Università degli studi di Trento

Group **MAR01**

REPORT OF THE EXPERIMENTS PERFORMED IN THE COURSE OF PHYSICS LABORATORY III

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October 19, 2016

Contents

Experiment 1

Basic circuits with an operational amplifier

In this experiment we have built five different circuits. The first is an open loop circuit with the operational amplifier uA741, the goal was to find the maximum voltage output by the op-amp. The last four circuits are in closed loop configuration with a negative feedback, they consist in a follower, a non inverting amplifier, an inverting amplifier and a weighted summing amplifier. We have measured the voltage input and the voltage output of every circut.

1.1 Materials

- Operational amplifier uA741
- Resistors, nominal value: 100 Ω, 220 Ω
- Power supply RIGOL DP831A
- Waveform generator RIGOL DG1032
- Multimeter RIGOL DM3068
- Oscilloscope AGILENT 54261A

1.2 Experiment setup

In the first four circuits the output of the waveform generator was a sine wave of 100Hz frequency and a peak-peak voltage of 100mV. We measured the waveform input signal v_{in} and the output voltage v_o of the op-amp. The measurements were performed using an oscilloscope triggered externally, the signal acquired is an 8 cycles average. The voltage supply of the op-amp was set to v_{cc} = 15V for all the circuits.

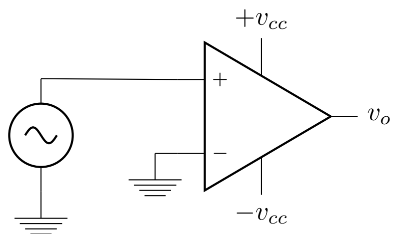

Figure 1.1: Open loop circuit

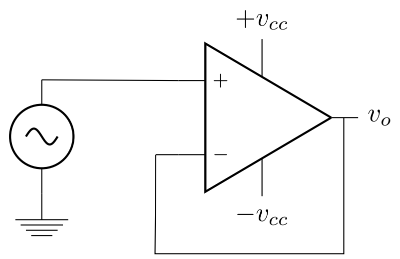

Figure 1.2: Follower

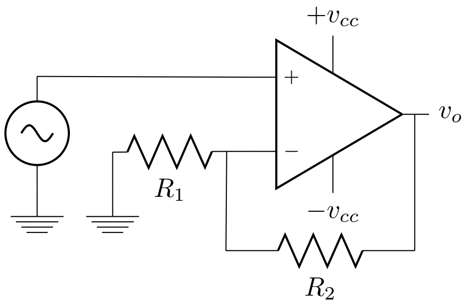

Figure 1.3: Non inverting amplifier

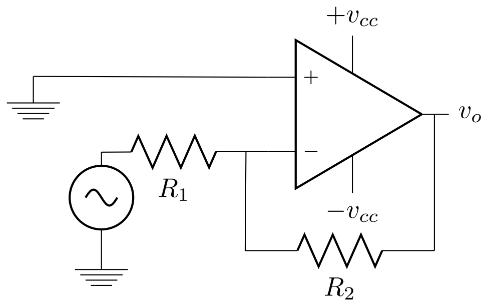

Figure 1.4: Inverting amplifier

For the last circuit we used another sine wave signal with the same 100Hz frequency and a different peak-peak voltage. The oscilloscope's setting and the measurement taken was the same as before. The values of the resistor are: $R_1 = 99.89 \pm 0.02\,\Omega$, $R_2 = 218.37 \pm 0.04\,\Omega$, $R_3 = 99.89 \pm 0.02\,\Omega$ (the measurement were made with the multimeter).

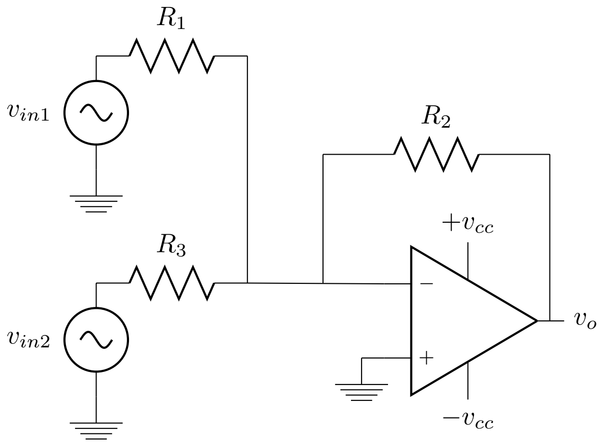

Figure 1.5: Weighted summing amplifier

1.3 Data analysis

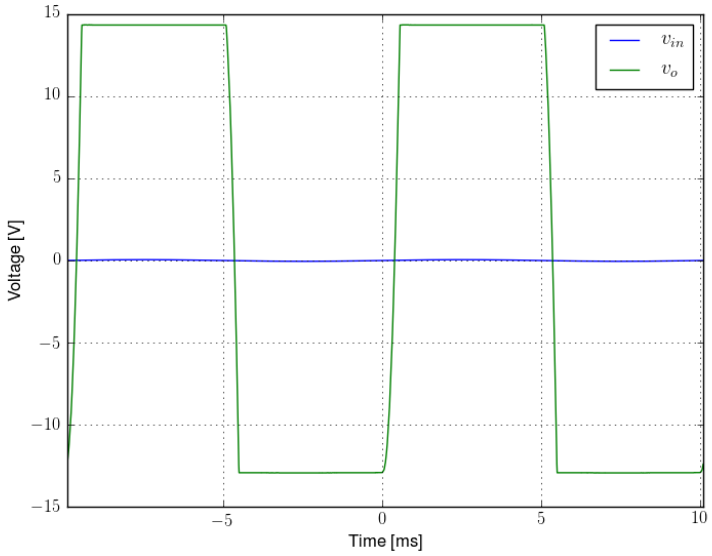

Figure 1.6: Open loop configuration

In the open loop configuration we get an output (visible in the figure one) that has a max absolute value of 14.35 ± 0.16[1] V and a minimum value of -12.94 ± 0.16[1] V. In the ideal model we would expect the output to be infinite, as justified from the equation $v_o = A_{ol}(v_+ - v_-)$ where A_{ol} tends to infinity. In the physical case the output voltage is costrained by the saturation voltage that's determinated by the voltage applied to the op-amp. The minimum and maximum value of the output have different absolute value, due to the lack of symmetry between the *npn* and *pnp* trasistors in the final push-pull stage of the op-amp.

