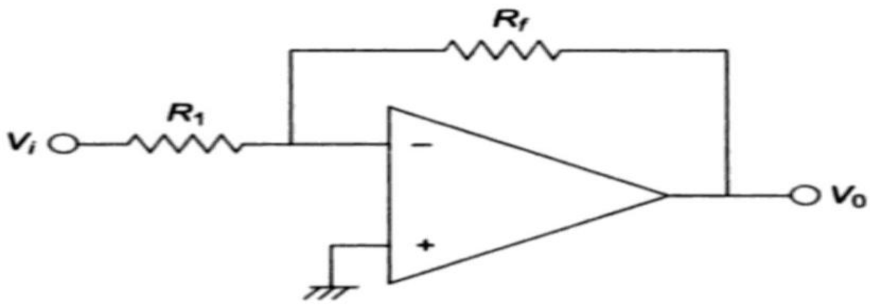

Figure 4. Op-amp in closed-loop configuration [5].

3 Operational Amplifier Circuit

The operational amplifier circuits are described below as an inverting amplifier and a non-inverting amplifier.

3.1 Inverting Operational Amplifier

The inverting amplifier circuit of an operational amplifier with a controlled amount of voltage gain is shown in Figure 5. In the inverting (-) input, the input signal is applied through an input resistor, and the noninverting (+) input is grounded. The output is fed back through the feedback resistor R_f to the inverting input.

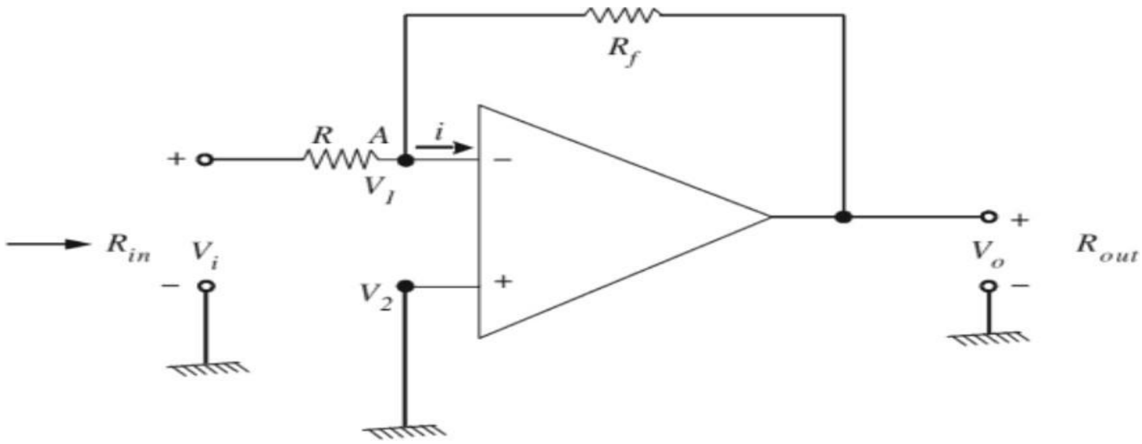

Figure 5. Inverting operational amplifier circuit [1,65]

Here, the ideal op-amp parameters are useful in simplifying the analysis of the circuit. The concept of the infinite input impedance which implies zero current at the inverting input. If there is a zero current through the input impedance, then there must be no voltage drop between the inverting and noninverting inputs. The noninverting (+) input is grounded, which means the voltage at the inverting (-) input is also zero. This condition is referred to as virtual ground at the inverting input terminal.

Since there is no current at the inverting input terminal, the current through the input resistor and the feedback resistor is equal.

$$I_{in} = I_f \tag{2}$$

The voltage across the input resistor is equal to the input voltage because the resistor is connected to the virtual ground at the inverting input of the op-amp. Therefore,

$$I_{in} = \frac{V_{in}}{R_i} \tag{3}$$

In addition, the voltage across the feedback resistor is equal to the output voltage because of the virtual ground, and therefore,

$$I_f = \frac{-V_{out}}{R_f} \tag{4}$$

Since $I_{in} = I_f$,

$$\frac{V_{in}}{R_i} = \frac{-V_{out}}{R_f} \tag{5}$$

Rearranging the terms,

$$\frac{V_{out}}{V_{in}} = \frac{-R_f}{R_i} \tag{6}$$

The overall gain of the amplifier is V_{out}/V_{in},

$$A_v = -\frac{R_f}{R_i} \tag{7}$$

The above equation (7) shows the ratio of the feedback resistor (R_f) and the input resistor (R_i) is the closed-loop voltage gain of the inverting operational amplifier (A_v). It is independent of the op-amp´s internal open-loop gain. Thus, the negative feedback stabilizes the voltage gain. The negative sign indicates the output signal is an inversion of the input signal. [3,617.]

3.2 Non-Inverting Operational Amplifier

The noninverting amplifier circuit of an operational amplifier with a controlled amount of voltage gain is shown in Figure 6. The input signal is fed through the noninverting input (+) of the op-amp. The output signal is fed back to the inverting input (-) through a feedback network consisting of two resistors: the input resistor (R_i) and feedback resistor (R_f). This configuration introduces negative feedback. The resistors R_i and R_f act as a voltage divider, which reduces V_{out} and applied the reduced voltage V_f to the inverting input. The feedback voltage is presented in equation (8).

$$V_f = \left(\frac{R_i}{R_i + R_f}\right) V_{out} \tag{8}$$

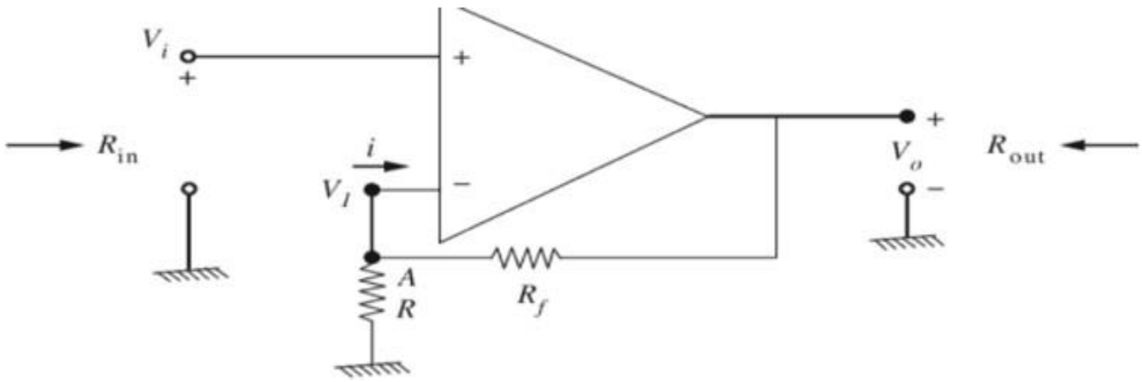

Figure 6. Non-inverting operational amplifier circuit [1,66].

The difference in voltage between the input voltage (V_{in}) and feedback voltage (V_f) is the differential input voltage to the op-amp. This differential input voltage is amplified by the open-loop voltage gain of the op-amp (Aol) and the final output of the op-amp is given as

$$V_{out} = A_{ol}(V_{in} - V_f) \tag{9}$$

Substituting the value of V_f,

$$V_{out} = A_{ol} \left(V_{in} - \frac{R_i}{R_i + R_f}\right) V_{out} \tag{10}$$

Or

$$V_{out} + A_{ol} \frac{R_i}{R_i + R_f} V_{out} = A_{ol} V_{in} \tag{11}$$

Or

$$V_{out}\left(1+\frac{A_{ol}R_i}{R_i+R_f}\right)=A_{ol}V_{in} \tag{12}$$

Or

$$\frac{V_{out}}{V_{in}}=\frac{A_{ol}}{1+\frac{A_{ol}R_i}{R_i+R_f}} \tag{13}$$

The value of $\frac{A_{ol}R_i}{R_i+R_f}$ is typically much greater than 1, so the above equation can be simplified as

$$\frac{V_{out}}{V_{in}}=\frac{A_{ol}}{\frac{A_{ol}R_i}{R_i+R_f}} \tag{15}$$

Or

$$\frac{V_{out}}{V_{in}}=\frac{R_i+R_f}{R_i} \tag{16}$$

The overall gain of the amplifier is V_{out}/V_{in},

$$A_v=1+\frac{R_f}{R_i} \tag{17}$$

The above equation (17) shows the overall closed-loop voltage gain of the op-amp. The voltage gain can be set by selecting the values of the input resistor and feedback resistor under the condition, $\frac{A_{ol}R_i}{R_i+R_f}$ >>1. [3,615.]

4 Non-ideal Characteristics of an Operational Amplifier

An Operational amplifier (op-amp) is essentially a differential amplifier with high noise immunity. By using a multistage amplifier circuit configuration, the op-amp achieves a large voltage gain. Furthermore, in the internal schematic, the input stage circuit provides high input impedance, and the output stage circuit delivers low output impedance. The output stage circuit also provides the required current drive to supply the output power Po, defined as $P_o = V_o I_o$, to the load Z_n. The op-amp operates with external DC sources ($+V_{cc}$ and $-V_{cc}$), which bias the internal transistor circuit. Multistage amplifier circuit configuration ensures that the op-amp draws minimal current from the external DC source because of its high input impedance. Therefore, the op-amp avoids the loading effect. Additionally, the op-amp delivers maximum output power because of its low output impedance.

Based on these electrical characteristics, biasing voltages applied to the op-amp and the current drawn by the op-amp from the DC source, many of the op-amp's parameters are defined. These parameters are explained in subchapters 4.1 to 4.6. Figure 7 illustrates the pin configuration of the commonly used 741 IC. [5,10.]

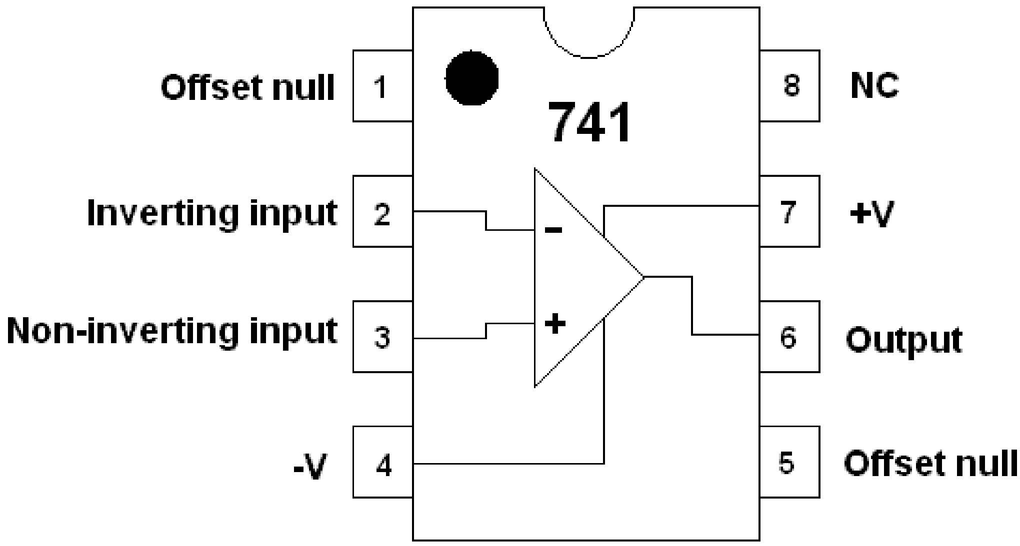

Figure 7. 741 Pinout Configuration [6].

4.1 Input Offset Voltage

Ideally, if there is no external input signal applied to the non-inverting and inverting input terminals of the op-amp, then the output must be zero. It can also be explained that if $V_i = 0$, then $V_o = 0$. However, in practice, the op-amp draws a small bias current from the external DC source (+Vcc and –Vcc), and due to asymmetry in the differential amplifier configuration, the output is typically not exactly zero. This deviation is known as an offset.

To achieve an exact zero output voltage when no input signal is applied, a small compensating voltage must be applied between the two input terminals of the op-amp. This required voltage is called the input offset voltage. It is the voltage that must be applied between the two input terminals of the operational amplifier to force the output voltage to zero. Figure 8 illustrates this concept, where an ideal op-amp would have an input offset voltage $V_{io} = 0$ V. Typically, the practical value of the input offset voltage is 100 μV. [5,11.]

