Operational Amplifier

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1 Basic Circuits of Operational Amplifiers

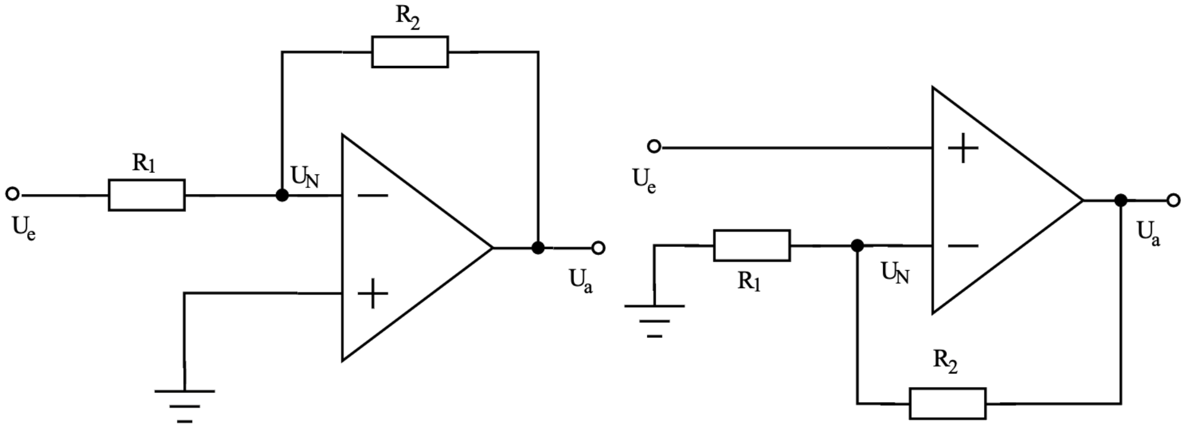

Figure 1: Basic circuits of the OP-AMP: (left) The inverting amplifier and (right) the non-inverting or electrometer amplifier

The two basic circuits according to Fig. 1 are operated with $R_1 = 10\,\mathrm{k\Omega}$ and $R_2 = 47\,\mathrm{k\Omega}$. The function generator with low frequencies (approx. 50 Hz) serves as the signal source u_e. The operational amplifiers LM741 are powered with $\pm 15\,\mathrm{V}$.

1.1 Part 1 - Inverting Amplifier

The inverting amplifier Fig. 1 (left) amplifies with the voltage gain v_U given by Eq. (1). The voltage u_N at the inverting input of the OP-AMP is zero (virtual ground). When the input voltage reaches $u_e > 3\,\mathrm{V}$ ($u_{e_{pp}} > 6\,\mathrm{V}$), the OP-AMP saturates and Formula 1 no longer holds.

$$v_U = -\frac{R_2}{R_1} \tag{1}$$

Hence a voltage gain of $v_U = -4.7\,\mathrm{V}$ is expected.

1.1.1 Evaluation

For an input peak to peak voltage $u_{e_{pp}} = 1.26\,\mathrm{V}$ the output peak to peak voltage $u_{a_{pp}} = 5.64\,\mathrm{V}$ is measured, see Fig. 2. Which corresponds to a voltage gain of $v_U = \frac{u_a}{u_e} = -4.47\,\mathrm{V}$ which is reasonably close to the expected value described by formula 1.