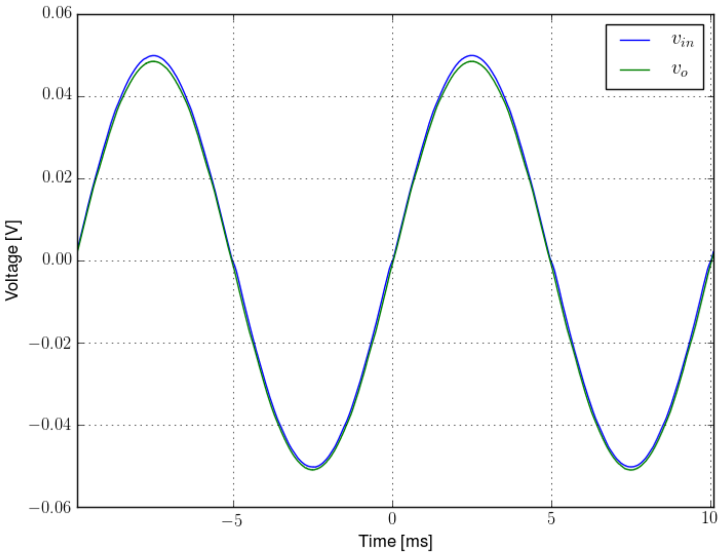

Figure 1.7: Emitter follower

[1] Error based on oscilloscope's 8 bit resolution

In the emitter follower we expect, ideally, an output voltage equal to the input one. But we can see in the plot a small discrepancy between the two signals: that is determined probably by the op-amp's offset, as we can see a downward translation in the output, and also by some other non ideal features of the op-amp.

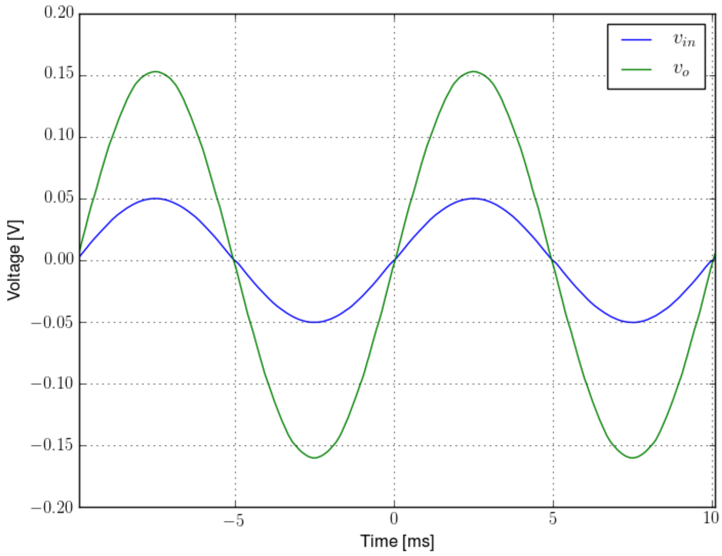

Figure 1.8: Non-inverting amplifier

In the non-inverting amplifier configuration we expect the output to be: $v_o = v_{in}(1+\frac{R_2}{R_1})$. The theoretical value calculated using the v_{in} and R_2, R_1 is 320.3 ± 1.9 mV. This prediction is not compatible with the output measured 313.4 ± 0.8 mV, probably because the op-amp is not ideal.

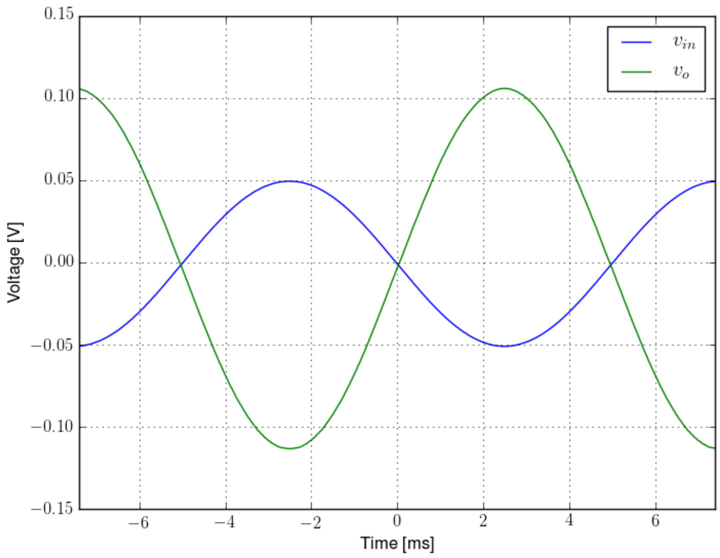

Figure 1.9: Inverting amplifier

In the inverting amplifier the output should be : $v_o = -v_{in}\frac{R_2}{R_1}$. The pk-pk of the output is 219.4 ± 0.8 mV that is compatible with theoretical value 219.8 ± 1.9 mV.

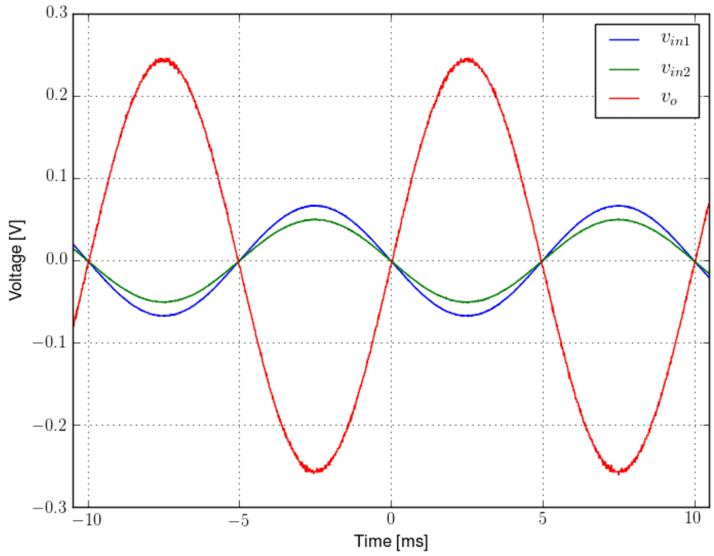

Figure 1.10: Weighted summing circuit

In the circuit (1.5) we used two inputs for aquiring an output voltage. This configuration sums these signals $v_1 = 135.1 \pm 0.8$ mV and $v_2 = 101.3 \pm 0.8$ mV using the resistors R_1 and R_3 as weights, giving as output $v_o = -R_2(\frac{v_1}{R_1} + \frac{v_2}{R_3})$, which gives a pk-pk value of 516.7 ± 2.7 mV. The theory in this case it's not at all compatible with the measurement 506 ± 0.8 mV, but that's, most likely, caused by the noise in the output.