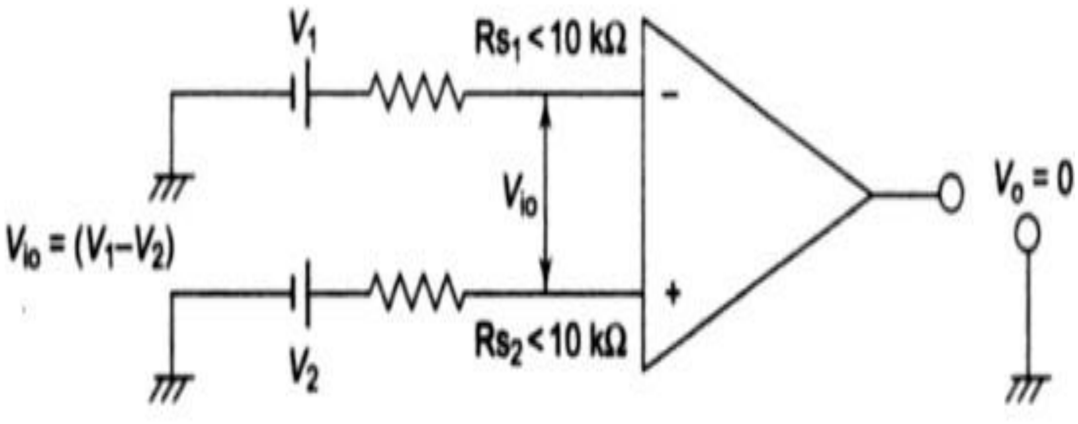

Figure 8. Input Offset Voltage [5,11].

4.2 Input Bias Current and Input Offset Current

The input terminals of the bipolar differential amplifier are the transistor bases. The input currents are base currents which required by the amplifier to properly operate the first stage. The average of the input currents that flow into the non-inverting and inverting terminals of the op-amp is called the input bias current. The equation for input bias current is given in equation (18).

$$I_B = \frac{I_{B1} + I_{B2}}{2} \tag{18}$$

For an ideal op-amp, the value of input bias current is 0. Typically, the practical values of input bias current are 10 to 100 nA. Figure 9 below illustrates the concept of input bias current. [3,608; 7,417.]

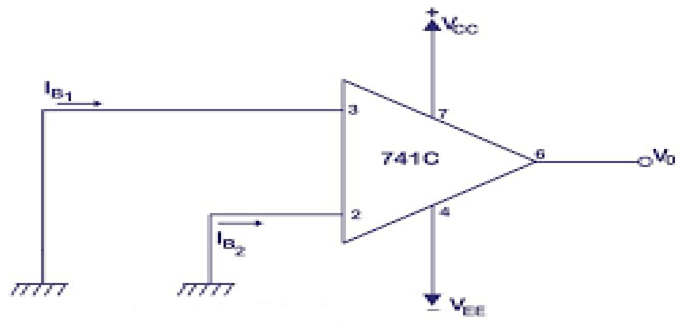

Figure 9. Input bias current [5,11]

The input impedance of the ideal op-amp is ∞, which is not as practical. So, the op-amp draws a small amount of current from the voltage source. In other words, the two input bias currents are equal for an ideal op-amp, and their difference is zero. This is not often the practice case. The absolute difference between these two input bias currents is called the input offset current. The equation for input offset current is given in equation (19). [3,609; 5,11.]

$$I_{os} = |I_{B1} - I_{B2}| \tag{19}$$

4.3 Gain Bandwidth

Operational amplifiers include internal compensation circuitry that causes voltage gain drop off as the input signal frequency increases. Manufacturers usually provide a graph showing gain versus bandwidth in op-amp specifications. Figure 10 below shows the relation between gain and frequency for a typical op-amp.

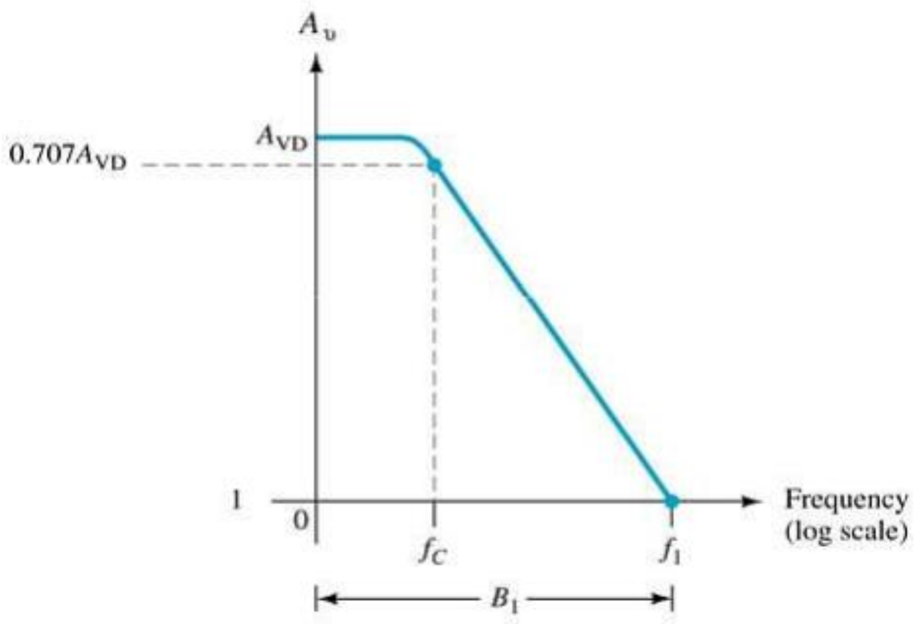

Figure 10. Relation between gain and frequency plot [8,632].

At very low frequencies, including DC, the voltage differential gain (A_{VD}) is specified by the manufacturer, which is typically very high. When the frequency of the input signal increases, the open-loop gain decreases until it eventually reaches unity (gain = 1). The frequency at which this event occurs is called unity-gain bandwidth (B1). This term is often used to describe the total frequency range of an op-amp where it can operate with different gains.

In the above Figure 10, another important frequency presented is the cutoff frequency (f_c). At the cutoff frequency, the gain drops by 3 dB (or to 0.707 times the dc gain, A_{VD}). The relation between unity-gain frequency and cutoff frequency is given in equation (20).

$$f_1 = A_{VD} * f_C \tag{20}$$

This relationship shows that the unity-gain frequency of the op-amp may also be called a gain-bandwidth product. If the gain of the op-amp increases, the bandwidth decreases proportionally and vice versa. [8,632.]

4.4 Slew Rate

Slew rate is the parameter of an op-amp that reflects its ability to handle varying signals. Slew rate is the highest speed at which the output voltage of the op-amp can change. The equation for slew rate is given in equation (21).

$$SR = \frac{\Delta V_{out}}{\Delta t} \tag{21}$$

Where, V_{out}= + V_{max} - (-V_{max}). The unit of the slew rate is volts per microsecond (V/µs). The slew rate provides a parameter specifying the maximum rate of change of the output voltage when a large step input signal is applied. When the input signal changes very quickly, for example in a sudden step or high frequency sine wave, the op-amp may not be able to make the output follow instantly. As a result, the waveform gets distorted or clipped.

In practical terms, slew rate is important when working with high-frequency or large-amplitude signals. It limits how fast and how accurately the op-amp can respond to rapid input signal changes. [8,632.]

4.5 Common Mode Rejection Ratio

An op-amp is said to be operating in a common-mode configuration if the same input voltage is applied to both input terminals. It might be unwanted ac, dc, or a combination of ac and dc voltage, such as noise picked from power lines. Ideally, an op-amp amplifies only differential input voltage, and there should not be a common-mode voltage appearing at the output. However, it is not possible in practice. Common mode rejection is the ability of the op-amp to ignore this common input voltage and amplify the differential input voltage.

Ideally, an op-amp provides a very high gain for differential input voltage and zero gain for common mode input voltage. However, in practical op-amps, there is a small, usually less than 1, common mode gain, while providing a high open-loop differential voltage gain (typically several thousand). The ratio of open-loop differential voltage gain (A_{ol}) to common-mode voltage gain (A_{cm}) is called the Common Mode Rejection Ratio (CMMR). The equation for CMMR is given in equation (22).

$$CMMR = \frac{A_{ol}}{A_{cm}} \tag{22}$$

The higher value of CMMR of op-amps is better to use. A very high value of CMMR means that op-amps have a better ability to reject common-mode voltage, such as 60Hz induced noise voltages. The CMMR value is often large and therefore usually specified in decibels (dB).

$$CMMR\ (dB) = 20 \log\left(\frac{A_{ol}}{A_{cm}}\right) \tag{23}$$

The CMMR is a function of frequency and decreases as the frequency is increased. This parameter is essential where interference is common, such as sensor circuits, instrumentation, and audio systems. [9,153.]

4.6 Rail to Rail and Non-Rail to Rail

The rails are the power supply voltages of the op-amp. When the output of the op-amp is able to swing from the negative supply rail to the positive supply rail, then it is said to be Rail to Rail. The rail-to-rail op-amps allow the use of almost the full voltage range without clipping. Rail-to-rail op-amps are suitable for low-voltage circuits (e.g., microcontrollers) and full-range signal usage.

On the other hand, when the output of the op-amp cannot swing from the negative supply rail to the positive supply rail, then it is said to be Non-Rail to Rail. The part of the supply range is unusable or clipped earlier. Non-rail-to-rail op-amps are suitable where precision, low noise, or high speed is more important than full voltage range, such as precision instrumentation, audio amplifiers, sensor interfaces, and data gathering systems. [10.]

5 Comparison of 10 different op-amps

Most commonly used op-amp samples are presented in Table 1 below. Table 1 contains op-amps with their prices and non-ideal parameter values. These values are taken from the op-amps data sheet. The manufacturer of the given op-amps provides these values. The purpose of the thesis is to explore the non-ideal characteristics of the op-amps, which is the reason the Table 1 contains only some non-ideal parameter values. From Table 1, three samples will be analyzed in terms of their specified parameters. For the analysis process, simulation will be performed using Multisim, the schematic and PCB design will be created in KiCad, and the measurement test will be conducted at the electronics lab at Metropolia University of Applied Sciences.

Table 1. Comparison of 10 different op-amps

Op-amps	Price €	Offset voltage mV	Bias current nA	Open loop voltage Gain dB	Gain Bandwidth Product MHz	Slew rate V/ µs	CMMR dB	Rail to Rail Output
LM741	0.76	1	80	106	1.5	0.5	95	Not
LM358	0.741	2	45	100	0.7	0.3	80	Not
LM324	0.456	3	-20	100	1.2	0.5	80	Not

LM709	2.71	1	200	93		0.25	90	Not
LM1458	1.17	1	200	83	1		90	Not
TL082	0.219	1	±1	120	5.25	20	105	Not
NE5534	0.931	0.5	500	100	10	13	100	Not
OP07	1.91	0.03	±1.2	112	0.6	0.3	123	Not
OPA2134	4.54	±1.2	±0.05	120	8	20	100	Not
TLV2371	1.52	2	0.001	110	3	2.4	72	RTR

Three op-amps samples were selected from the above table 1 for schematic design and their parameter analysis. The samples were chosen on the basis of their key parameters such as input offset voltage, bias current, slew rate and gain bandwidth product. The samples can be distinguished by measuring these parameters values such as LM741 has high input bias current and OPA134 has high GBP. Another reason for selecting these op-amps because they all have same pin configuration. The benefit of having same pin configuration is that the study needs only to mill one PCB board to measure non-ideal parameters for all selected op-amps.

Table 2. Selection of op-amps for simulation

Op-amps	GBP MHz	Slew Rate V/ μs	Offset Voltage mV	Input Bias Current nA
LM741	1.5	0.5	1	80
OP07	0.4-0.6	0.1-0.3	30 – 75 uV	±1.2 - ±4
OPA134	8	±20	±1 – 3.5	±5 – 100 pA

6 Design Process

The circuit is designed in a such way that the non-ideal parameters of the op-amps can be measured such as offset voltage, input bias current, gain, gain bandwidth product and slew rate. From these measurements, the different kinds of op-amps can be distinguished. The design circuit will be simulated in Multisim to obtain non-ideal parameter values. The input and feedback resistors are chosen so that the amplification values are 20dB and 40dB. The gain and gain bandwidth product will be measured through AC sweep analysis. The slew rate will be measured through transient response. The input frequency and amplitude will be increased until the sawtooth is seen at output. The slew rate is the angular coefficient of triangle. The input bias current and offset voltage will be measured by grounding all the inputs. From the measured output voltage, the input bias current and offset voltage are calculated.