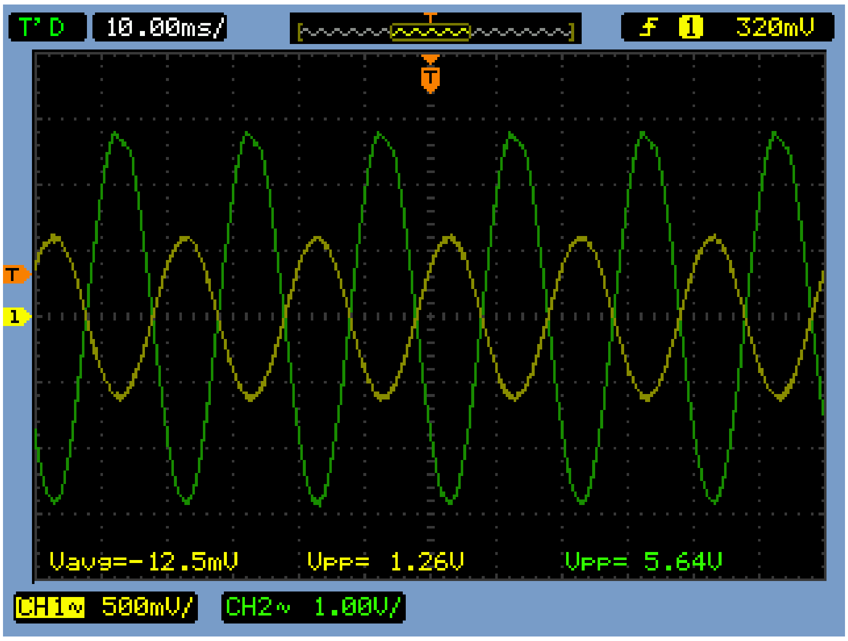

Figure 2: Voltages measured with oscilloscope. Input Voltage U_e (yellow) and output voltage U_a (green).

If the input voltage is increased, saturation behaviour can be observed from $u_{e_{pp}} = 5.96\,\mathrm{V}$, as can be seen in Fig. 3.

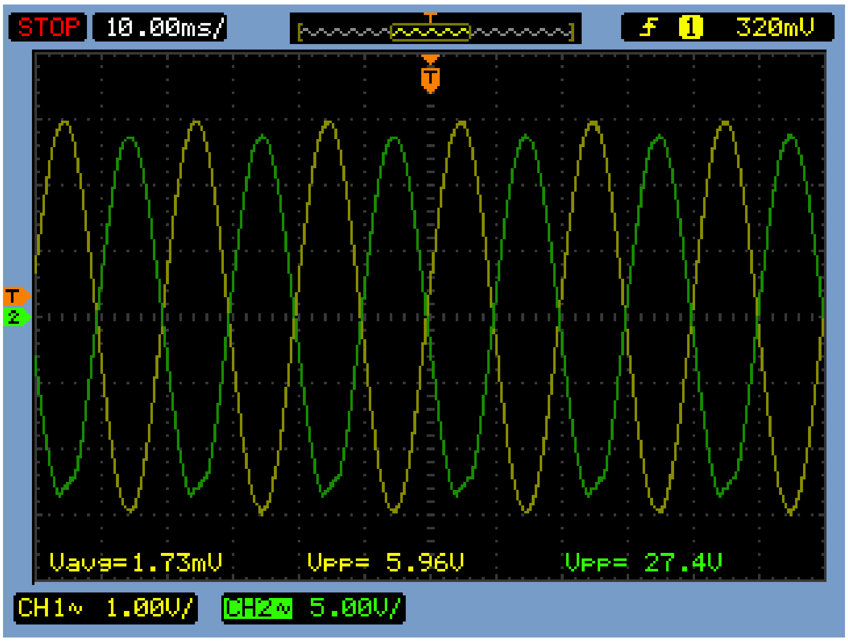

Figure 3: Voltages measured with oscilloscope for inverting amplifier with maximum input voltage U_e (yellow) and output voltage U_a (green).

1.2 Part 2 - Inverting Amplifier with loaded Output

If the amplifier output is loaded with $R_L = 100\,\Omega$, u_a practically does not change in the linear range, but the saturation voltage becomes significantly smaller. Determine Z_a in the unsaturated range, or at least estimate an upper limit.

1.2.1 Evaluation

For an input peak to peak voltage $u_{e_{pp}} = 1.05\,\text{V}$ the output peak to peak voltage $u_{a_{pp}} = 4.48\,\text{V}$ is measured. Which corresponds to a voltage gain of $v_U = \frac{u_a}{u_e} = -4.27\,\text{V}$.