Experiment 2

Let's get more confident with our little friend op-amp

We designed a non-inverting amplifier with a variable gain by using a trimmer. The second circuit designed was a summing amplifier with an unitary gain. We built a current source generator of 1 mA and tested it with a variable load. We tested the efficacy of the emitter follower configuration in mismatching the source's impedence. Last we designed a differential amplifier with a predetermined gain.

2.1 Materials

- Operational amplifier uA741
- Resistors and trimmers
- Power supply RIGOL DP831A
- Waveform generator RIGOL DG1032
- Multimeter RIGOL DM3068
- Oscilloscope RIGOL MS02102A
- Two capacitance of nominal value of 100nF

2.2 Experiment setup

In each circuit we powered the op-amp with a ± 15 V DC voltage and, in order to reduce possible noises, we added two 100nF capacitors connecting the op-amp's pins for the power supply with the ground. The input signal has a frequency of 100 Hz and a peak-peak voltage of 1V except for the differential amplifier.For every specific circuit we designed them as follow:

- Inverting amplifier: we placed a 10kΩ trimmer along the feedback branch in series to a resistor $R_f = 983.9 \pm 0.1\Omega$. In order to have a minimal gain of 5, we used $R_{in} = 199.84 \pm 0.03\Omega$ as in figure (2.1).
- Summing amplifier: caring for the simplest calculations, we used $R_1 = 1484.7 \pm 0.2\Omega \simeq R_2 = 1483.5 \pm 0.2\Omega$ so the equation is $\frac{v_1 + v_2}{2}\left(1 + \frac{R_4}{R_3}\right)$. For obtaining the sum of the input in output, we had to choose $R_3 = R_4 = 1001.3 \pm 0.1\Omega$. The inputs v_1 and v_2 are the same 100 Hz, 1 V peak-peak sine wave signal.

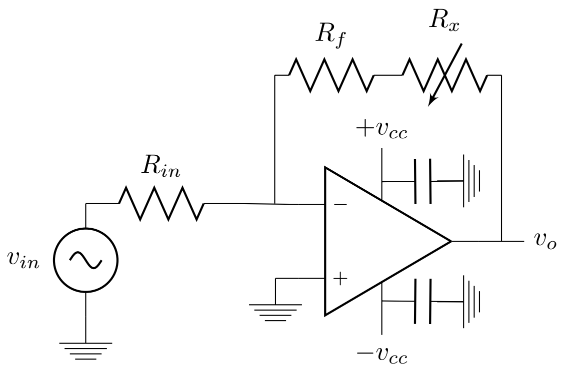

Figure 2.1: Inverting variable amplifier

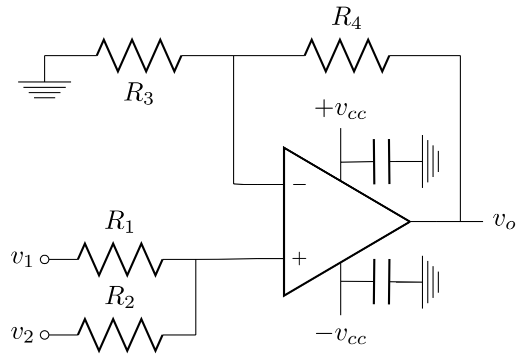

Figure 2.2: Non-inverting summing amplifier, unitary gain

- Emitter follower test: at first we built a circuit without the emitter follower using an input impedence of $R = 100.2 \pm 1\,\text{k}\Omega$ and a load of $R_L = 19.8 \pm 2\,\text{k}\Omega$. Then we added the op-amp stage and compared the output measurements in the 2 different cases.

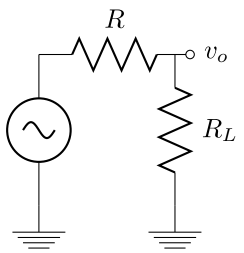

Figure 2.3: Test circuit without follower

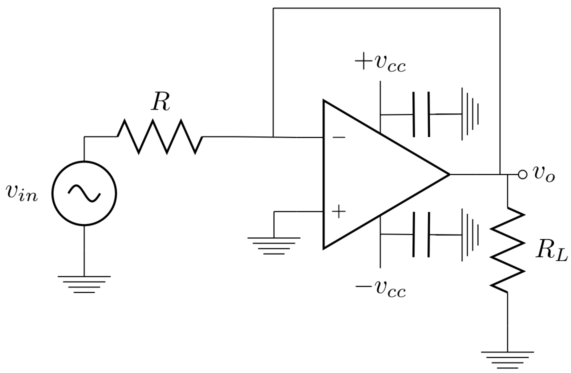

Figure 2.4: Test circuit with follower

- Current generator: the aim of this circuit is to generate a stable fixed current indipendent from the load. We generated a 1 mA current using a DC voltage source of 5 V and a 4.9693 ± 0.7 kΩ resistor. The load was simulated with a trimmer.

- Differential amplifier: the full equation the circuit in figure (2.6) is the following:

$$v_o = \frac{R_F}{R_1}\left[\frac{v_b}{1 + R_f/Ry}\left(1 + \frac{R_1}{R_f}\right) - v_a\right]$$

  we first set to ground v_b, in this way we were able to set up the gain of the circuit (we chose it to be $A = 2$ with $R_F = 3 \pm 0.2\,\text{k}\Omega$ (5% error of nominalvalue)). After that we put the same signal of v_a in v_b with a resistor R_f and a variable resistor R_y made with R_2 in series with a trimmer. We managed with the trimmer to get the output as close to zero as possibile (Figure (2.7)). This means in the equation $R_f/R_y = R_1/R_F$ so the new output is exaclty what we want $v_0 = A(v_b - v_a)$. For testing the amplifier we used $v_a = 5$ V DC and for v_b a sine wave 1 V peak-peak 100 Hz with an offset of 5 V.

