Lab 2: **Op-Amp – dc and ac Effects and Limitations**

In this experiment, you will examine the main limitations and parameters of the op-amp.

The offset voltage and currents will be determined with dc measurements and then the null adjustment circuit for LM741 will be verified.

The frequency dependent characteristics, transition frequency, bandwidth and slew rate will be determined with ac measurements. The circuits are shown in figure 1 and the board is presented in Annex 1.

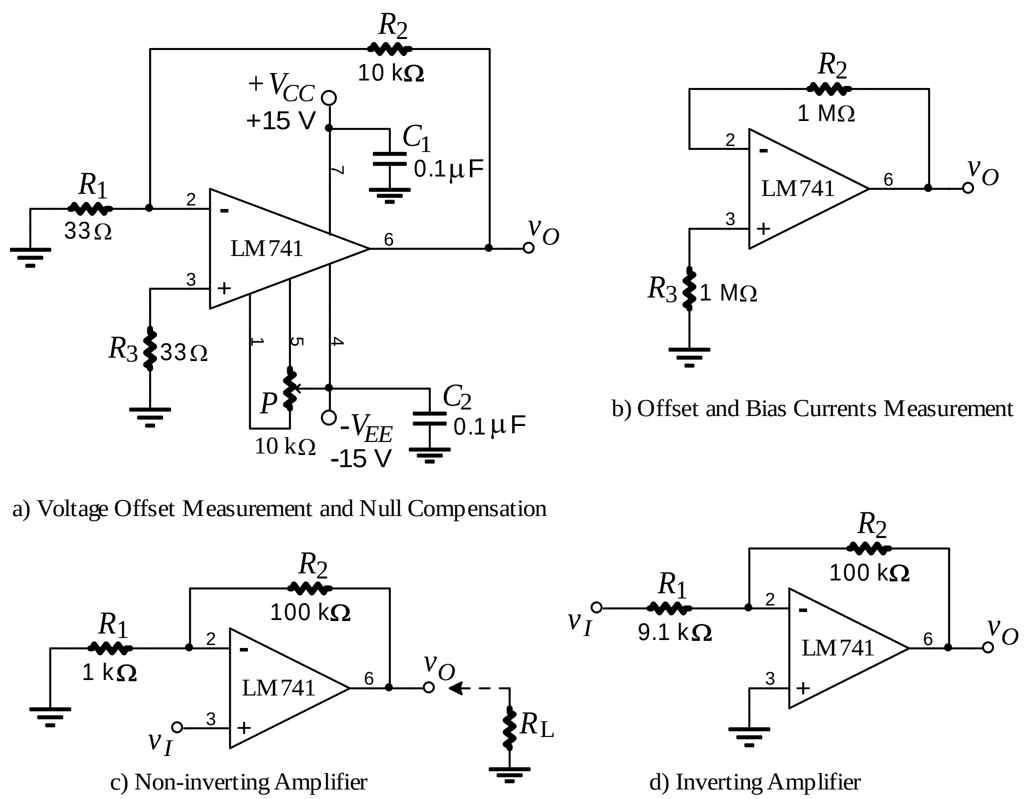

Figure 1: Circuits for op-amp dc and ac effects analysis

The power supplies are indicated on the first circuit only; to simplify the schematics the power supplies are omitted from the other circuits, but there are always present. Annex 1 presents the photo of the experimental board with the components labeled.

Offset Voltage

Figure 1.a) shows the circuit used to measure the offset voltage of an op amp.

Disconnect the null compensation potentiometer from the circuit.

Measure the resistances (R_1, R_2 – out of the board) and complete the first part of table 1. The input offset voltage V_{I0} can be computed with the theoretical gain:

$$A_{Th} = 1 + \frac{R_2}{R_1} \cong \frac{V_O}{V_{I0}}, \qquad V_{I0} = \frac{V_O}{1 + R_2/R_1}.$$

The effect of offset and bias currents was neglected. After the determination of the input offset current I_{I0} compute the error ε (in %) produced by I_{I0} on V_{I0} determination:

$$\varepsilon \cong \frac{I_{I0} \cdot R_2}{V_{I0}} \cdot 100$$

Table 1. The offset voltage and null compensation limits

R_1 (Ω)	R_2 (kΩ)	V_O (mV)	V_{I0} (mV)	I_{I0} (nA)	ε (%)	V_{O_min} (V)	V_{O_Max} (V)	V_{I0_min} (V)	V_{I0_Max} (V)

Null compensation circuit

Connect the null compensation potentiometer in the circuit (*P*: A21-B22-A23).

Adjust the potentiometer at its limits, measure the null compensation limits at the output and compute input offset voltage limits that can be compensated (consider the voltage gain as in the first set of formulas).

Finally adjust the potentiometer to compensate the offset (get zero volts at the output).

Bias and Offset Currents

The circuit schematic is indicated in figure 1.c). To implement the circuit modify the previous circuit implementation as follows:

- remove the resistor R_1 (from B7 – B12),
- measure an 1 MΩ resistor and then replace R_2 with it (R_2: C12 – C17),
- measure another 1 MΩ resistor and then replace R_3 with it (R_3: A13 – GND13),

Write the resistor values in the next table.
Measure the output voltage (V_{O0}) and write its value in the table.
Connect a wire in parallel with R_2 (e.g. wire: D12 – D17) and measure the effect produced at the output (V_{O+}) by the bias current of the non-inverting input (I_{B+}). Write its value in the table.
Connect a wire in parallel with R_3 (e.g. wire: B13 – GND14) and measure the effect produced at the output (V_{O-}) by the bias current of the inverting input (I_{B-}). Write its value in the table.