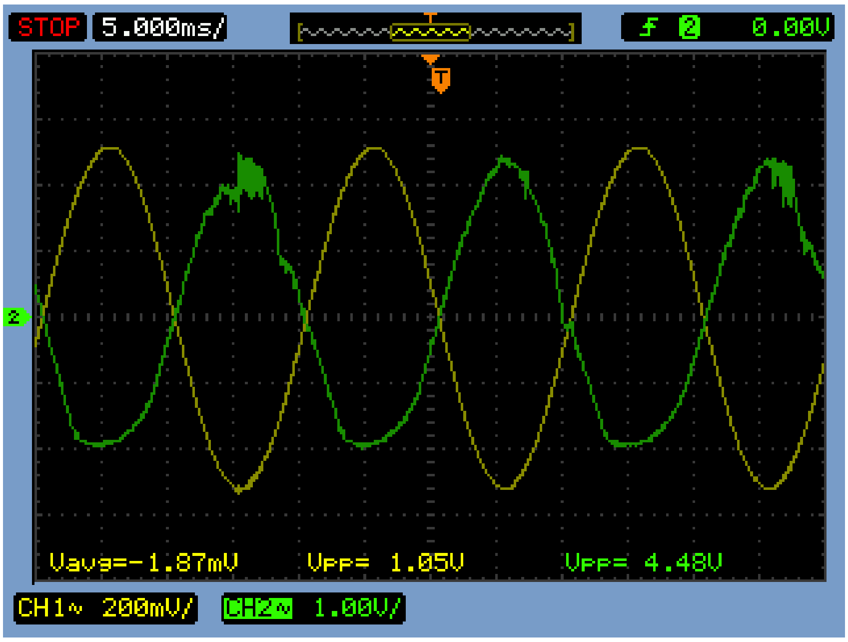

Figure 4: Voltages measured with oscilloscope. Input Voltage U_e (yellow) and output voltage U_a (green).

From the measurement in the previous example, which can be seen in Fig. 3 the saturated output voltage in an unloaded case is $\overline{U} = 27.4\,\text{V}$. For further calculus we assume that there is no current flowing between R_2 back to the input of the OP-AMP. We can describe our OP-AMP as depicted in Fig. 5 with an internal voltage source and an internal resistor Z_a. Since there is no current at all flowing throughout the internal resistor Z_a (because we assumed that there is no current flowing through R_2) there is no voltage drop appearing at Z_a and the saturated output-voltage $\overline{U}$ we measured is the maximum which the internal voltage source of the OP-AMP can provide.

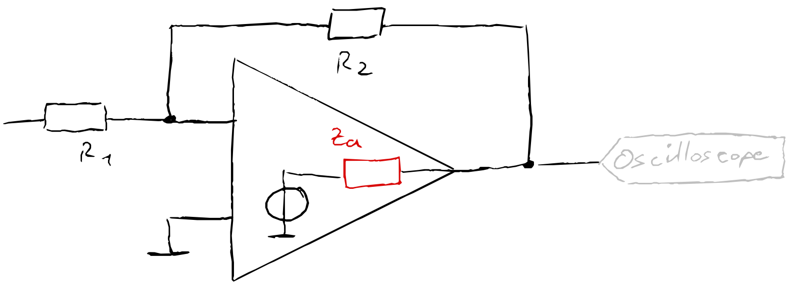

Figure 5: Saturated unloaded OP-AMP

Now we take a look at the case where the load resistor $R_L = 100\,\Omega$ was added, see Fig. 6. With this change there is current flowing through Z_a and R_2 and the oscilloscope measured the voltage in between the resistors. We still assume that in there is no current flothing through R_2 and in case of saturation the internal voltage source still supplies the circuit with the previously measured maximum of $\overline{U} = 27.4\,\text{V}$. Now we only take the attenuator in account which is formed by the two resistors Z_a and R_L as depicted in Fig. 6. We know the maximum supply voltage $\overline{U}$, we measured the maximum voltage in between the resistors in Fig. 4 and therefore we know the voltage drop accross the resistors and we know the resistance of the load $R_L = 100\,\Omega$. From this information the output impedance Z_a can be calculated.