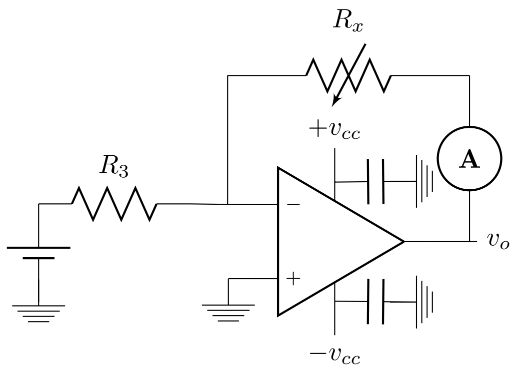

Figure 2.5: Current source generator

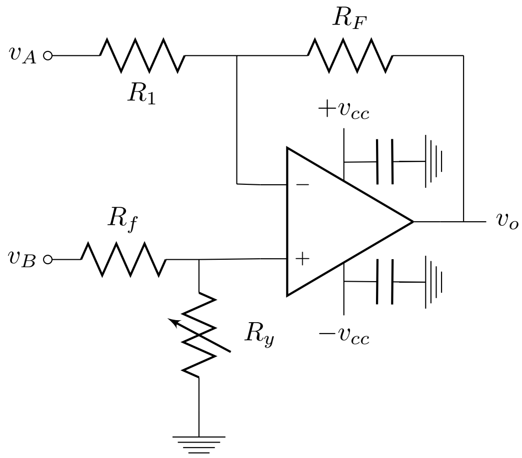

Figure 2.6: differential amplifier

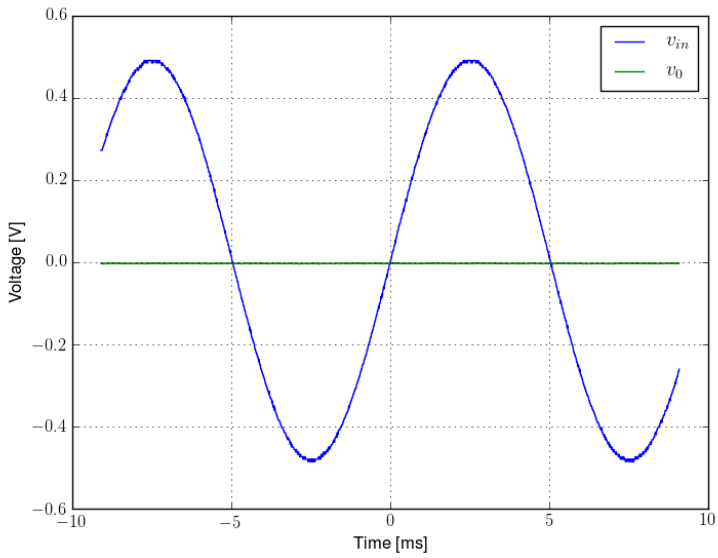

Figure 2.7: Calibration of the differential amplifier

2.3 Data analysis

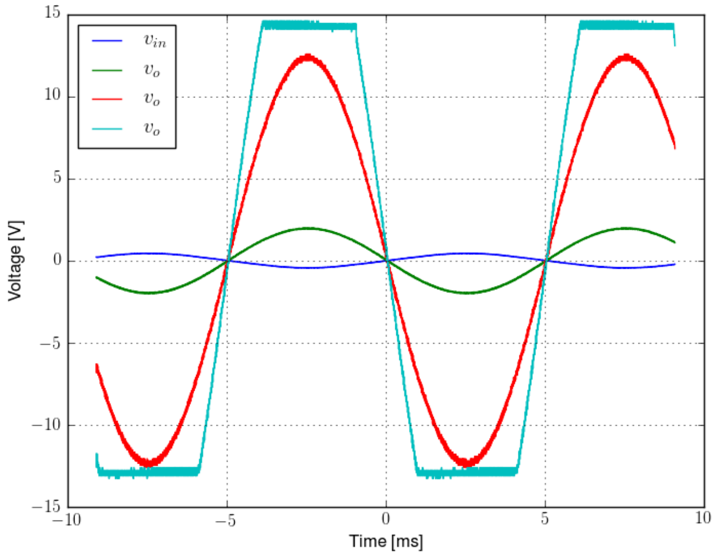

Figure 2.8: Variable amplifier

In the inverting amplifier we used a trimmer in order to vary the gain, in fact the equation is:

$$v_o = -v_{in}\frac{R_f + R_x}{R_{in}}$$

so increasing R_x cause output to linear increasing. The output voltage is limited by the op-amps's power supply voltage, it cannot increase further and the signal goes flat, as we can see in figure (2.8) (light blue line), this behavior is called "Clipping". The graphic also shows a discrepance between the absolut value of maximum and minimum voltage during the clipping: this is due to the asimmetry between *pnp* and *npn* transistors in the op-amp's final stage.

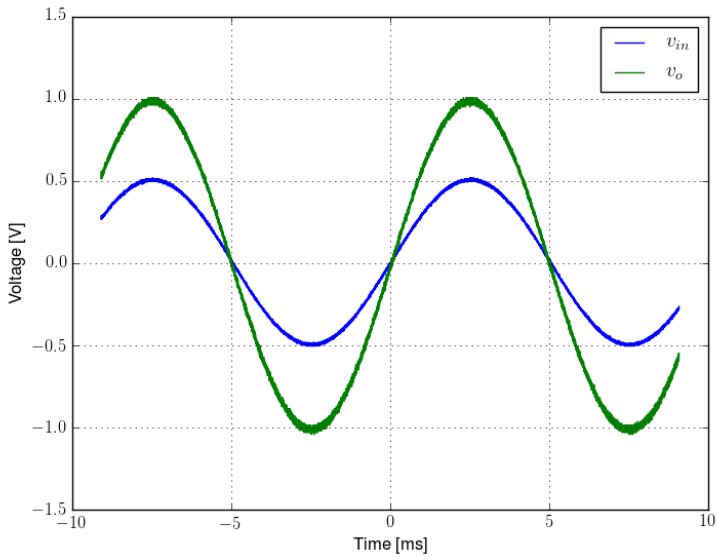

Figure 2.9: Weighted summing amplifier

In the non-inverting summing amplifier circuit we wanted the output to be the simple sum of the signals in entrance, that were identical: it means that the output signal must have double amplitude compared to the input one. The peak-peak voltage's theoretical expectation is 2.0496 ± 0.0009 V while the measured one is 2.032 ± 0.001 V. The incompatibility probably is due to the op-amp's non-ideality.

