Lab 1: **Op-Amp – Basic Applications**

In this experiment, you will examine some op-amp basic applications analyzed with the ideal op amp model. You will be using LM741, which is one of the earliest popular operational amplifiers. The circuits are shown in figure 1.

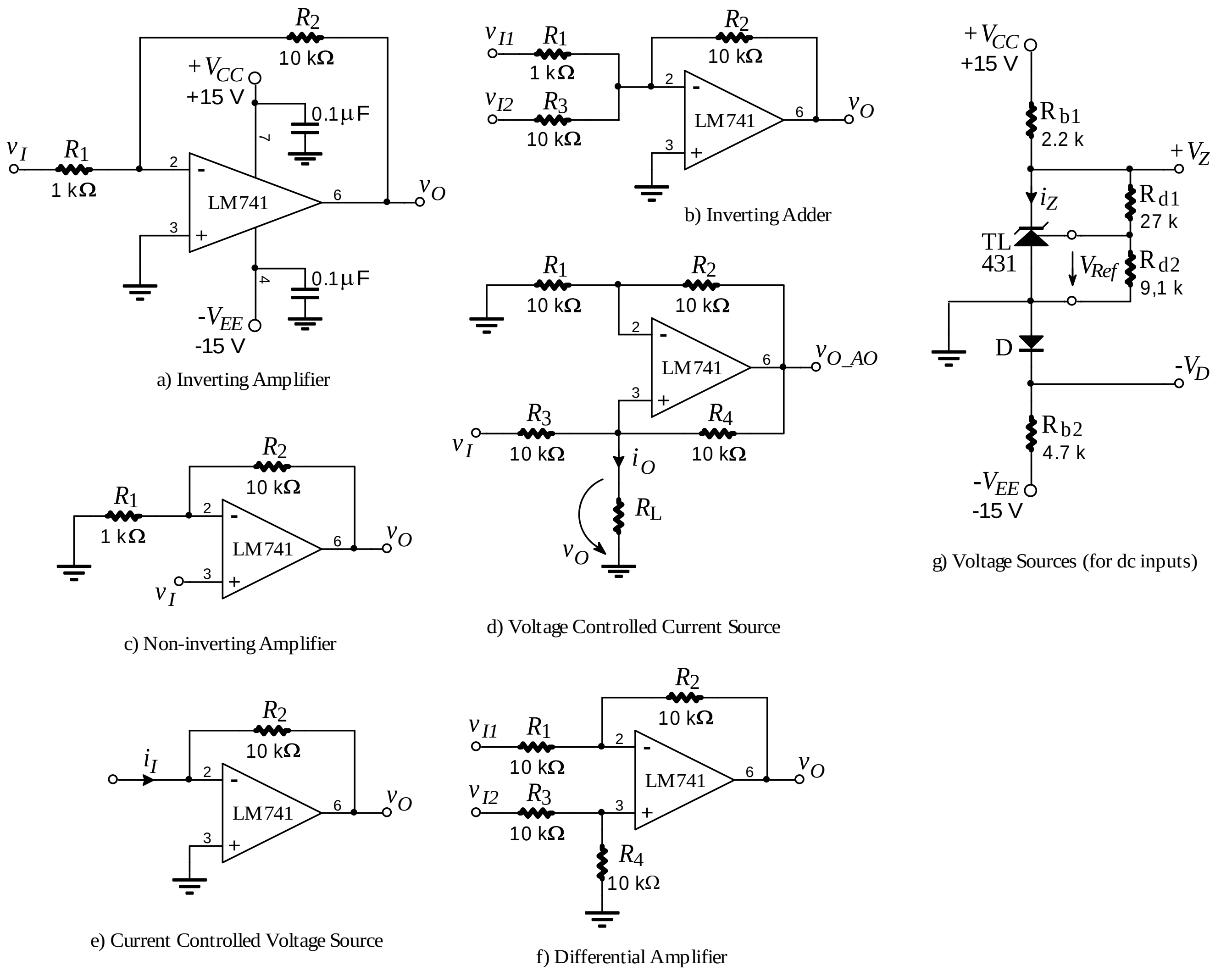


Figure 1: Circuits for op-amp basic applications

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.

Inverting Amplifier

Figure 1.a) shows the circuit of an inverting amplifier.

Measure the resistances (with a precision of 3 digits) and complete the first part of table 1. R_1 can be measured in the circuit (do not connect any source at v_I input). To measure R_2 take it out from the board. The theoretical gain, input resistance (computed with the ideal op amp model) and gain error ε (in %) are:

$$A_{Th} = -\frac{R_2}{R_1}, \quad R_{i\_Th} = R_1, \quad \varepsilon = \frac{A_{Exp} - A_{Th}}{A_{Th}} \cdot 100$$

The experimental value of the gain is the ratio of voltages (the output over the input). To determine the dc gain apply $-V_D$ at the input (the voltage drop over a diode), measure the input and output voltage, compute the gain and write them in the first line of table 1.