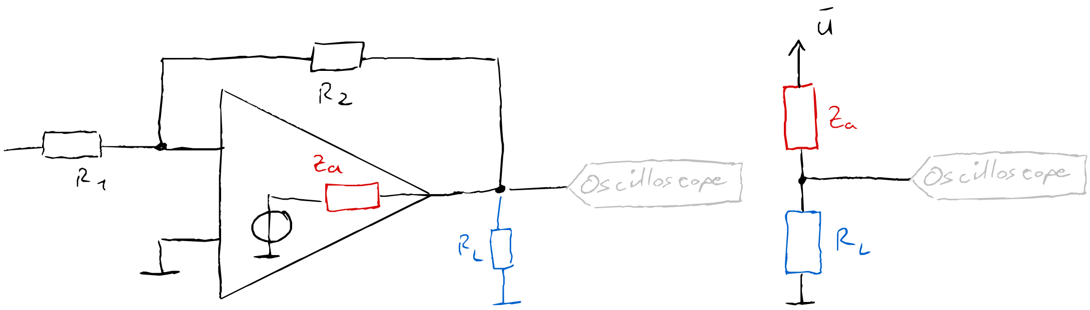

Figure 6: Saturated loaded OP-AMP (left) and the corresponding attenuator (right)

The voltage drop across Z_a calculates to $U_a = \overline{U} \cdot \frac{Z_a}{R_L + Z_a}$. Furthermore the sum of all voltages must be preserved which gives us a second equation: $U_a = \overline{U} - U_L$. Here U_L is the voltage drop across R_L. This value can be obtained from Fig. 4: $U_L = 4.48\,\mathrm{V}$. The final result can be gathered by exploring the equations to

$$Z_a = R_L \cdot \left(\frac{\overline{U}}{U_L} - 1 \right) \tag{2}$$

and after filling the values the final result equals $Z_a = 511.6\,\Omega$.

1.3 Part 3: maximum permissible current load

The circuit diagram for this exercise can be seen in Fig.1 part a). Additionally the OP-AMP gets loaded with a $100\,\Omega$ Resistor. The goal of this exercise is to register the overload signal at U_{N}. The overload signal occurs just before the OP-AMP saturates and is caused by a protection circuit in the OP-AMP.

During the experiment we had some difficulties in grounding the circuit properly. Insufficient grounding causes a lot of noise which overshadows the voltage signal at $\mathrm{U_N}$. The noisiness of the signal is still clearly visible in the yellow line in 7. We estimated the saturation voltage of the loaded OP-AMP to be $58\,\mathrm{mV}$ and the amplification factor $a = \frac{4.36\mathrm{V}}{0.058\mathrm{V}} = 75.17$.
From this we can calculate the maximum current load of the OP-AMP to be

$$\mathrm{I_{meas}} = \frac{4.36/2\,\mathrm{V}}{100\Omega} = 0.0218\,\mathrm{A} = 21.8\,\mathrm{mA} \tag{3}$$

In the Datasheet of the LM741 OP-AMP the Output short circuit current is given as $\mathrm{I} = 25\mathrm{mV}$. Therefore $\mathrm{I_{meas}}$ seems to be a reasonable value.