6.1 LM741 Circuit Design & Simulation

Figure 11 is the circuit design of the LM741. The switch S1 is for the 40 dB and 20 dB amplification. The switch S2 is for offset voltage and input bias current measurement.

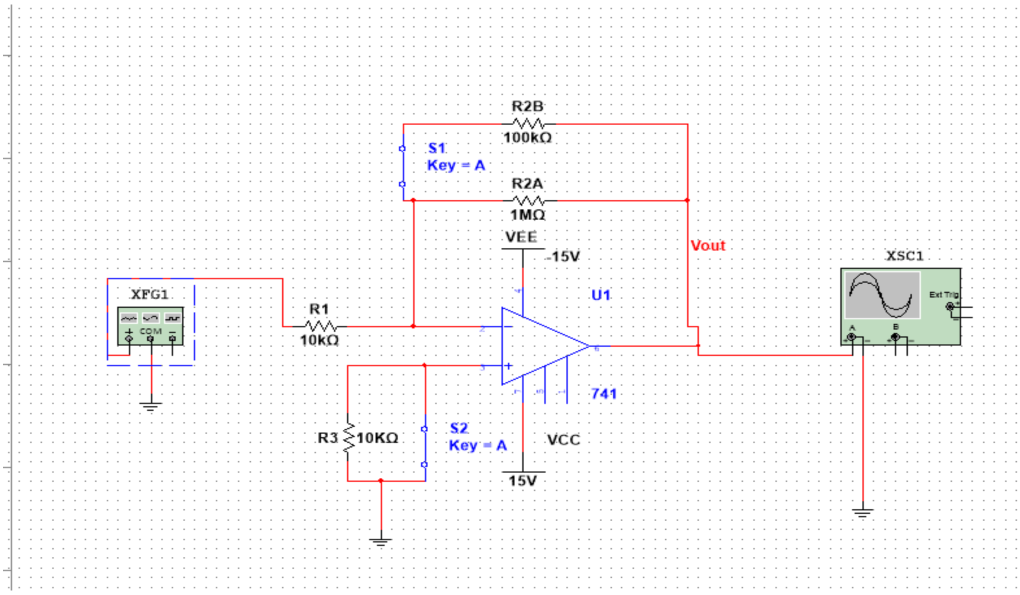

Figure 11. Circuit design of LM741

In the figure,

Inverting Input resistance R1 = 10K

Feedback resistance R2A = 1M & R2B = 100K

Non-Inverting input resistance R3 = 10K

Supply voltage VCC = 15V & VEE = -15V

6.1.1 GBP Measurement of LM741

The gain of the op-amp was measured through an AC sweep simulation. The input sine wave was fed through the signal generator. The amplitude of the input was 2 Vpp, and the frequency range was 100 Hz to 100 MHz. The cut-off frequency was taken from the gain graph and multiplied by the gain to obtain the gain bandwidth product.

When S1 was open and S2 closed,

R2 = R2A

Amplification,

$$A_v = -\frac{R2}{R1}$$

$$A_v = -\frac{1M}{10K}$$

$$A_v = -100$$

$$A_v = 40dB$$

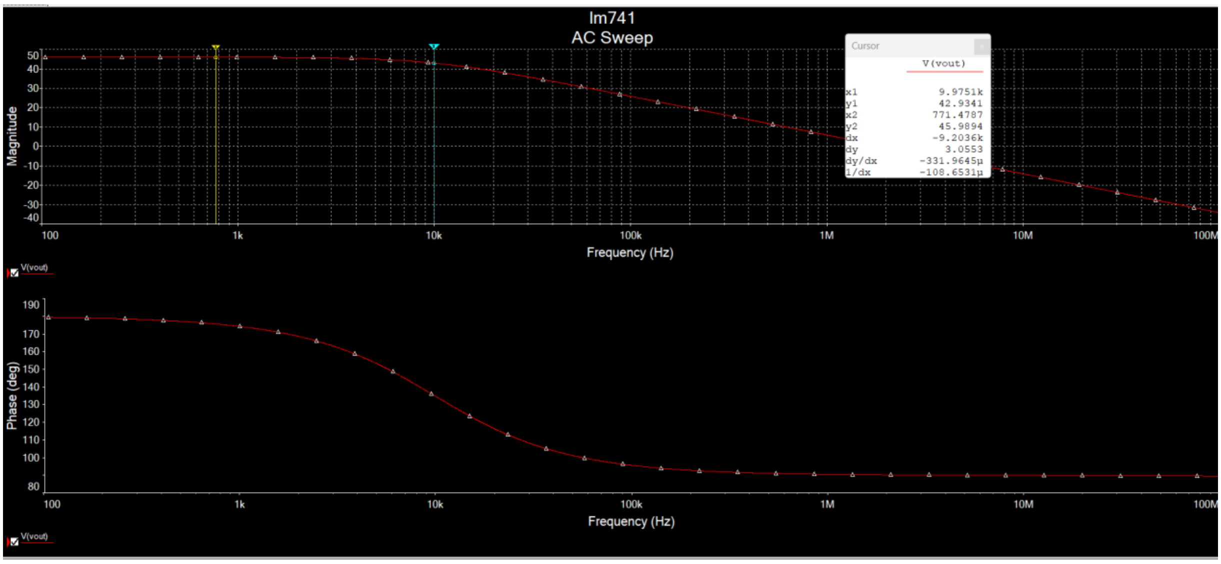

Figure 12. AC sweep analysis of LM741 when S1 open & S2 close

From the above figure 12, cut-off frequency (f_C) = 9.97 kHz

Gain Bandwidth Product,

$$GBP = A_v * \text{ fc}$$

$$GBP = 100 * 9.97\ KHz$$

$$GBP = 0.9\ MHz$$

When S1 and S2 closed,

$$R2 = R2A\ / /\ R2B$$

$$R2 = 1M\ / /\ 1K$$

$$R2 = 91\ K$$

Amplification,

$$A_v = -\frac{R2}{R1}$$

$$A_v = -\frac{91K}{10K}$$

$$A_v = -9.1$$
$$A_v = 19.1\ dB$$
$$A_v \simeq 20\ dB$$

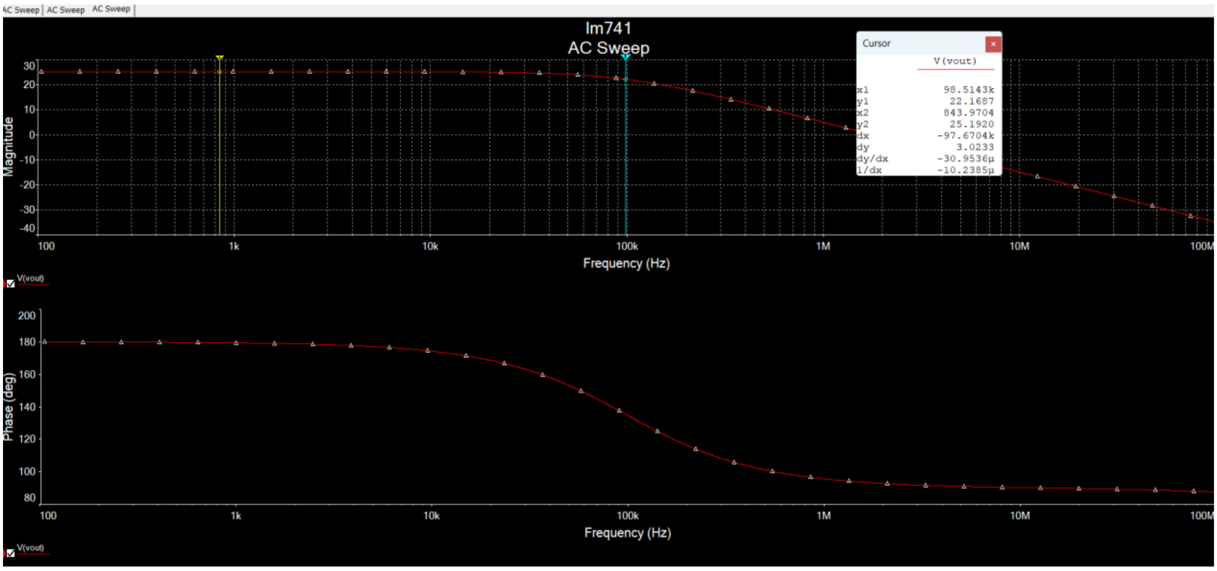

Figure 13. AC sweep analysis of LM741 when S1 close & S2 close

From the above figure 13, cut-off frequency (f_C) = 98.5 KHz

Gain Bandwidth Product,

$$GBP = A_v * \text{ fc}$$
$$GBP = 9.1 * 98.5\ KHz$$
$$GBP = 0.9\ MHz$$

6.1.2 Slew Rate Measurement of LM741

To measure the slew rate, the input frequency and amplitude was increased until the sawtooth was observed at the output. The circuit was simulated in transient response, and the slew rate was measured through the angular coefficient of triangle.

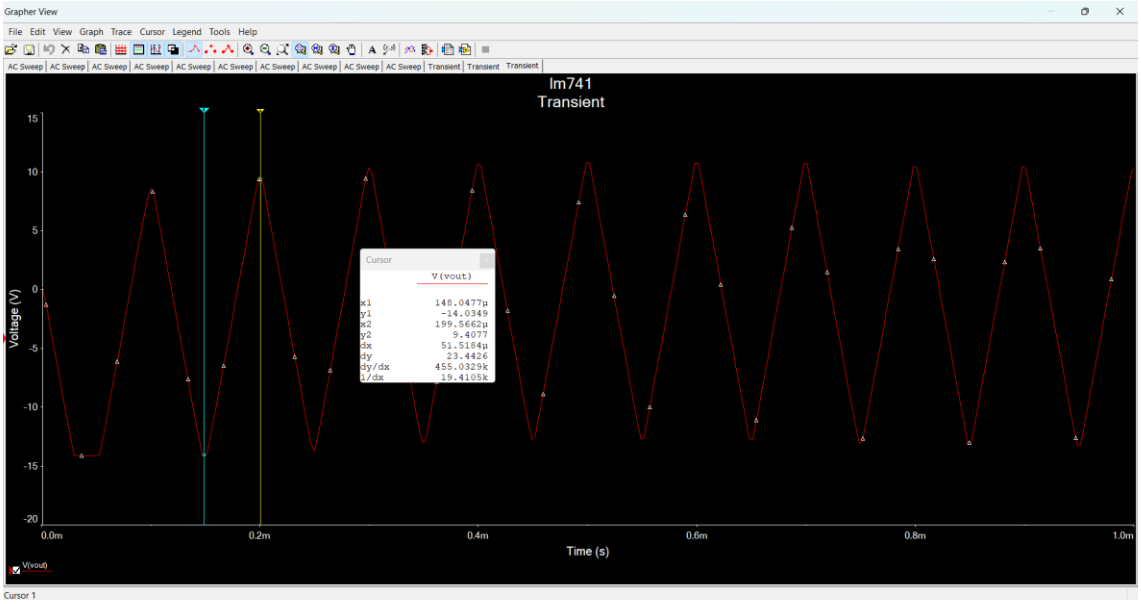

Figure 14. Transient response of LM741

From the figure 14,

$$SR = \frac{dy}{dx}$$

$$SR = \frac{23.44\ V}{51.5\ \mu s}$$

$$SR = 0.43\ \mathrm{V}/\ \mu s$$

The slew rate of LM741 was measured $0.43\ \mathrm{V}/\ \mu s$.

6.1.3 Offset Voltage and Input Bias Current Measurement of LM741

All the inputs of the op-amp were grounded to measure the offset voltage and input bias current as shown in Figure 15 below. The switches S1 and S2 were open and both input resistances R1 and R3 are set equal to cancel the voltage drops by the input bias current.