Table 1. The inverting configuration

R_1 (kΩ)	R_2 (kΩ)	A_{Th}		v_I (V)	v_O (V)	A_{Exp}	ε (%)	V_{CC} (V)	$-V_{EE}$ (V)	V_{Sat+} (V)	$-V_{Sat-}$ (V)
			dc								
			ac								

Saturation voltages

Disconnect the input source and apply the supply voltages to the input (first $-V_{EE}$ and then V_{CC}). Measure the power supply voltages and the saturation voltages (at the output). Compare the saturation voltages with the corresponding supply voltages (compute the difference).

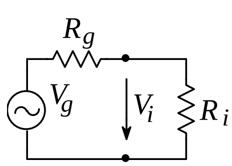
ac Operation

Apply an input signal with an amplitude less than 1 V (rms voltage less than 0.7 V) and a frequency of 100 Hz; complete the second line of table 1 (with the rms voltages).
Visualize the input and output waves with an oscilloscope (CRO), sketches them (one over the other) and determines the phase shift between input and output.

Increase the signal level up to the point where both positive and negative saturation occurs at the output. Sketch the output waveform and estimate the positive and the negative saturation levels. Complete the last cells on table 1.

The input resistance

Reduce the input signal to avoid saturation (to a rms value less than 0.7 V). Measure the generator voltage V_g as the no-load generator voltage (disconnect the generator from the input), the input voltage V_i with the generator connected to the input and complete 1st line of table 2 (with rms voltages). Determine the experimental input resistance from next figure. The generator resistance is written at the generator output (it is usually 600 Ω).



$$R_{i\_Exp} = \frac{v_I}{i_I} = \frac{V_i}{V_g - V_i} \cdot R_g$$

Table 2. The input resistance of inverting config.

Config.	V_g (mV)	V_i (mV)	R_{i_Exp} (Ω)	R_{i_Th} (Ω)	ε (%)
Inv.					
Non-Inv.					///

Inverting adder

The circuit shown in figure 1.b) is implemented on the experimental board.
The resistance R_3 can be measured in the circuit (do not connect any source at v_{I2} input). R_1 and R_2 are the same resistances used in the previous configuration.

Apply the source $-V_D$ at the first input (v_{I1}) and $+V_Z$ at the second input (v_{I2}). Measure the input voltages and compute the theoretical value of output (as linear combination of the inputs):

$$v_{O\_Th} = -\frac{R_2}{R_1}\cdot(-V_D) - \frac{R_2}{R_3}\cdot V_Z .$$

The Zener voltage V_Z (estimated from fig.1.g) is: $V_{Z\_th} = \left(1+\frac{R_{d2}}{R_{d1}}\right)\cdot V_{ref} = \left(1+\frac{27}{9.1}\right)\cdot 2.5 = 10$ V.

Measure the experimental output voltage, compare with the theoretical value, compute the error (with a formula similar with the one used in the previous paragraph) and complete table 3.

Table 3. The inverting adder

R_1 (kΩ)	R_2 (kΩ)	R_3 (kΩ)	v_{I1} (V)	v_{I2} (V)	v_{O_Exp} (V)	v_{O_Th} (V)	ε (%)

Non-inverting Amplifier

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

- disconnect V_Z from the second input (v_{I2}),
- remove connection from ground to pin 3 of LM741 (A13 – GND13),
- move R_1 to connect pin 2 of LM741 to GND (R_1: B12 – GND12),
- connect $-V_D$ to input (wire: H2 – C13) for line 3 of table 1,
- disconnect the dc input, connect the ac input with a wire from line 6 to line 13 and connect the signal generator for line 4 of table 1. Set the signal generator to 100 Hz and the rms voltage to avoid saturation (less/equal than 0.7V).

Measure the input and output voltage and complete the last 2 lines from table 1.
The theoretical gain and input resistance are:

$$A_{Th} = 1+\frac{R_2}{R_1}, \qquad R_{i\_Th} = \infty .$$

Table 3. The non-inverting configuration

R_1 (kΩ)	R_2 (kΩ)	A_{Th}		v_I (V)	v_O (V)	A_{Exp}	ε (%)
			dc				
			ac				

Sketch the input and output waves (one over the other) and determines the phase shift between input and output. Estimate the input resistance with the procedure indicated in the previous paragraph and write the results in the last line of table 2.

Voltage follower

Disconnect the resistor R_1 from ground. The theoretical gain becomes 1.

Apply different voltages at the input and complete table 4. The first ac voltage can be the one used previously and the second can one will be set to avoid saturation (less/equal than 7 V rms). Compute the error by comparing the output voltage with the input voltage.