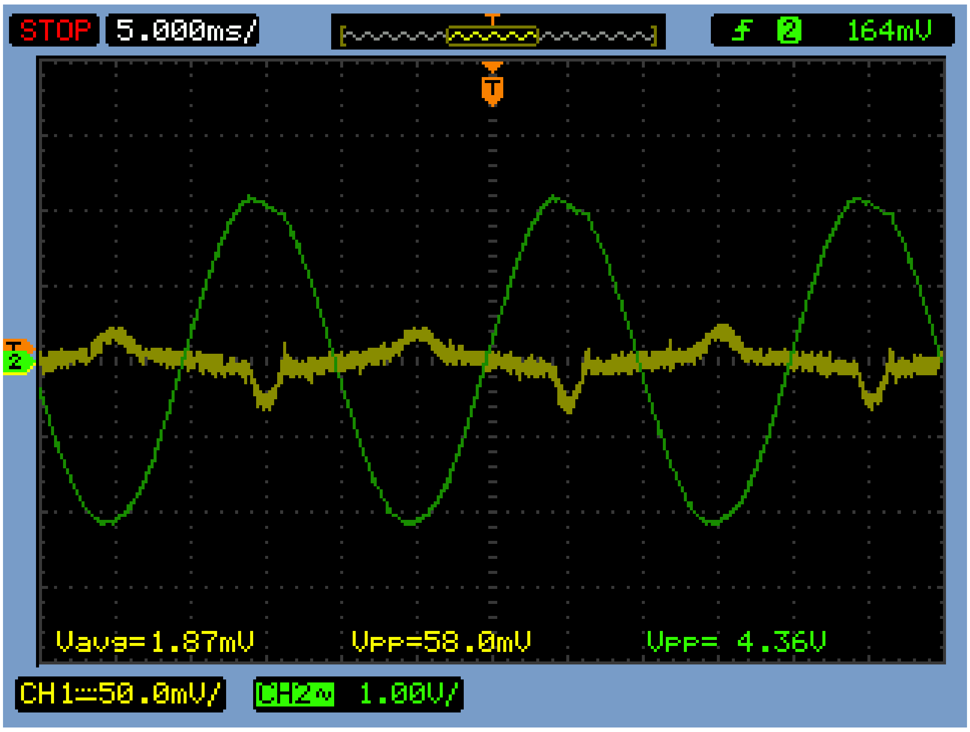

Figure 7: Part 3: The signal (yellow) occurs when the input Voltage (green) clips.

1.4 Part 4: Non-Inverting Amplifier

For next part of the exercise the circuit in Fig. 1 part b) is used. The expected voltage gain is given as

$$v_{\mathrm{u}} = 1 + \frac{R_2}{R_1} = 1 + \frac{47\,\mathrm{k}\Omega}{10\,\mathrm{k}\Omega} = 5.7 \tag{4}$$

As one can see in Fig.8 the input voltage $V_{\mathrm{in}} = 1.40\,\mathrm{V}$ is amplified to $V_{\mathrm{out}} = 7.52\,\mathrm{V}$ which corresponds to a amplification factor $a = 5.37$. The result deviates from the expected value by about 6%.