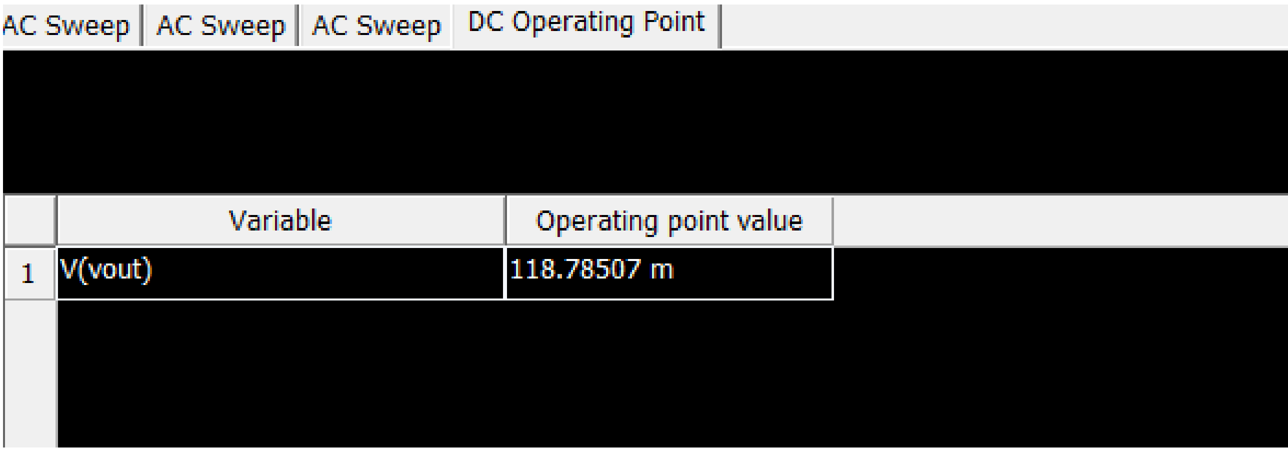

Figure 15. DC operating point analysis of LM741 when S1 & S2 open

From the above figure 15, when S2 and S1 open

Output voltage Vo = 118 mV

To calculate offset voltage Vos,

$$Vo = \left(1 + \frac{R_{2A}}{R_1}\right) V_{os}$$

$$118\,mV = (1 + 100)V_{os}$$

$$Vos = 1.16\,mV$$

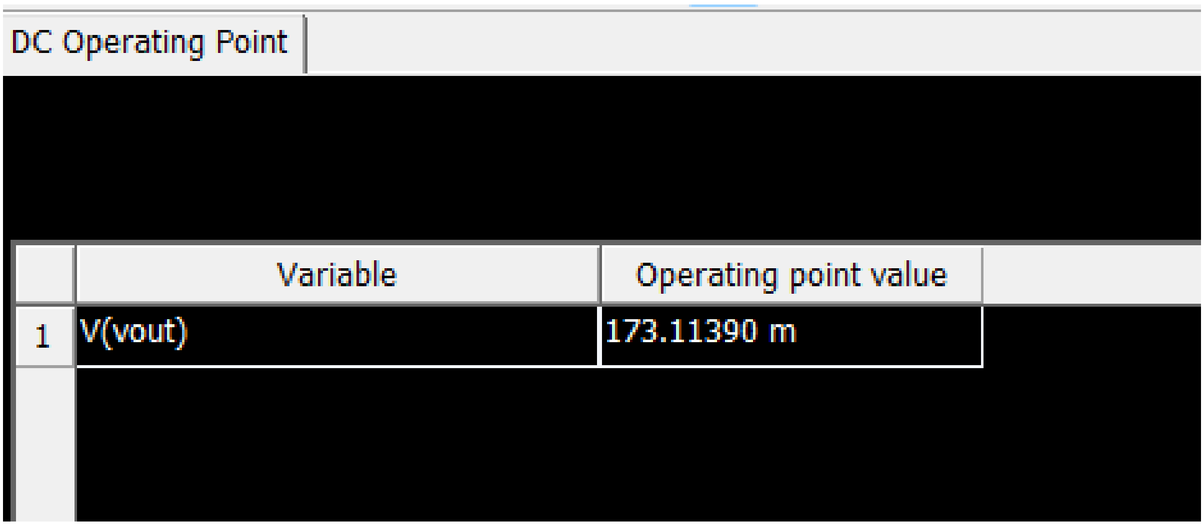

Figure 16. DC operating analysis of LM741 when S1 open and S2 close

From the figure 16, When S1 open and S2 close,

Output voltage Vo = 173 mV

To calculate bias current (I_B)

$$Vo = \left(1 + \frac{R_{2A}}{R_1}\right) V_{os} + (-I_B) * R_{2A}$$

$$173\ mV = (1 + 100) * 1.16\ mV + (-I_B) * 1\ M$$

$$I_B = 50\ nA$$

From the simulation and calculation, the offset voltage was obtained as 1.16 mV, and the input bias current was 50 nA.

6.2 OP07 Circuit Design & Simulation

Figure 17 below is the circuit design of the op-amp OP07. The switch S1 is for the 40 dB and 20 dB amplification. The switch S2 is for offset voltage and input bias current measurement. This circuit was designed and simulated in Multisim.

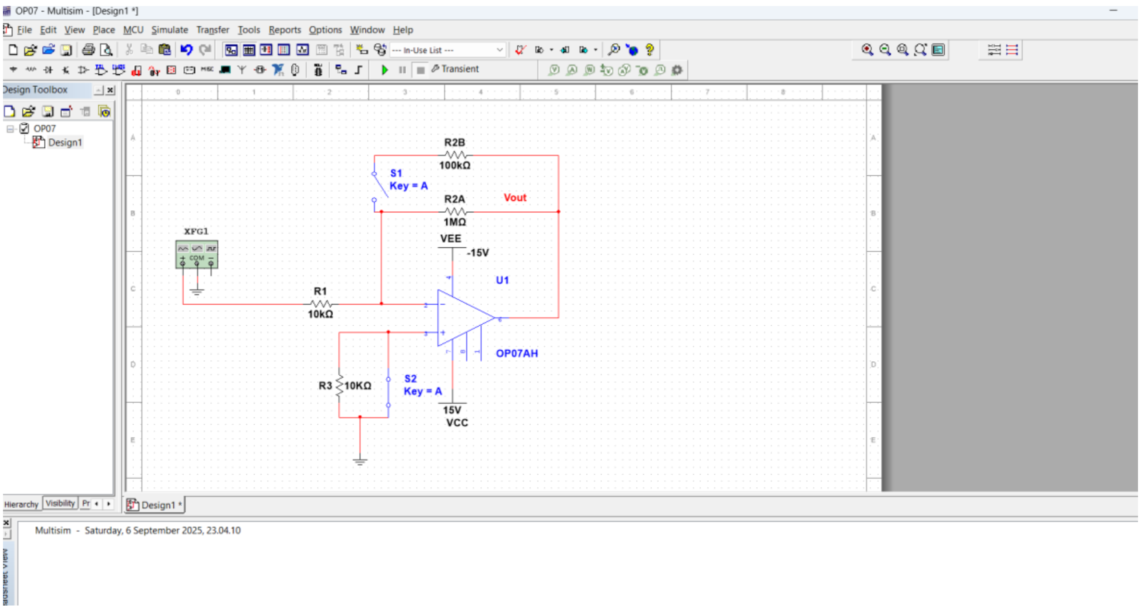

Figure 17. Circuit design of OP07

In the figure,

Inverting Input resistance R1 = 10K

Feedback resistance R2A = 1M & R2B = 100K

Non-Inverting input resistance R3 = 10K

Supply voltage VCC = 15V & VEE = -15V

6.2.1 GBP Measurement of OP07

The gain of the op-amp was measured through an AC sweep simulation. In Figure 18 below, the input sine wave was fed through the signal generator. The amplitude of the input was 2Vpp and the frequency range was 100 Hz to 100 MHz. The cut-off frequency was taken from the gain graph and multiplied by gain to obtain gain bandwidth product.

When S1 was open and S2 closed, R2 = R2A

The gain is the ratio of feedback resistor and input resistor,

$$A_v = -\frac{R2}{R1}$$

$$A_v = -\frac{1M}{10K}$$

$$A_v = -100$$

$$A_v = 40dB$$

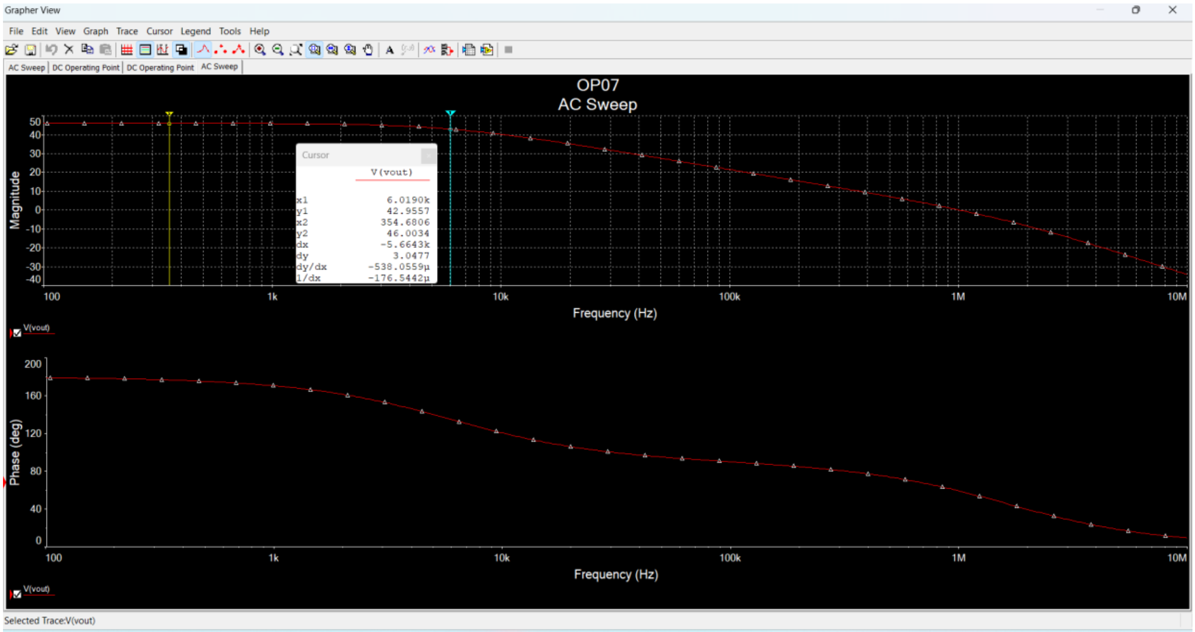

Figure 18. AC sweep analysis of OP07 when S1 open & S2 closed

From the above figure 18, cut-off frequency (f_C) = 6 KHz

Gain Bandwidth Product,

$$GBP = A_v * \text{ fc}$$

$$GBP = 100 * 6\ kHz$$

$$GBP = 0.6\ MHz$$

The gain bandwidth product of op-amp OP07 was obtained 0.6 MHz.