Table 2. The offset and bias currents

R_2 (kΩ)	R_3 (kΩ)	V_{O0} (mV)	I_{O0} (nA)	V_{O+} (mV)	I_{B+} (nA)	V_{O-} (mV)	I_{B-} (nA)	$\lvert I_B \rvert$ (nA)

Calculate the currents with formulas:

$$I_{I0} \equiv \frac{V_{O0}}{R_2}, \quad I_{B+} \equiv \frac{V_{O+}}{R_3}, \quad I_{B-} \equiv -\frac{V_{O-}}{R_2}.$$

Compare theirs value with the values given in the datasheet of LM741. The input offset voltage does not produce errors because it was compensated previously.

Indicate the actual direction of the bias current, based on theirs sign (sink or source by the op-amp inputs) and verify this direction considering the input transistors type (from the schematic diagram given in the LM741 datasheet).

Sketch the offset equivalent circuit of op-amp (add the input bias and input offset voltage sources to the ideal op-amp equivalent circuit – with theirs direction and values).

Gain Bandwidth

Implement the non-inverting amplifier from figure 1.c) as follows:

- Remove the components of the previous implementation: the null compensation potentiometer *P*, the resistors (R_2, R_3) and the short-circuit wire;
- Connect the resistors: R_2 (100 kΩ : C12 – C17) and R_1 (1 kΩ : A12 – GND12);
- Connect the ac input with a wire from line 6 to line 13 (e.g. B6 – B13). Set rms voltage of the signal generator to avoid slew-rate (*SR*) limitations (less/equal than 50 mV);
- Monitor the output wave with an oscilloscope (CRO).

Modify the frequency at the signal generator and complete table 3 (do not modify the voltage). The portable multimeter can be used for frequencies lower than 400 Hz; for higher frequencies utilize an ac voltmeter or the oscilloscope.

Table 3. The gain-frequency characteristic of the non-inverting configuration

f (Hz)	100	1 k	2 k	5 k	10 k	20 k	50 k	100k	200k	f_B =
V_i (mV)										
V_o (V)										
A_v										
A_v (dB)										

Determine the break frequency (or –3 dB frequency or bandwidth) and write the results in the last column of table 3. The output voltage (and gain) at this point is the voltage (gain) at low frequency divided by $\sqrt{2}$ (multiplied by 0.707, or reduced with 3 dB). Modify the frequency until the desired voltage (and gain) is obtained.

Compute the gain-bandwidth product (*GBP*) based on the dc or low frequency gain A_{v0}:

$$GPB = A_{v0} \cdot f_B = f_T$$

GBP is also the transition frequency; compare the result with the value in the datasheet (f_{T_th}). Write the results in the first line of table 4.

Draw the gain-frequency characteristic on log-log scale (with the gain in dB and the frequency on a logarithmic scale). On the same graph sketch the asymptotic characteristics. Verify the –20 dB characteristic roll-off at high frequencies; compute ΔA_v (dB) for 20 to 200 kHz.

Table 4. Transition frequency

Configuration	R_1	A_{v0}	$A_v(f_B)$	f_B (kHz)	f_T (kHz)	f_{T_th} (kHz)
non-inverting	1 kΩ					
	10 kΩ					
inverting	9.1 kΩ					

Replace R_1 with a 10 kΩ resistance (10 kΩ : A12 – GND12), and measure low frequency gain A_{v0} (at 100 Hz) and the bandwidth f_B.

Compute the GBP (f_T) and compare it with the one from the previous configuration and with f_T from the data-sheet (f_{T_th}). Write the results in table 4.

Inverting amplifier bandwidth

The inverting configuration presented in figure 1.d) is implemented as follows:

- Remove resistor R_1 and connect the new resistor R_1 (9.1 kΩ : B6 – B12);
- Remove the wire from line 6 to line 13 and connect the non-inverting input to ground (wire: A13 – GND13);
- Set the rms voltage of the signal generator to avoid SR limitations (less than 50 mV);

Determine the break frequency (with the procedure indicated previously), compute the transition frequency and write the results in the last line of table 4:

$$f_T = \frac{|A_{v0}|}{|1 + A_{v0}|} \cdot f_B$$

Slew Rate

With the previous circuit, apply an input square wave (switch to rectangular or square wave) and increase its amplitude (at the generator) to get about 10 V amplitude at the output (to avoid op amp saturation). Modify the frequency from 100 Hz up to about 100 kHz and analyse the effect at the output with a CRO.

Sketch the output wave at a frequency of 10 kHz, measure the rise time of the wave and determine the SR (as the output voltage variation in time):

$$SR = \frac{\Delta v_O}{\Delta t}.$$

Compare the result with its theoretical value indicated in the LM741data-sheet (SR_{Th}). Complete table 5, compute the error by comparing the theoretical and experimental values.

Table 5. Slew Rate

Δv_O (V)	Δt (μs)	SR (V/μs)	SR_{Th} (V/μs)	ε (%)	V_{o_p} (V)	f_{SR} (kHz)	f_{SR_Th} (kHz)

Sine wave frequency limitations

Apply at the circuit input a sine wave with amplitude of about 1 V (switch to sine wave at the generator and adjust the signal level to get an output amplitude of about 10 V). Determine the output amplitude either from the wave form or measure its rms value by a voltmeter and multiply it by $\sqrt{2}$. Compute the maximum frequency undistorted (by SR):

$$f_{SR\_Th} = \frac{SR_{Th}}{2 \cdot \pi \cdot V_{o\_p}}.$$

Identify as best you can the frequency at which slew rate distortion start to occur. Compare the measured value with the expected (theoretical) value. (This frequency is difficult to measure precisely, since distortion is not always apparent.)

Annex 1: The board with the fig.1.a) circuit.