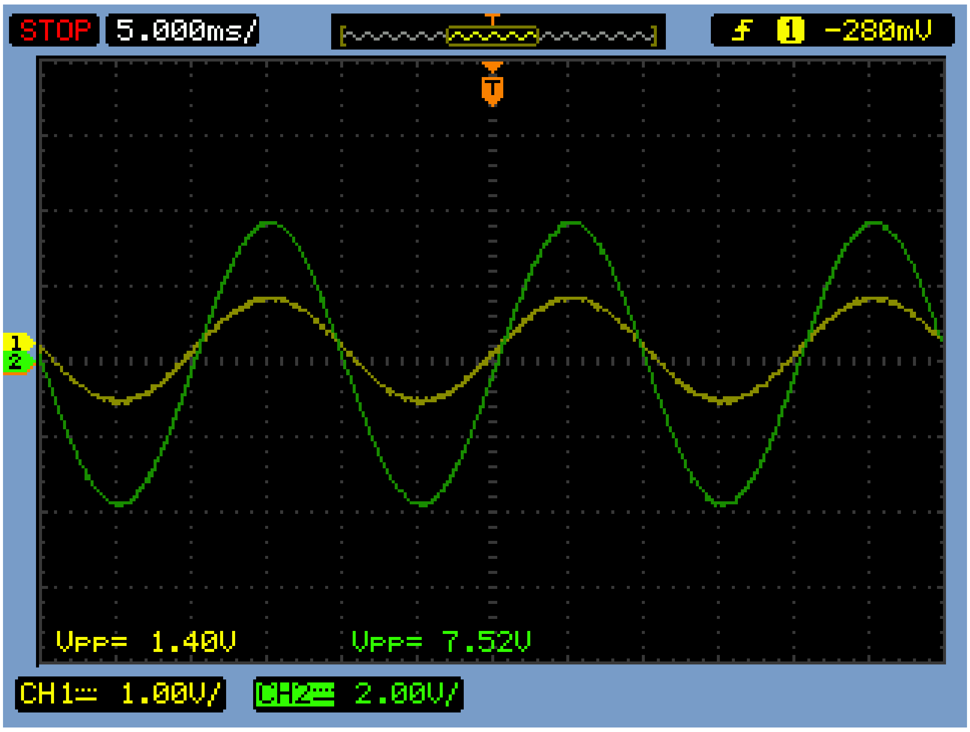

Figure 8: Part 4: The input-signal is amplified to the output signal (green).

1.5 Part 5: Capacitor connected to the circuit

Now there is a 100nF capacitor between the input of the Non-Inverting Amplifier and ground a circuit diagram can be seen in Fig9.

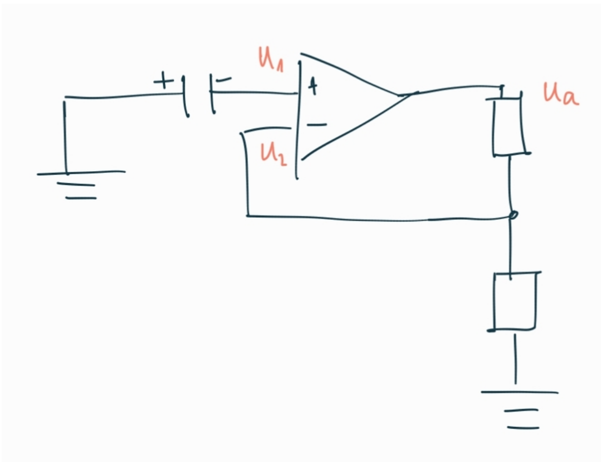

Figure 9: Part 5: The circuit diagram.

As long as the capacitor is shortend it does not charge up, the leaking current of the OP-AMP is draining. If the shortening is removed, the capacitor gets charged, following this the Voltage U_1 sinks. The OP-AMP then minimizes the difference between U_1 and U_2 by lowering U_a.

From Fig. 10 one can read of $\frac{dU}{dt} = (-2V/500ms)$. The measurement is stopped after 3.5s.

$$I_e = \frac{\mathrm{C}}{\mathrm{v_u}} \cdot \frac{dU}{dt} = \frac{100\mathrm{nF}}{5.7} \frac{2\mathrm{V}}{500\mathrm{ms}} = 0.07\mu\mathrm{A} = 70\mathrm{nA} \tag{5}$$