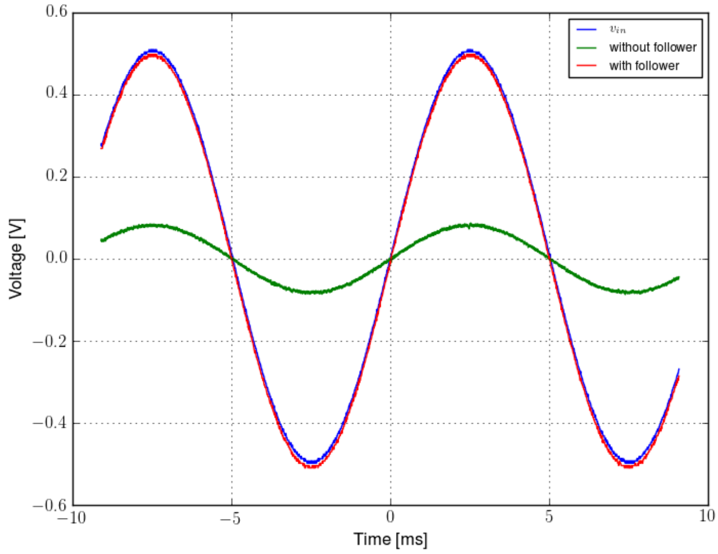

Figure 2.10: Emitter follower comparison

Let's now analyse the differences between circuits with and without follower stage. We can see in figure (2.10) that using the follower we obtain a replicated signal while without it the signal is shrinked due to the input impedence, in fact the op-amp stage's purpose is the impedence mismatching.

In the current generator circuit we firstly measured the output current that was the expected one, than we observed the indipendency from the trimmer resistence of the current value.

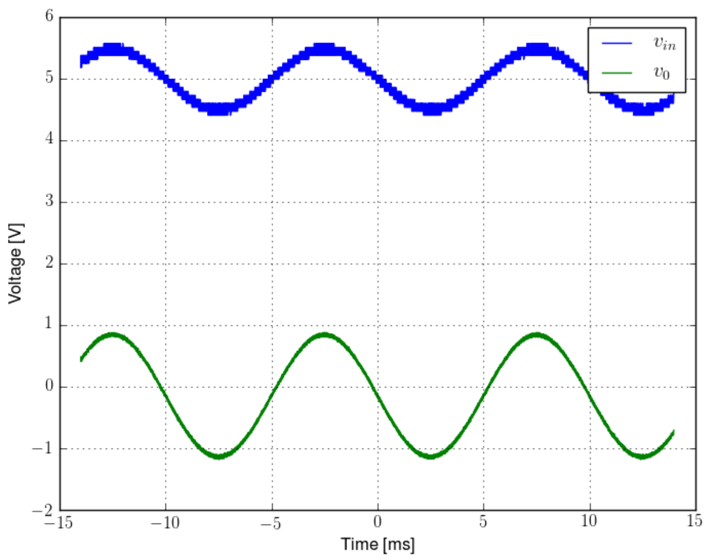

Figure 2.11: Differential amplifier

In the differential amplifier circuit we measured an output cleared from the DC part present in the input, the output value was the AC part doubled compared to the input one. This is exactly how we expected the circuit to behave.

Experiment 3

Unfortunately the op-amp is not so ideal

In this set of experiments we dealt with the problems of a real op-amp such as the offset v_{os}, the bias currents i_{b+}, i_{b-}, the slew-rate, the maximum current output and the common gain A_{cm}, we performed the measures of these real parameters. The offset is studied with 3 different circuit and then compensated with a trimmer in the configuration suggested by the op-amp's datasheet. The bias currents was measured in two way, one for the bias current in the $+$'s op-amp input and one for the $-$'s op-amp input. The other parameters are studied simply adjusting the input for the measurement's purpose.

3.1 Materials

- Operational amplifier uA741
- Resistors, trimmer
- Power supply RIGOL DP831A
- Waveform generator RIGOL DG1032
- Multimeter RIGOL DM3068
- Oscilloscope RIGOL MS02102A

List of resistors used		
Resistor name	Value [Ω]	Uncertainty [Ω]
$R_{M\Omega}$	982.0×10^3	0.1×10^3
$R_{100k\Omega}$	99.22×10^3	0.01×10^3
$R_{10k\Omega}$	9906.2	1.2
$R_{k\Omega}$	1001.4	0.1
$R_{10\Omega}$	9.963	0.01
$R^*_{10k\Omega}$	9926.4	1.2
$R^*_{10\Omega}$	10.00	0.01

3.2 Experiment setup

In all the circuits we placed on the power supply's pins two capacitor each, one with high capacitace (nominal value 470 ± 23 nF) and one with low capacitance (10.0 ± 0.5 nF). These were used for suppressing the high-frequency noise and contrastig the effect of any eventual change in the voltage of the power supply, that could move the offset voltage.