When S1 and S2 closed,

$$R2 = R2A\ / /\ R2B$$

$$R2 = 1M\ / /\ 1K$$

$$R2 = 91\ K$$

Amplification,

$$A_v = -\frac{R2}{R1}$$

$$A_v = -\frac{91K}{10K}$$

$$A_v = -9.1$$

$$A_v = 19.1\ dB$$

$$A_v \simeq 20\ dB$$

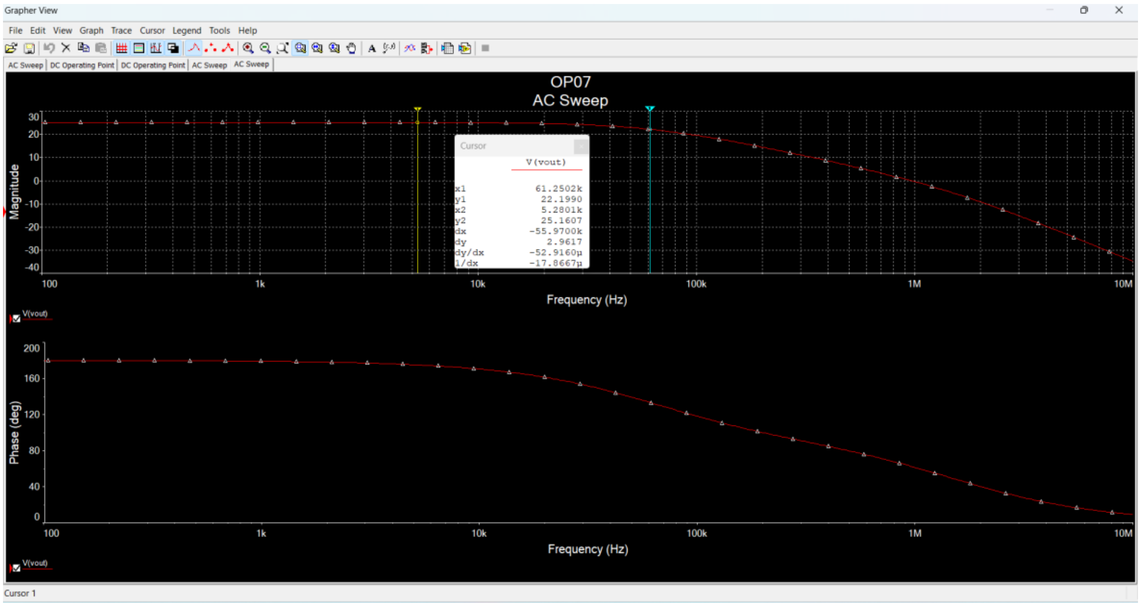

Figure 19. AC sweep analysis of OP07 when S1 & S2 closed

From the above figure 19, cut-off frequency (fc) = 61 kHz

Gain Bandwidth Product,

$$GBP = A_v * \text{ fc}$$

$$GBP = 9.1 * 61\ KHz$$

$$GBP = 0.6\ MHz$$

The gain bandwidth product of OP07 was obtained 0.6 MHz in both case.

6.2.2 Slew Rate Measurement of OP07

To measure the slew rate, the input frequency and amplitude was increased until the sawtooth was observed at the output. The circuit was simulated in transient response, and the slew rate was measured through the angular coefficient of triangle.

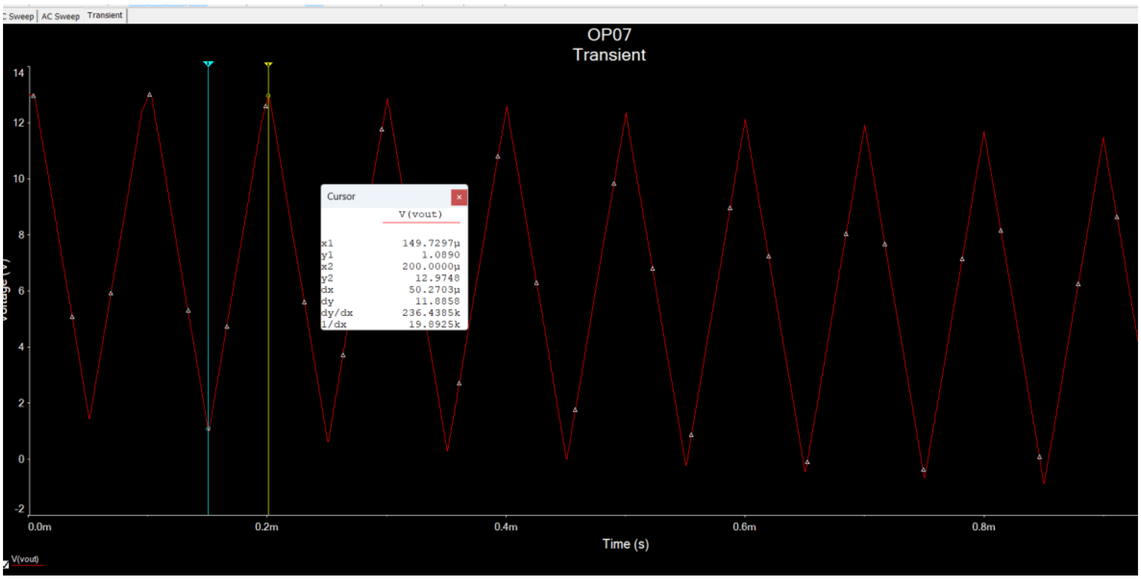

Figure 20. Transient response of OP07

From Figure 20,

$$SR = \frac{dy}{dx}$$

$$SR = \frac{11\ V}{50\ \mu s}$$

$$SR = 0.22\ \mathrm{V/\ \mu s}$$

The slew rate of OP07 was measured $0.22\ \mathrm{V/\ \mu s}$.

6.2.3 Offset Voltage and Input Bias Current Measurement of OP07

All the inputs of the op-amp were grounded to measure the offset voltage and input bias current, as shown in Figure 21 below. The switches were S1 closed and S2 open. Both input resistances R1 and R3 were set equal to cancel the voltage drops by the input bias current.

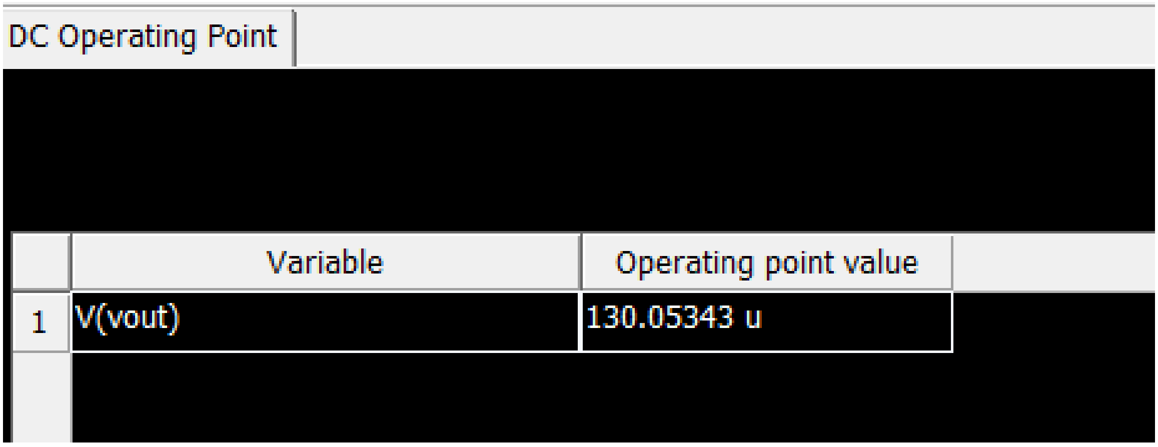

Figure 21. DC operating point analysis of OP07 when S1 close & S2 open

From the above figure 21,

Output voltage Vo = 130 uV

To calculate offset voltage Vos,

$$Vo = \left(1 + \frac{R_2}{R_1}\right) V_{os}$$

$$130\ uV = (1 + 100) V_{os}$$

$$Vos = 13\ uV$$

The offset voltage of the OP07 was obtained as 13 µV.

When S1 and S2 closed,

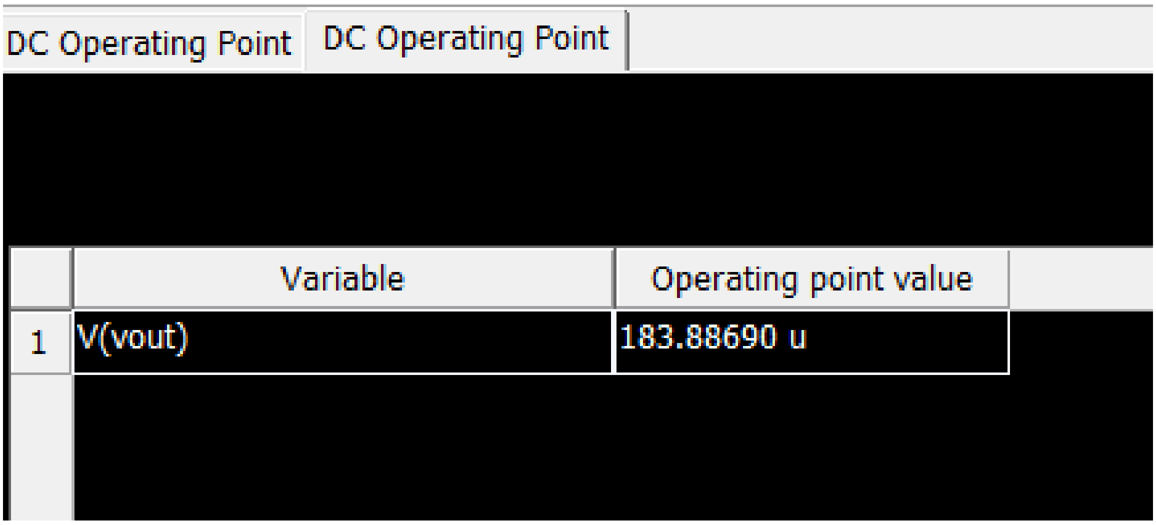

Figure 22. DC operating analysis of OP07 when S1 and S2 are closed

From Figure 22,

Output voltage Vo = 183 uV

To calculate bias current (I_B)

$$Vo = \left(1 + \frac{R_2}{R_1}\right) V_{os} + (-I_B) * R_2$$

$$183\ uV = (1 + 9.1) * 13\ uV + (-I_B) * 91\ K$$

$$I_B = 0.6\ nA$$

From the simulation and calculation, the offset voltage was obtained as 13 µV, and the input bias current was 0.6 nA.

6.3 OPA134 Circuit Design & Simulation

Figure 23 below is the circuit design of the op-amp OPA134. The switch S1 is for the 40 dB and 20 dB amplification. The switch S2 is for offset voltage and input bias current measurement. This circuit was designed and simulated in Multisim.

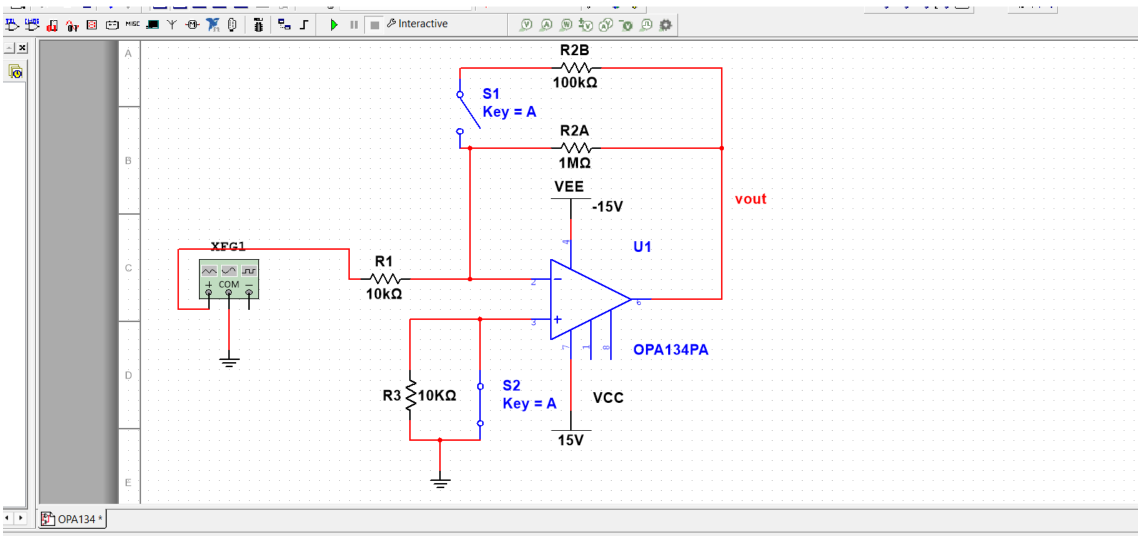

Figure 23. Circuit design of OPA134

In the figure,

Inverting Input resistance R1 = 10K

Feedback resistance R2A = 1M & R2B = 100K

Non-Inverting input resistance R3 = 10K

Supply voltage VCC = 15V & VEE = -15V

6.3.1 GBP Measurement of OPA134

The gain of the op-amp was measured through an AC sweep simulation. In Figure 24 below, the input sine wave was fed through the signal generator. The amplitude of the input was 2Vpp, and the frequency range was 100 Hz to 100 MHz. The cut-off frequency was taken from the gain graph and multiplied by the gain to obtain the gain bandwidth product.