The Datasheet states the Input biased current to be 80 nA typically.d

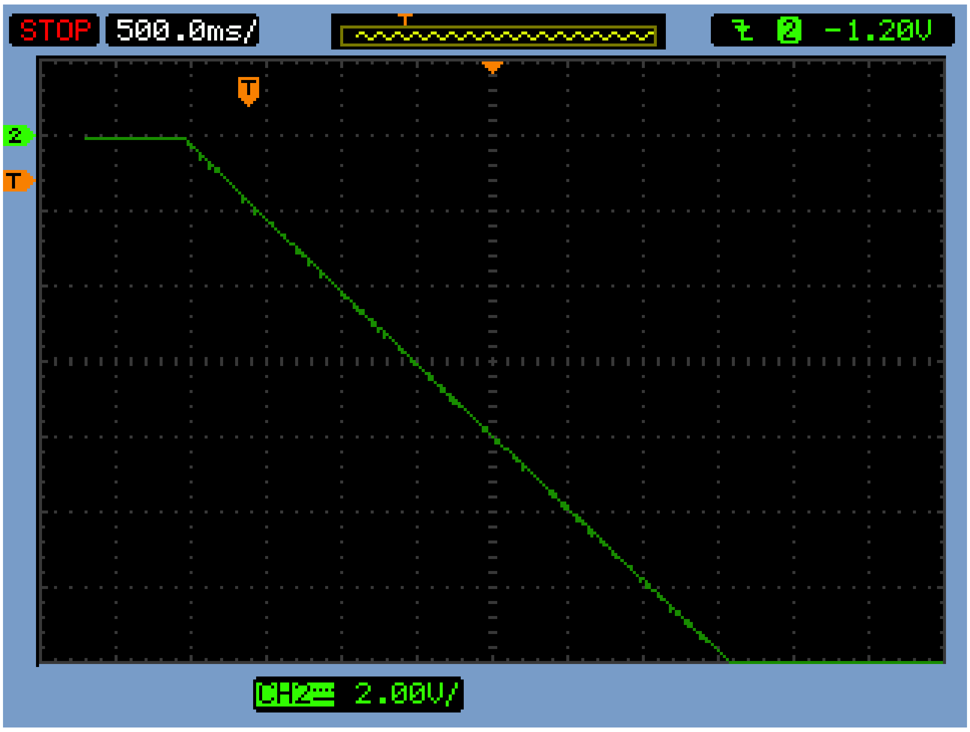

Figure 10: Part 5: The circuit diagram.

2 Analog Subtraction (S)

This exercise is simulated using LTspice. We are using the circuit in Fig. 11 as a source to generate two symmetrical AC voltages $+u$ and $-u$. The voltage source provides a sinusoidal voltage with an amplitude of $\pm 5\,\mathrm{V_{pp}}$ at a frequency of 100 Hz. To simulate an electrical transformer with two colis which have a number of windings ration of 1 : 2 the ratio needs to be defined by the inductance of the coils. The inductance can be calculated for ideal coils using the following equation: $L = \mu_0 \cdot \mu_r \cdot N^2 \cdot \frac{A}{l}$. Therefore a ratio of 1 : 2 for the number of windings results in a ratio of 1 : 4 for the coil inductance. The transformer decouples the electrical potential of the voltage which is inducted in the second coil. This floating voltage is used to drive an attenuator with two identical resistors, resulting in the same voltage drop across both of them. Since this part of the circuit is floating the reference ground is positioned in the center of the attenuator. From this circuit a positive and a negative voltage $\pm u$ can be taken to drive the differential input of an OP-AMP.
The task for this exercise is to verify the circuit in Fig. 12 which takes two input voltages u_1 and u_2 and provides an output voltage which follows the equation $u_a = u_2 - u_1$. To verify this behavior it should be connected in a way to produce output voltages of $u_a = 0\,\mathrm{V}$, $\pm u$ and $\pm 2u$.