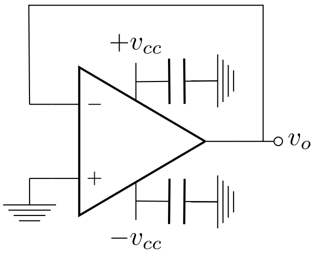

Figure 3.1: Offset voltage's direct measure

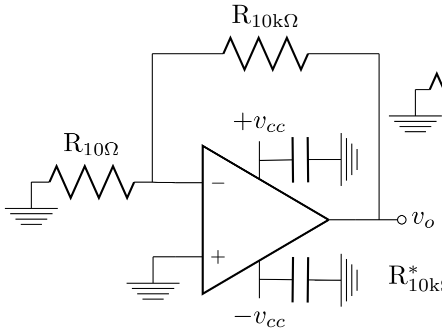

Figure 3.2: Offset voltage's direct measure with gain

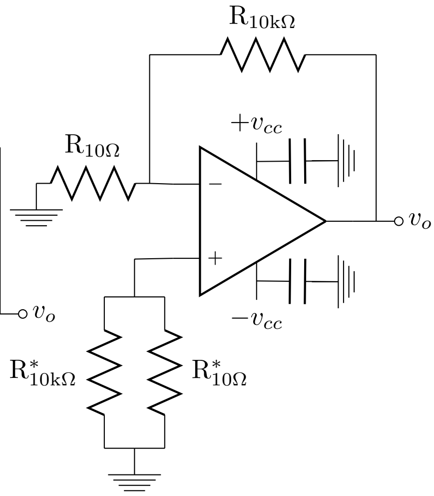

Figure 3.3: Offset voltage's direct measure with gain and bias current correction

In the first circuit we aquired v_{os} directly by measuring with the multimiter the output voltage. We used the second circuit to amplify v_{os}, thus we used the output to calculate v_{os}.
The third circuit is identical to the second circuit except for the added resistors in parallel that connect + to the ground. This was done for removing the influence of the bias current in the measurament. Exploiting this last circuit we removed v_{os} by using a trimmer and trying to make the output closest that we could to 0.

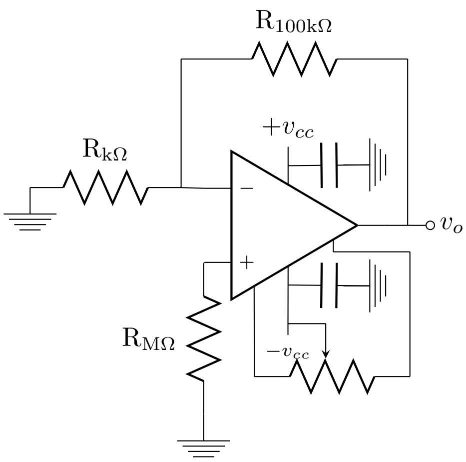

Figure 3.4: Positive bias current measure

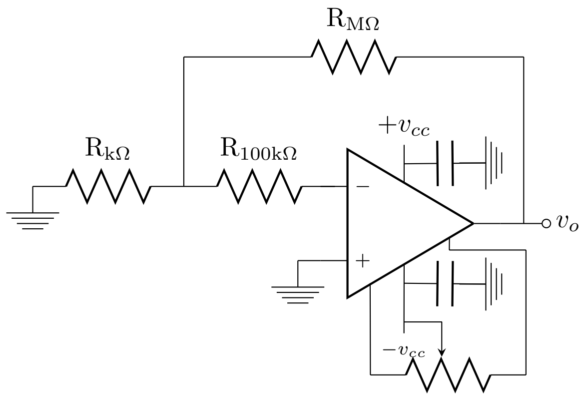

Figure 3.5: Negative bias current measure

The fourth circuit and fifth are used for measuring the current of bias indirectly using how the two currents are related to the output.
The sixth circuit was used for measuring the maximum current that the op-amp can erogate. In this configuration the oscilloscope's internal resitor was set to 50Ω

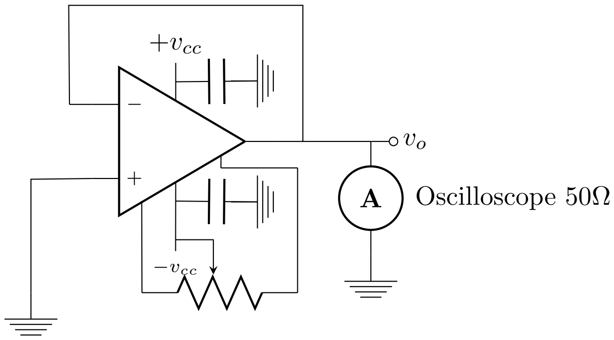

Figure 3.6: Max current measure

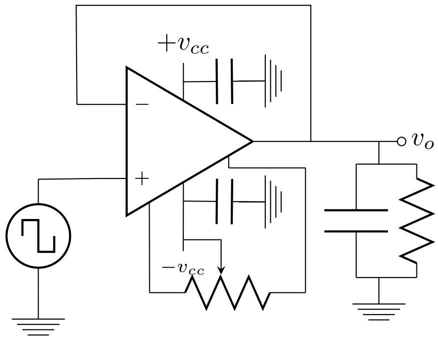

Figure 3.7: Slew rate

In the seventh circuit we measured the slew rate. As load the capacitor used was 1 ± 0.05 nF and the resistor 2 ± 0.1 kΩ. The input used was a 10 V square wave, so we aquired the image of the raising output.
In the last circuit we measured the common gain by using the differential amplifier with the same input 2 V peak-peak and 100 Hz.

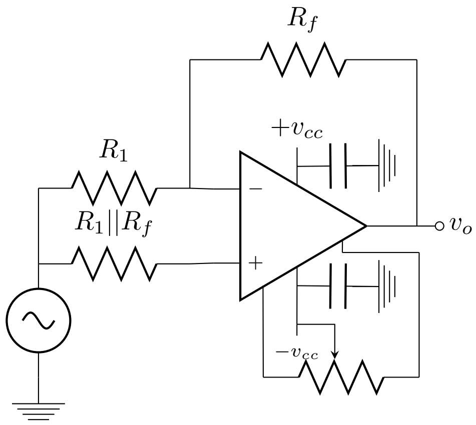

Figure 3.8: Common Gain

3.3 Data analysis

In the emitter follower (3.1) the output measured is -1.484 ± 0.005 mV. Being such a small output we expect to have problem with parassite resistor and other form of noise, that's why we don't consider the output too reliable, but it gives us an order of magnitude that is in agreement with the datasheet of the op-amp, that propouses a typical value of 1 mV and a maximum value of 5 mV.
In the amplifier (3.2) we can find v_{os}, by using

$$v_{os} = \frac{v_o}{1 + \frac{R_{10\text{k}\Omega}}{R_{10\Omega}}}$$

from the calculation we get $v_{os} = -1.333 \pm 0.001$ mV, which is has the same order of magnitude and same sign of the previous result.
Then as stated in the experimental setup we corrected the circuit (3.3) for compensating the effect of the current of bias. With the same formula used for the previous amplifier we get an offset voltage of 1.307 ± 0.001 mV. We used this circuit for nulling the offset with the trimmer.
In the fourth circuit (3.4) we calculated the current flowing in the non invertent pin by using

$$i_{b+} = \frac{v_o}{R_{\text{M}\Omega}(1 + \frac{R_{100\text{k}\Omega}}{R_{1\text{k}\Omega}})}$$