When S1 was open and S2 closed,

R2 = R2A

The gain is the ratio of the feedback resistor and the input resistor,

$$A_v = -\frac{R2}{R1}$$

$$A_v = -\frac{1M}{10K}$$

$$A_v = -100$$

$$A_v = 40dB$$

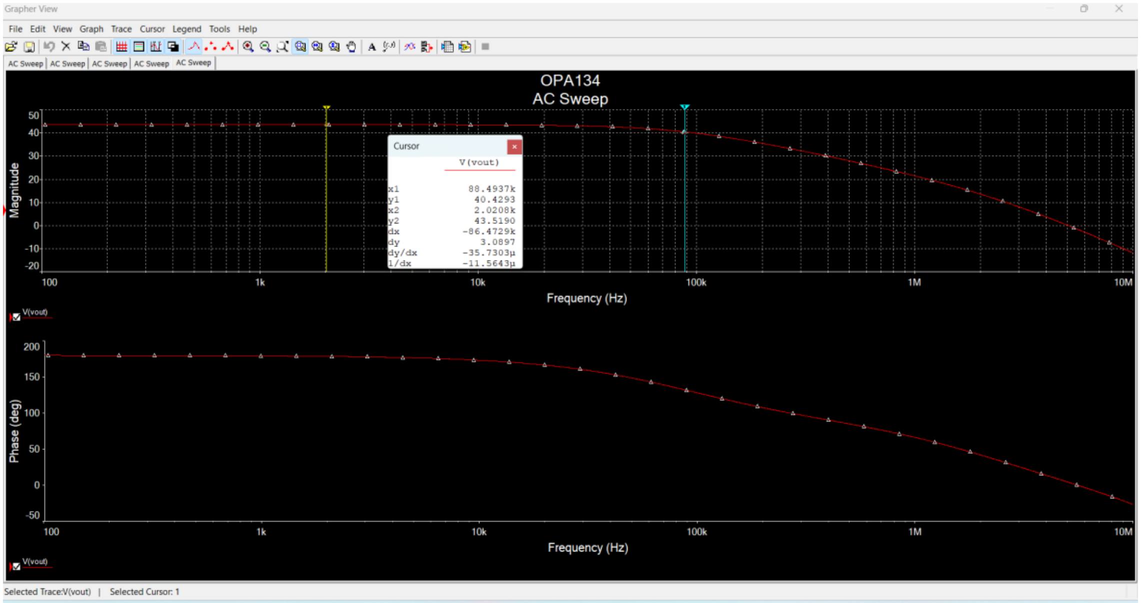

Figure 24. AC sweep analysis of OPA134 when S1 open & S2 closed

From the above figure 24, cut-off frequency (fc) = 88 kHz

Gain Bandwidth Product,

$$GBP = A_v * \text{ fc}$$

$$GBP = 100 * 88\ KHz$$

$$GBP = 8.8\ MHz$$

The gain bandwidth product of op-amp OPA134 was obtained 8.8 MHz.

When S1 and S2 closed,

$$R2 = R2A\ //\ R2B$$

$$R2 = 1M\ //\ 1K$$

$$R2 = 91\ K$$

Amplification,

$$A_v = -\frac{R2}{R1}$$

$$A_v = -\frac{91K}{10K}$$

$$A_v = -9.1$$

$$A_v \simeq 20\ dB$$

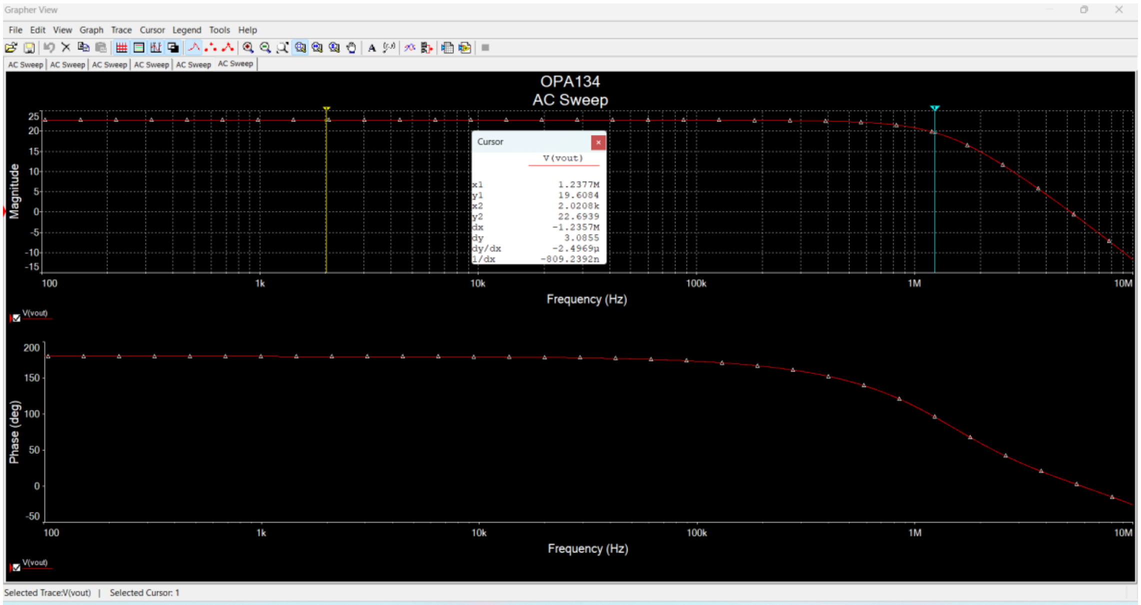

Figure 25. AC sweep analysis of OPA134 when S1 & S2 closed

From the above figure 23, cut-off frequency (f_C) = 1.2 MHz

Gain Bandwidth Product,

$$GBP = A_v * \text{ fc}$$

$$GBP = 9.1 * 1.2\ MHz$$

$$GBP = 10.9\ MHz$$

The gain bandwidth product of OPA134 was obtained 10.9 MHz.

6.3.2 Slew Rate Measurement of OPA134

To measure the slew rate, the input frequency and amplitude are increased until the sawtooth is observed at the output. The slew rate is measured through the angular coefficient of the triangle. Figure 26 below shows the transient response of the OPA134 circuit.

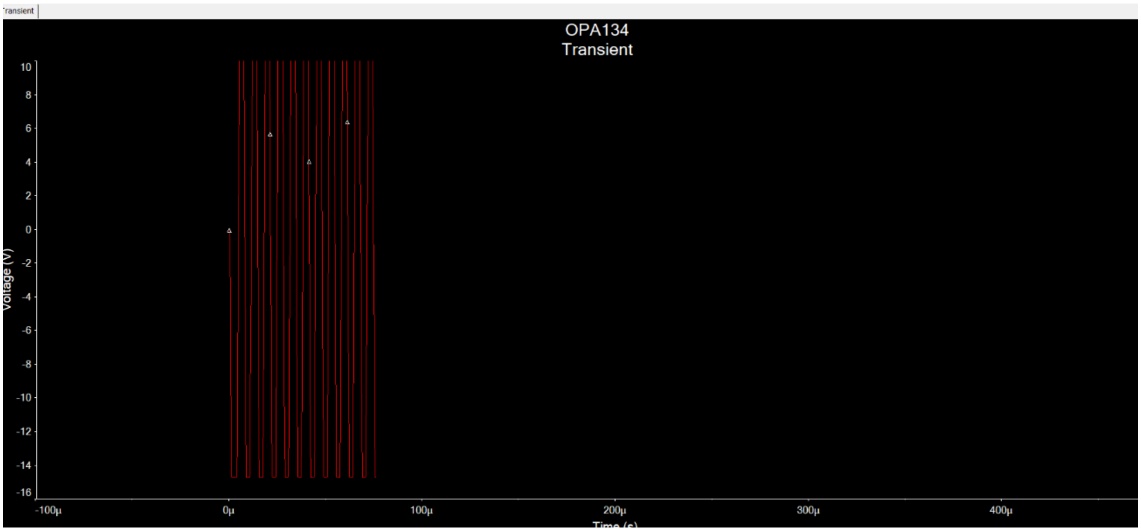

Figure 26. Transient response of OPA134

In this measurement setup, the sawtooth at the output was not achieved until the frequency was increased to 150 kHz. This is because of the high slew rate of OPA134, which was 20 V/μs. The slew rate was not measured in this thesis project due to unable to obtain perfect sawtooth at output within available frequency band.

6.3.3 Offset Voltage and Input Bias Current Measurement of OPA134

All the inputs of the op-amp were grounded to measure the offset voltage and input bias current, as shown in Figure 27 below. The switches were S1 closed and S2 open. Both input resistances R1 and R3 were set equal to cancel the voltage drops by the input bias current.

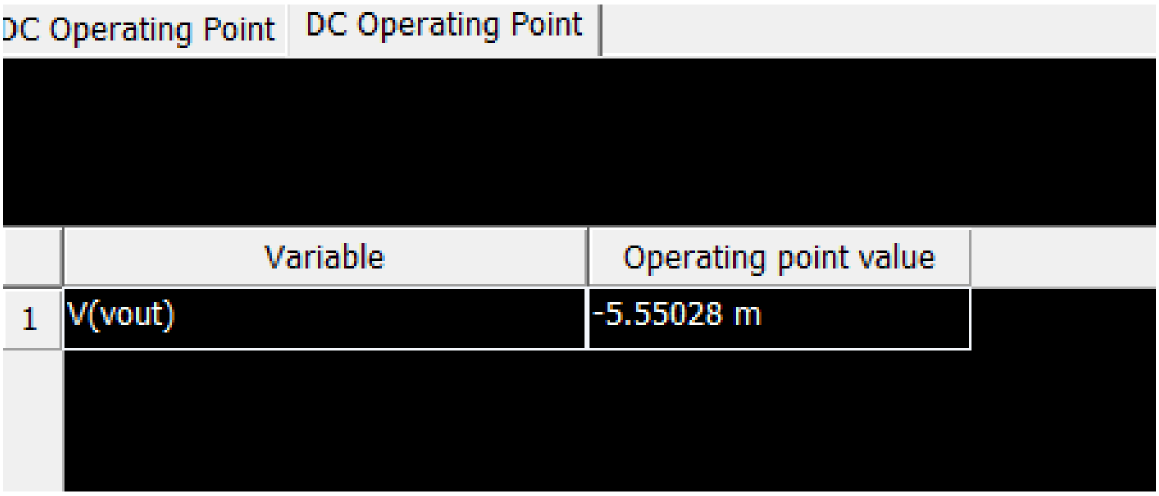

Figure 27. DC operating point analysis of OPA134 when S1 close and S2 open

From the above figure 27,

Output voltage Vo = -5.55028 mV

To calculate offset voltage Vos,

$$Vo = \left(1 + \frac{R_2}{R_1}\right) V_{os}$$

$$-5.55028\, mV = (1 + 9.1) V_{os}$$

$$Vos = -0.5495\, mV$$

The offset voltage of OPA134 was obtained as -0.5 mV.

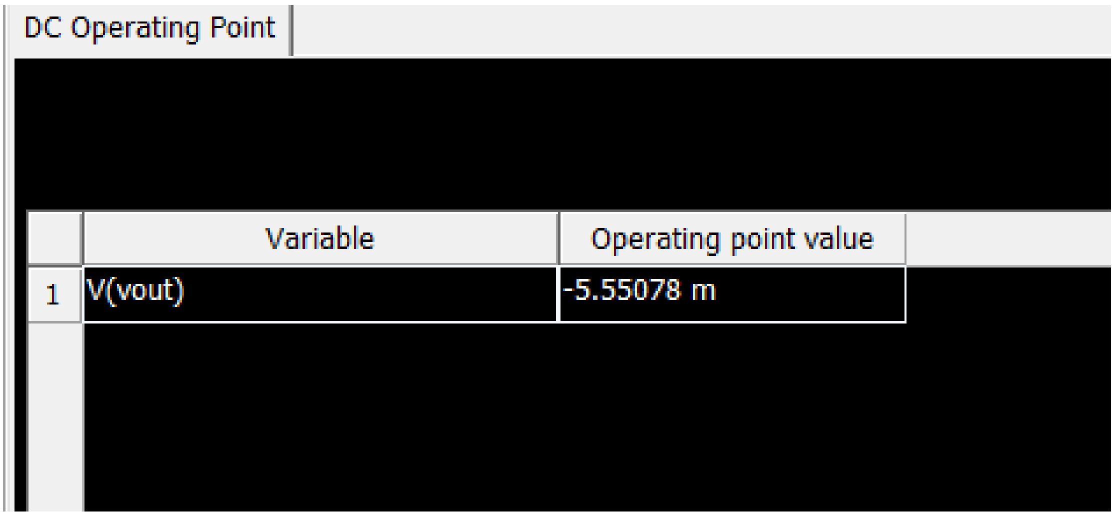

Figure 28. DC operating analysis of OPA134 when S1 and S2 are closed

From Figure 28, When S1 and S2 closed,

Output voltage Vo = -5.55078 mV

To calculate bias current (I_B)

$$Vo = \left(1 + \frac{R_2}{R_1}\right) V_{os} + (-I_B) * R_2$$

$$-5.55078\ mV = (1 + 9.1) * -0.5495\ mV + (-I_B) * 91\ K$$

$$I_B = 9\ nA$$

From the simulation and calculation, the offset voltage was obtained 0.5 mV, and the input bias current was 9 nA.