Table 4. Voltage follower gain

	ac: 1st	ac: 2nd	$-V_D$	$+V_Z$	GND
v_I (V)					0
v_O (V)					
ε (%)					///

Voltage Controlled Current Source (VCCS)

The circuit schematic is indicated in figure 1.d). The current source with grounded load, also known as Howland source, use four resistors selected to have identical values. Measure resistors: R_3, it can be measured in the circuit (with the input source disconnected) and the 1 kΩ load resistance (disconnect it from the circuit); write their values in table 5.

Connect V_Z at the input and measure the input voltage v_I and the output voltage v_O (over R_L). The theoretical and experimental currents and the maximum load resistance are:

$$I_{Th} = \frac{v_I}{R} = \frac{V_Z}{R_3}, \qquad I_{Exp} = \frac{v_O}{R_L}, \qquad R_{L\max} = \frac{v_{O\max}}{I} = \frac{V_{Sat}}{2 \cdot I}.$$

V_{Sat} is the saturation voltage at the op amp output (maximum of v_{O_AO}).
Complete table 5, compute the error by comparing the theoretical and experimental values.

Table 5. Howland current source

R_3 (kΩ)	R_L (kΩ)	v_I (V)	v_O (V)	I_{Th} (mA)	I_{Exp} (mA)	ε (%)	$R_{L\max}$ (kΩ)	$v_{O\max}$ (V)	$v_{O\_AO\max}$ (V)

Determine the maximum value of load resistance by including R_{adj} (a 10 kΩ adjustable resistance) in the load, as follows:

- Connect the 1 kΩ resistance (former R_L) in series with R_{adj} (E42 – E47),
- Monitor the output current by measuring the voltage over the 1 kΩ resistance (with V_Z connected at the input),
- Modify the adjustable resistance to the point where the current begin to decrease,
- Measure the maximum voltages at v_O and v_{O_AO} (indicated on figure 1.d).
- Disconnect the load from the output (move the 1kΩ resistance from to E47 – H47) and measure the $R_{L\max}$ (the 1kΩ + R_{adj}, resistance between H47 and GND).

Compare $v_{O\_AO\max}$ with the corresponding saturation voltage.

Current Controlled Voltage Source (CCVS)

The circuit schematic is drawn in figure 1.e). The inverting adder implementation can be used with no modification (if no source is connected at its inputs the resistances R_1 and R_3 have no effect on the circuit operation). From the voltage follower implementation, the non-inverting input should be grounded (with a wire: A13 – GND13). The input of the circuit is the inverting input of the op amp.

The previous circuit (Howland source) is used as a current generator (with V_Z connected at its input). Connect the output of Howland source to the input (wire: C42 – A12). Measure the output voltage and compare with its theoretical value (computed with I_{Exp} of Howland source):

$$v_O = -R \cdot i_I = -R_2 \cdot I_{Exp} = v_{O\_Th}.$$

Use the value of R_2 from the inverting / adder amplifier.

i_I (mA)	v_{O_Exp} (V)	v_{O_Th} (V)	ε (%)

Table 6. The current – voltage converter

Connect the 1 kΩ resistor at the Howland source output (R_L: A42 – GND42), it will represent now the output resistance of the current source. Verify that the output voltage does not change (that means the current source output resistance does not influence the output of the current – voltage converter). Explain why.

You can connect also the ac source with a low frequency (100 Hz) and with amplitude that avoids saturation (less/equal than 7 Vrms) at the input of Howland source and verify that the circuits are working properly for ac also (by monitoring the voltages with an oscilloscope).

Differential amplifier

The circuit schematic is drawn in figure 1.f). The Howland source (VCCS) implementation will be modified to get the differential amplifier implementation as follows:

- move R_1 to R_4 (from A35 – GND35 to A36 – GND36),
- move R_4 to R_1 (from C36 – C40 to C31 – C35)
- remove the 1 kΩ resistor from the Howland source output.

The theoretical value of the output can be computed with the formula:

$$v_O = \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{R_4}{R_4 + R_3} \cdot v_{I2} - \frac{R_2}{R_1} \cdot v_{I1} = v_{I2} - v_{I1}$$

Apply different voltages at the inputs, measure the output (experimental value) and compute the error to complete table 7. Imagine some valid combinations of $-V_D$, $+V_Z$, $+V_{CC}$, and $-V_{EE}$ for the last lines of table.

Table 7. Differential amplifier

v_{I1} (V)	v_{I2} (V)	v_{O_Exp} (V)	v_{O_Th} (V)	ε (%)
$+V_Z$ =	$+V_{CC}$ =			
$+V_{CC}$	$+V_Z$			
$+V_Z$	$+V_Z$		0	///
GND = 0	GND = 0		0	///

Comment the results of lines 3 and 4 (with identical voltages applied at both inputs).

Ac and dc voltages can be combined also: apply an ac source at v_{I1}, $-V_D$ at v_{I2} input and them reverse the inputs. Measure the input and output voltages and monitor the waves with an oscilloscope.

Annex 1: The board with the initial circuits