The value calculated is -39.042 ± 0.009 nA.
In the fifth circuit (3.5) instead we calculate the current flowing in the invertent pin by using

$$i_{b-} = \frac{v_o}{R_{100\text{k}\Omega}} \frac{R_{\text{k}\Omega}}{R_{\text{M}\Omega}}$$

above the value is -39.724 ± 0.009 nA. Now we can compute the current of bias $i_b = \frac{|i_{b-}|+|i_{b+}|}{2} = 39.383 \pm 0.006$ nA and the offset current $i_o = ||i_{b-}| - |i_{b+}|| = 0.68 \pm 0.01$ nA. i_b is less than 100 nA and near the typical value of 10 nA, as the datasheet states, but the offset current is a bit low being around a third of the typical value 2 nA.

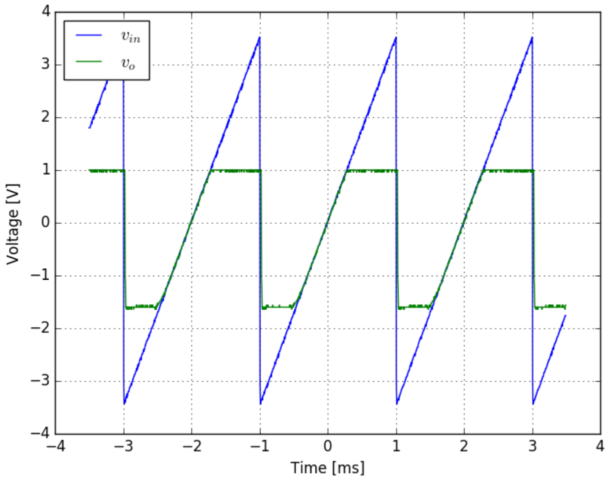

Figure 3.9: Saturated output caused by the maximum current erogated

In the sixth circuit (3.6) we calculated the maximum current erogated by computing the maximum/minimum output voltage over the resistance in the oscilloscope. In the plot is visible the different absolute value of the maximum and minimum output voltage, that's probably because the op-amp isn't perfectly symmetric in the packaging. So we opted to calculating two different maximum currents: $i_{max} = 0.0201 \pm 0.0001$ A (when the output was positive) and $i_{min} = 0.0328 \pm 0.0001$ (when the output was negative).

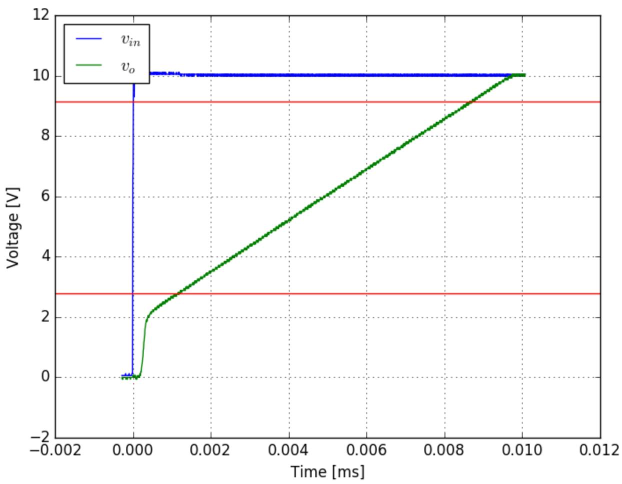

Figure 3.10: Saturated output caused by the maximum current erogated, red lines is 10% and 90% of the output

In the seventh circuit (3.7) we find that the slew rate of the op-amp used is $0.85\frac{\mathrm{V}}{\mu s}$, which is bigger than the typical value $0.5\frac{\mathrm{V}}{\mu s}$. One possible explenation of this would be that the slew rate depends on the amplitude of the signal, in our experiment the voltage was 50 times as large as in the test of visible in the datasheet, otherwise we have to conclude that our op-amp, has some difects that cause a larger slewrate.

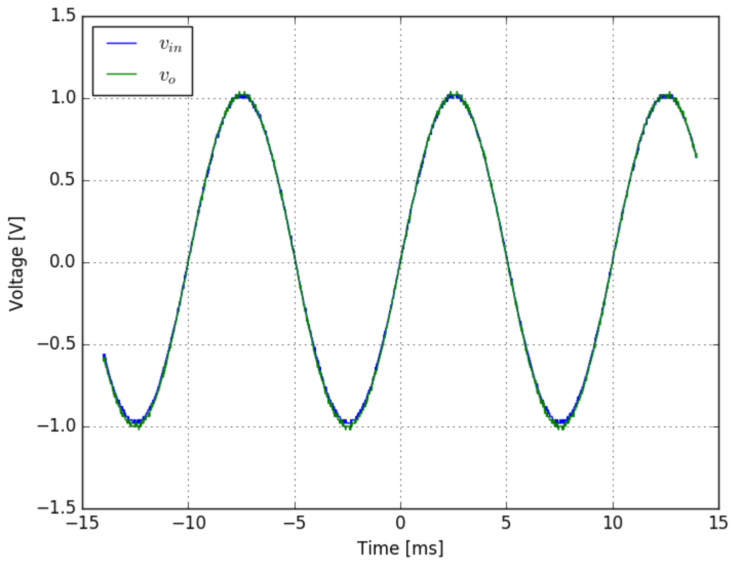

Figure 3.11: Saturated output caused by the maximum current erogated

In the last circuit (3.8) we measured the commond gain, by using

$$A_{CM} = \frac{2v_o}{v_{in1} + v_{in2}}$$

which gave us an unitary gain, as it is evident in the plot.

Experiment 4

Gain in function of the frequency

In a real op-amp the open loop gain (A_{ol}) is a function of the input frequency. In this experience we explored systematically this behaviour using 2 different circuits, one for the lower frequencies and the other for the higher one. After this study we built a non inverting amplifier with ≈ 10 and ≈ 100 gain for measuring its bandwidth.