7 Schematic and PCB Design

Figure 29 below is the schematic design of the circuit. The schematic was designed in KiCad. The components used in this design include four resistors, three connectors, two switches, and an op-amp. In the place of the op-amp, 8-pin THT sockets were placed. This allows for all measurements of different op-amps to be taken at a single PCB simultaneously. Connector J1 was used for the input supply, connector J2 for the power supply, and connector J3 for the output. The switch SW1 was used for bypass bias compensated resistor, and switch SW3 was used to achieve different gains.

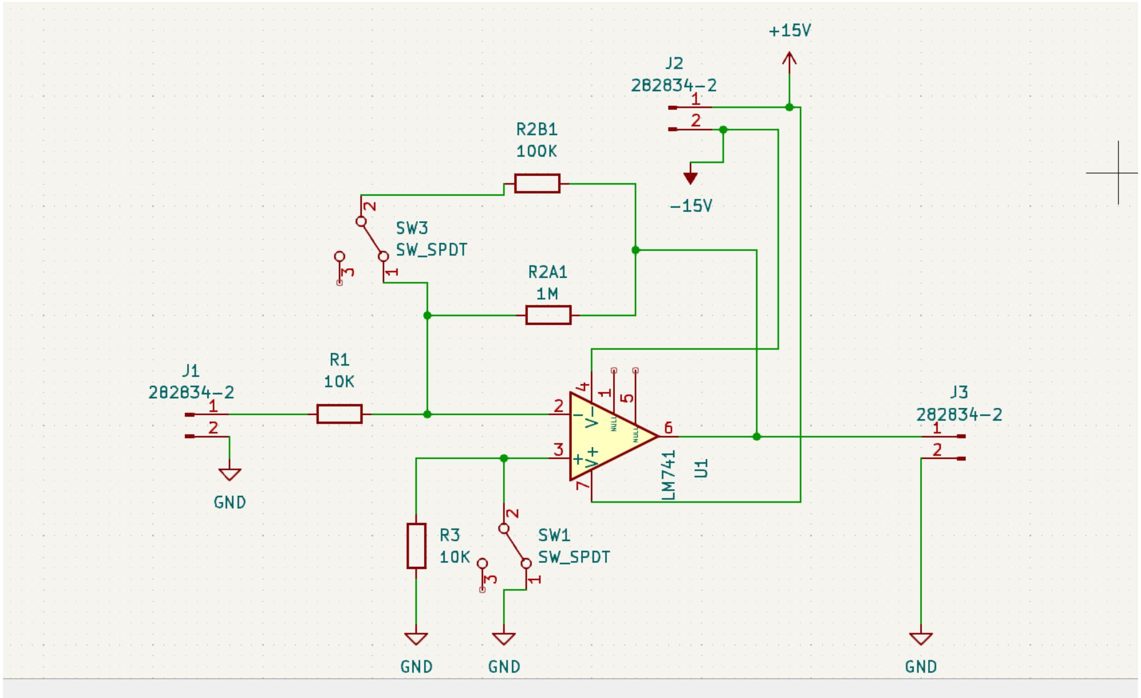

Figure 29. Schematic design of the circuit

Figure 30 below is the PCB design of the circuit. The PCB was designed using KiCad and was milled at the school lab. The dimension of the PCB is 3cm × 4 cm. All the components were soldered in electronics laboratory, Myyrmäki campus.

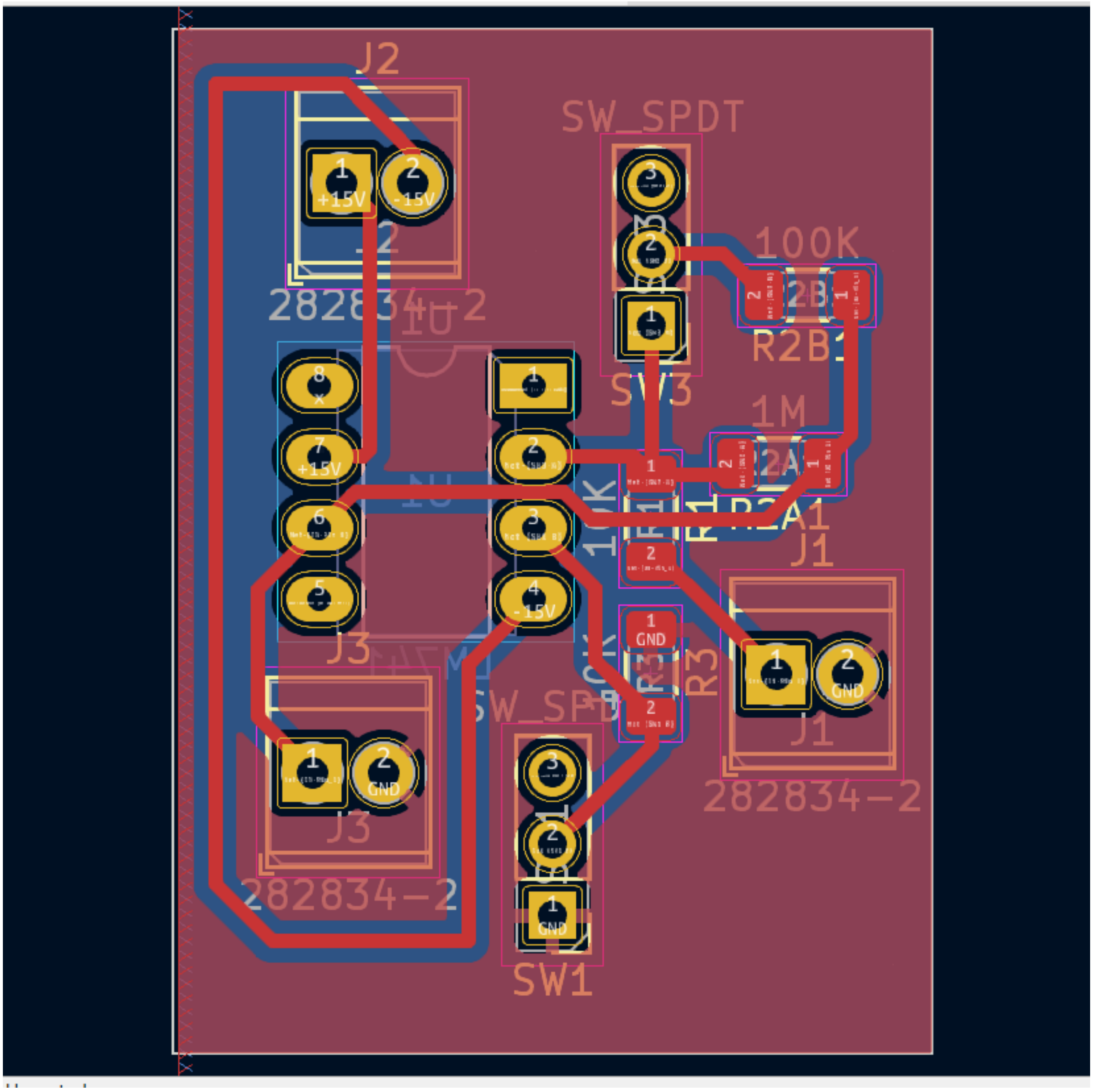

Figure 30. PCB design of the circuit

8 Result

The measurement setup for the Device Under Test is shown in Figure 31 below. The DUT received the power from the DC power supply. The DUT received +15V from the red wire and -15V from the blue wire, which were connected to the DC power supply. The DUT drew the input from the function generator. A sine wave with varying amplitude in different measurements and a zero offset voltage was fed to the DUT. The two channels of the oscilloscope were connected to the DUT to measure the input and output.

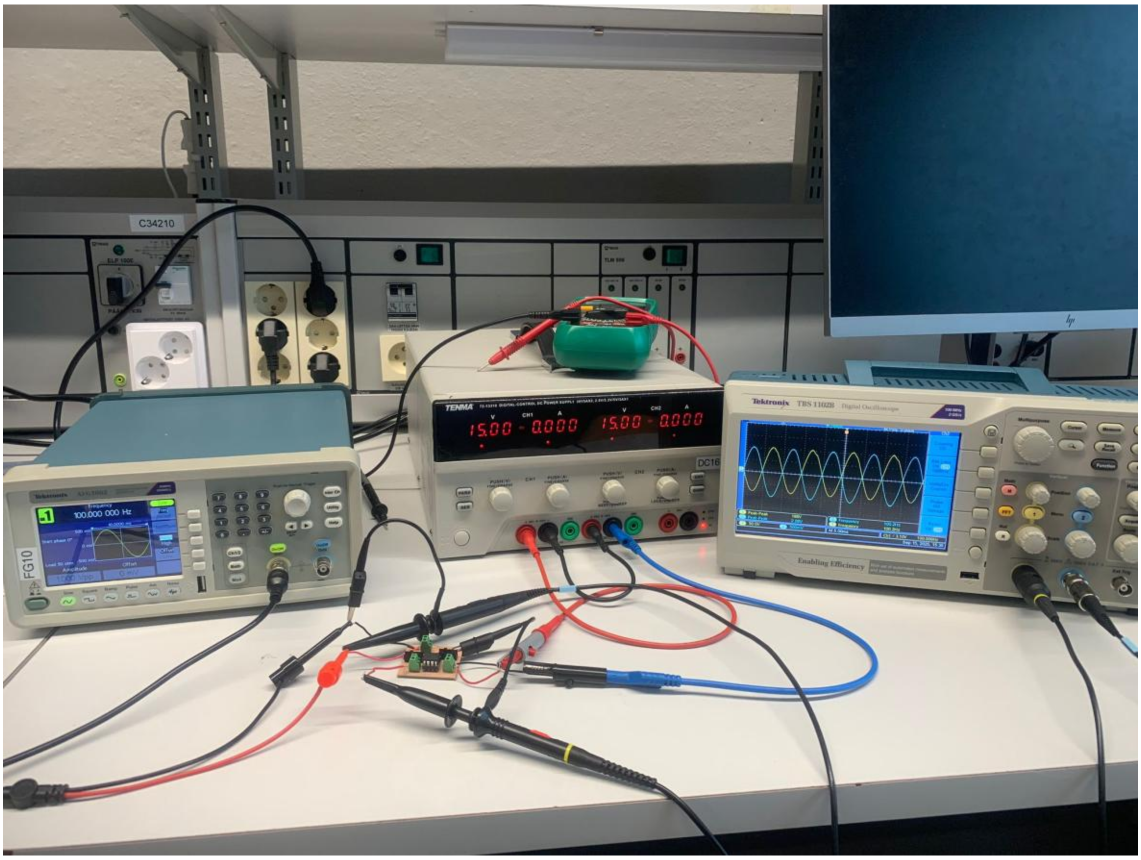

Figure 31. Measurement setup of PCB test circuit.

The measurement summary results from the Multisim simulation and the laboratory measurement are shown in Table 3 below. The overall laboratory measurement results are in the Excel spreadsheet attached to Appendix 1.

Table 3. Comparison of measurement results.