4.1 Materials

- Operational amplifier uA741
- Resistors, trimmer
- Power supply RIGOL DP831A
- Waveform generator RIGOL DG1032
- Multimeter RIGOL DM3068
- Oscilloscope RIGOL MS02102A

The resistor chosen were $R_1, R_2, R_3 = 10\text{k}\Omega$, $R_4 = 10\Omega$, $R_5 = 100\Omega, R_6 = 1\text{k}\Omega$ with an error of 5% of the value.

4.2 Experimental setup

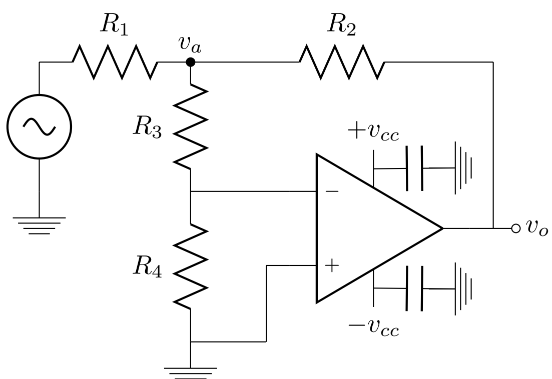

Figure 4.1: A_{ol} measure low frequencies

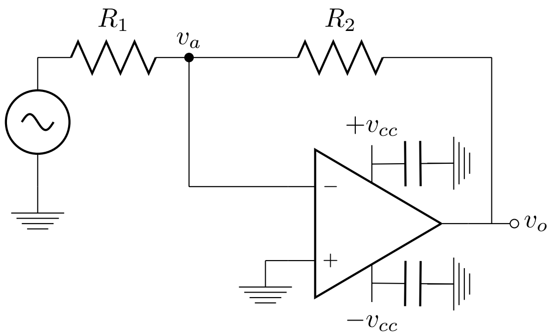

Figure 4.2: A_{ol} measure high frequencies

In this experience we took the measurament in all circuis by changing the frequency of the input, that was a sine wave signal 1 V peak-peak. The voltage chosen is not important, because we are interested

in the ratio between the amplitude of two signal. In the first circuit was used for calculating the gain in the open loop configuration A_{ol} in low frequencies by measuring v_a and v_o. This circuit was chosen for low freqencies instead of the second one, beacause the gain is too high for allowing us to acquiring directly the voltage difference between the two input pins. We didn't measure at lower frequencies than 30 Hz because the noise didn't allow us to make a reliable extimate of the amplitude of the two signals.
In the second circuit we measured v_o and the voltage of the non inverting pin v_a. The frequencies measured went from 10 - 200 kHz, because with high frequencies the absulute value of A_{ol} is low enough.
In the last two circuits we built an non inverting amplifier with gain of 100 and 10.

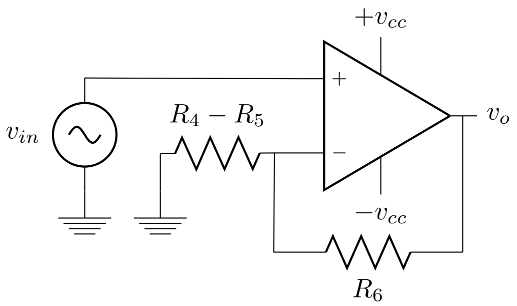

Figure 4.3: Non inverting amplifier

4.3 Data Analysis

4/decibel.png

In the first circuit we can extimate the open loop gain by using $A_{ol} = -\frac{v_o}{v_a}\frac{R_3+R_4}{R_4}$. In the second circuit we calculated $A_{ol} = -\frac{v_o}{v_a}$.

We can see from the plot that the data appears to be on a straight line, we can also see if that line is compatible with the values in the datasheet. We can compute the theoretical open loop gain with:

$$A_{ol}^{teo}(f) = \frac{A}{1 + j\frac{f}{f_0}}$$

Where $f_0 = 8$ Hz is a parameters available in the datasheet and $A = 1.5 \times 10^5$ was obtained with the best fit, j is the immaginary unit and f is the frequency. We can see from the plot that our data is consistent with the theory and the datasheet.
For the last two circuit we plotted $H = \frac{v_o}{v_{in}}$, the theoretical curve is the following:

$$H(f) = \frac{\frac{A_{ol}}{1+A_{ol}\beta}}{1 + j\frac{f}{(1+A_{ol}\beta)f_0}}$$

Experiment 5

A new device: the comparator

We can use an op-amp to compare two input signals: its output corresponds to a logic value (let's say 0) if $v_- > v_+$, to the other (1) in the opposite case. Verified this feature for two different op-amps, we build a Schmitt's trigger in order to adjust the comparator sensitivity and we try it in a twilight switch circuit.

5.1 Materials

- Operational amplifier UA741
- Operational amplifier LM311
- Fototransistor OP550A
- Resistors, trimmer, LED, capacitors
- Power supply RIGOL DP831A
- Waveform generator RIGOL DG1032
- Multimeter RIGOL DM3068
- Oscilloscope RIGOL MS02102A

MANCANO VALORI ED ERRORI DI CONDENSATORE, RESISTORI,LED

5.2 Experimental setup

We have always powered the op-amps with a ± 15 V DC voltage and, in order to reduce possible noises, we added two capacitors to both op-amps pins for the power supply and the ground, one of 100nF and the other of 10nF (4 in total).
At first we used the UA741 as a comparator in order to build a relaxation oscillator producing a square wave from a capacitor charge and discharge: we chose $R_1 = R_2 = 10k\Omega$ and a 0.1 nF capacitor. The circuit (see figure ?) has been tested with 5 different values of R: 1, 5, 10, 15, 20 kΩ in order to have different periods and no imput signal was needed. A measure has been taken also setting the oscilloscope in single mode and then switching on the power supply. We than tested the LM311 as both a non-invertent and an invertent comparator using $R_L = 1k\Omega$ and a triangular input signal of ? V and ? Hz.
Regarding the Schmitt's trigger, we added to the previous circuit the resistences $R_1 = 10k\Omega$ and $R_2 = 100\Omega$ in order to shift the reference voltage of a factor $\frac{1}{100}$ upward and downward and analyzed the behaviour at the point when $v_{in} \approx v_{ref}$.
At last, we built the twilight switch:
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