Op-amps		GBP (MHz)	Offset Voltage(mV)	Bias Current(nA)	Slew Rate (V/µs)
LM741	Datasheet	1.5	1	80	0.5
	Multisim	0.9	1.16	50	0.48
	lab	1.2	0.86	23	0.62
OP07	Datasheet	0.4 - 0.6	30 - 75 µV	±1.2 - ±4	0.1 – 0.3
	Multisim	0.6	12.87 µV	0.6	0.22
	lab	0.5	86 µV	11.8	0.26
OPA134	Datasheet	8	±1 – 3.5	±5 – 100 pA	±20
	Multisim	8.8	0.5	9 nA	-
	lab	6	0.4	20 nA	-

9 Conclusion

The thesis offers a detailed theoretical background of the operational amplifier. Operational amplifier´s inverting and non-inverting circuits are also explored. This study briefly explains its non-ideal characteristics, such as input offset voltage, input bias current, gain, gain bandwidth product, slew rate, common mode rejection ratio and rail to rail output.

This thesis takes three samples of op-amps in such a way that they can be distinguished from their non-ideal parameter values. The schematic and PCB were designed in KiCad to measure non-ideal characteristics. The non-ideal parameter values, such as input offset voltage, input bias current, gain bandwidth product, and slew rate of the samples, are measured through Multisim and PCB. The measured values are presented in the Result section.

This thesis can be used as learning material by the electronics engineering students for their analog electronics course. The design PCB can be used in the laboratory project for an analog electronics course to distinguish samples of op-amps. The limitation of this thesis is that it is unable to measure the slew rate of OPA134 because of its high value.

References

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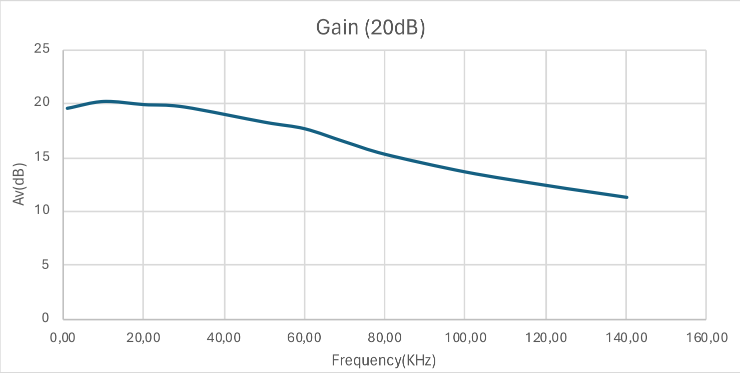
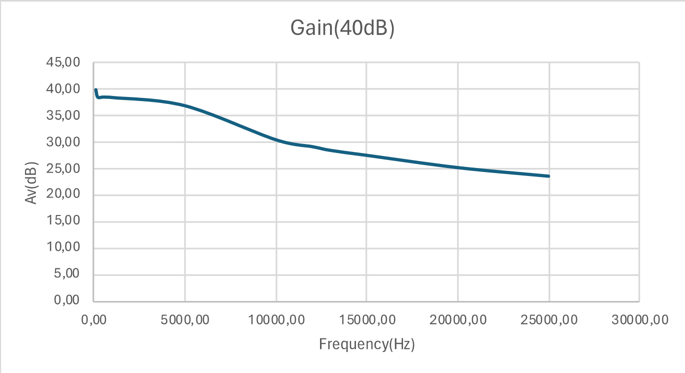
Lab Measurement Results of OP07

		S1 close		
Frequency (kHz)	**Vin (V)**	**Vout (V)**	**Amplication**	**Av (dB)**
1,00	1,02	9,68	9,4901961	19,5455
10,00	1,02	10,4	10,196078	20,16866
20,00	0,64	6,32	9,875	19,89074
30,00	0,42	4,04	9,6190476	19,66264
50,00	0,43	3,52	8,1860465	18,26148
60,00	0,43	3,28	7,627907	17,64811
70,00	0,44	2,92	6,6363636	16,4386
80,00	0,44	2,56	5,8181818	15,29575
100,00	0,44	2,12	4,8181818	13,65766
120,00	0,44	1,84	4,1818182	12,4273
140,00	0,44	1,62	3,6818182	11,32125



		S1 open					
Frequency (Hz)	**Vin(V)**	**Vout(V)**	**Av**	**Av(dB)**			
100,00	0,20	20,20	101,00	40,09			
200,00	0,24	20,60	85,83	38,67			
500,00	0,24	20,60	85,83	38,67			
1000,00	0,24	20,40	85,00	38,59	**Fc(Hz)**	**Gain**	**GBP(MHz)**
5000,00	0,24	17,00	70,83	37,00	5000	100	0,50
10000,00	0,32	10,70	33,44	30,48			
12000,00	0,32	9,20	28,75	29,17			
13000,00	0,32	8,48	26,50	28,46			
15000,00	0,32	7,60	23,75	27,51			
20000,00	0,32	5,80	18,13	25,17			
25000,00	0,32	4,80	15,00	23,52			



Slew Rate			
	Δvout(V)	time(μs)	SR(V/μs)
	13,8	52	0,265385

Offset voltage Vo = [1+R2/R1]*Vos

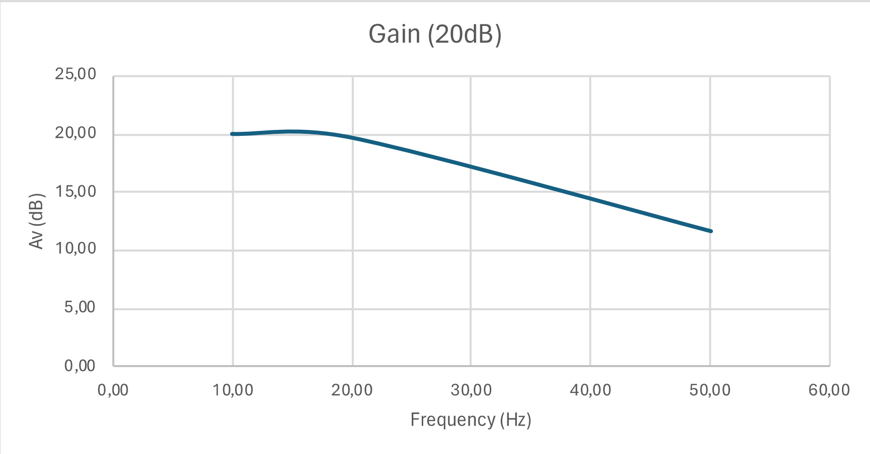
S2 open	Vo (mV)	Vos(μV)
	8,77	86

Bias Current Vo = [1+R2/R1] *Vos+ [-IB]*R2

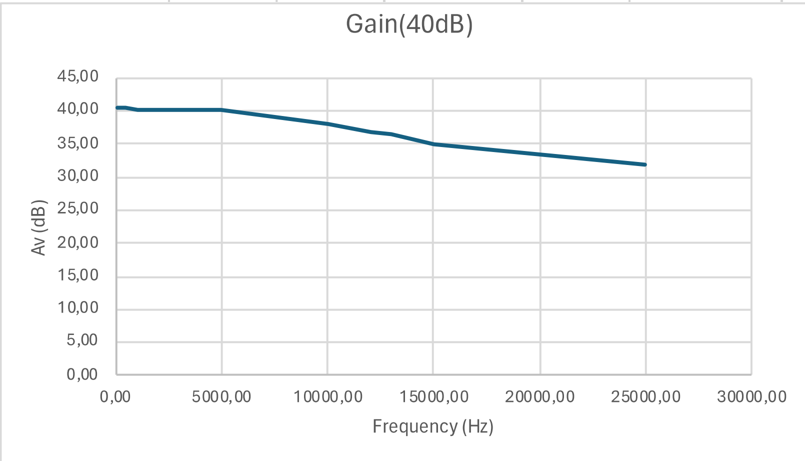
S2 close	Vo(mV)	IB(nA)
	20,40	11,80

Lab Measurement Results of LM741

		s1 close		
Frequency (KHz)	**Vin (V)**	**Vout (V)**	**Amplication**	**Av (dB)**
10,00	0,42	4,24	10,10	20,08
20,00	0,42	4,08	9,71	19,75
50,00	0,80	3,04	3,80	11,60



	s1 open						
Frequency (Hz)	**Vin(V)**	**Vout(V)**	**Av**	**Av(dB)**			
100,00	0,10	10,60	106,00	40,51			
200,00	0,10	10,60	106,00	40,51			
500,00	0,10	10,60	106,00	40,51	**Fc(Hz)**	**Gain**	**GBP(MHz)**
1000,00	0,10	10,40	104,00	40,34	12000	100	1,20
5000,00	0,10	10,40	104,00	40,34			
10000,00	0,10	8,00	80,00	38,06			
12000,00	0,10	7,00	70,00	36,90			
13000,00	0,10	6,60	66,00	36,39			
15000,00	0,10	5,70	57,00	35,12			
20000,00	0,10	4,64	46,40	33,33			
25000,00	0,10	3,92	39,20	31,87			



Slew Rate

Δvout(V)	time(μs)	SR(V/μs)
25	40	0,625

Offset voltage Vo = [1+R2/R1]*Vos

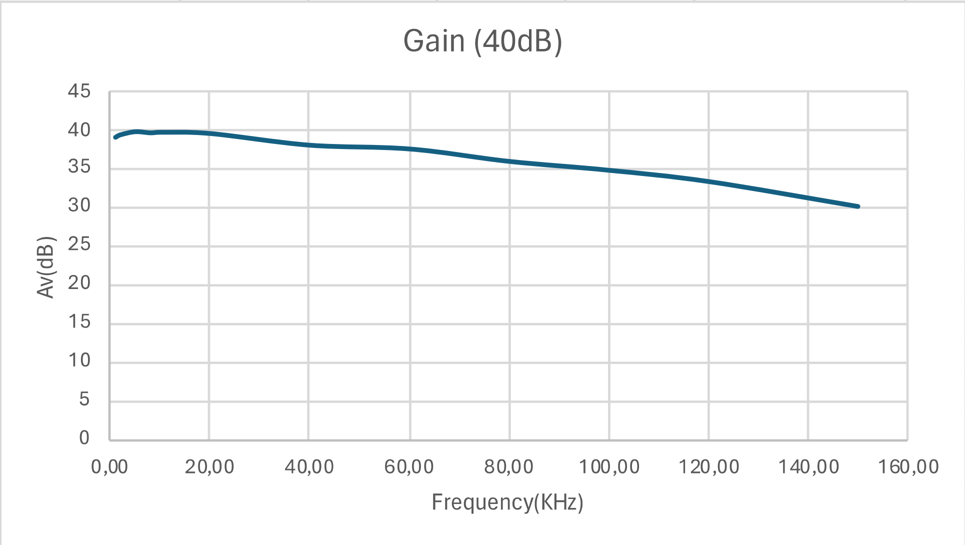
S2 open	Vo(mV)	Vos(mV)
	87	0,86

Bias Current Vo = [1+R2/R1] *Vos+ [-IB]*R2

S2 close	Vo(mV)	IB(nA)
	110	23

Lab Measurement Results of OPA134

		S1 open					
Frequency (KHz)	**Vin (V)**	**Vout (V)**	**Amplicatio**	**Av (dB)**			
1,00	0,22	20	90,90909	39,17215			
2,00	0,22	20,8	94,54545	39,51281			
5,00	0,22	21,8	99,09091	39,92068			
8,00	0,22	21,4	97,27273	39,75982			
10,00	0,22	21,6	98,18182	39,84062			
20,00	0,22	21,2	96,36364	39,67826	**Fc(KHz)**	**Gain**	**GBP(MHz)**
40,00	0,23	18,6	80,86957	38,1557	60	100	6,00
60,00	0,23	17,6	76,52174	37,6757			
80,00	0,23	14,6	63,47826	36,0525			
100,00	0,23	12,8	55,65217	34,90964			
120,00	0,23	10,8	46,95652	33,43392			
150,00	0,23	7,44	32,34783	30,1969			



		S2 close		
Frequency(KHz)	**Vin(V)**	**Vout(V)**	**Av**	**Av(dB)**
10	0,22	2,16	9,818182	19,84062
20	0,22	2,22	10,09091	20,07861
50	0,22	2,24	10,18182	20,15651
100	0,23	2,26	9,826087	19,84761
200	0,23	2,18	9,478261	19,53457
500	0,23	2,18	9,478261	19,53457

Offset voltage		Vo = [1+R2/R1]*Vos	
	S2 open	Vo(mV)	Vos(mV)
		4,28	0,4

Bias Current	Vo = [1+R2/R1]*Vos + [-IB]*R2	
S2 close	Vo(mV)	IB(nA)
	2,46	20