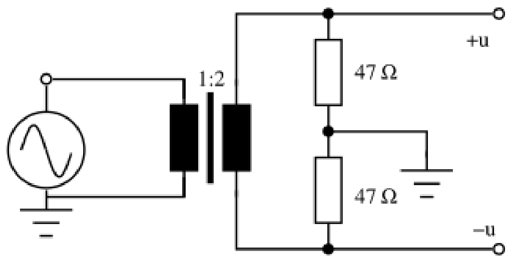

Figure 11: Symmetrical voltage Source

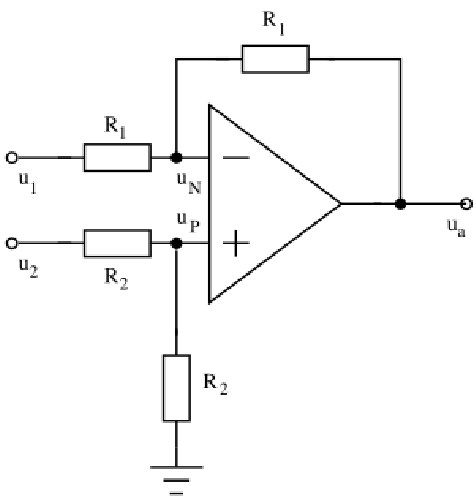

Figure 12: Aanalog Subtraction with OP-AMP

2.1 $u_a = 0\,\mathrm{V}$

From the formula $u_a = u_2 - u_1 = 0\,\mathrm{V}$ follows that this behavior can be achieved by setting the voltages to $u_1 = u_2$. The simulated circuit and the voltages in there can be seen in Fig. 13. The green curve in this figure shows the voltage $+u$ and the blue one the voltage $-u$ and therefore confirms that the circuit in Fig 11 works as expected. The red curve shows the output voltage u_a of the OP-AMP, confirming that for the case $u_1 = u_2$ the output voltage is constantly $0\,\mathrm{V}$.

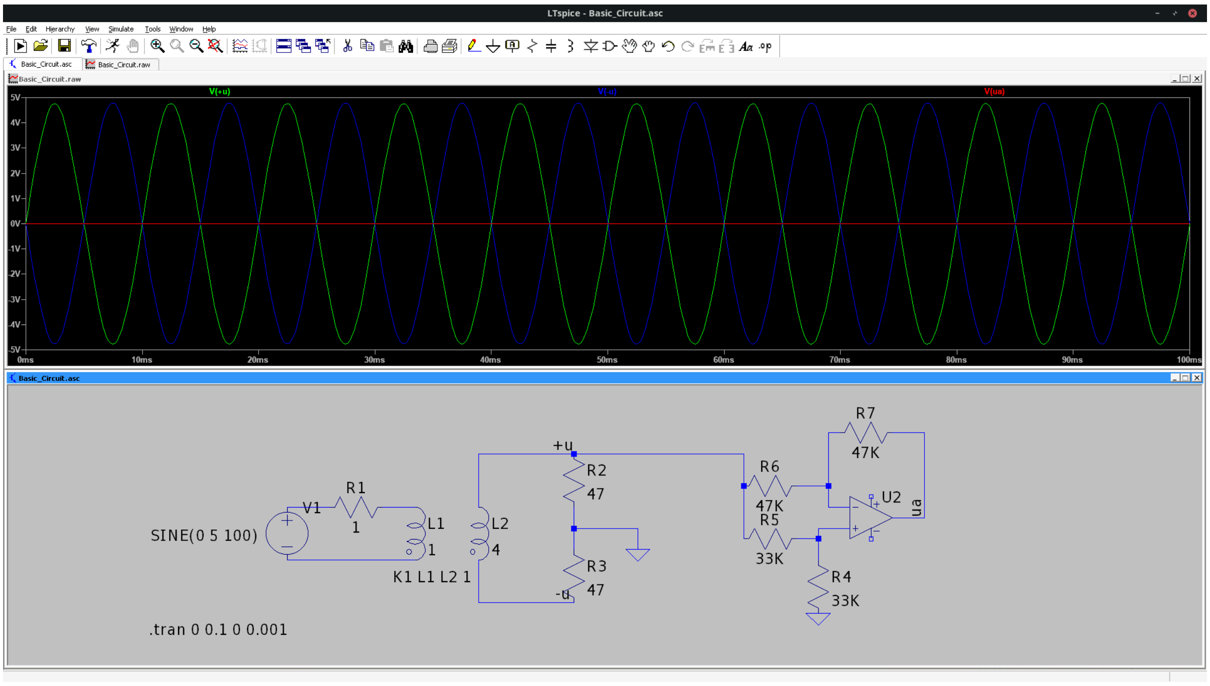

Figure 13: Analog Subtraction resulting in $u_a = 0\,\mathrm{V}$

2.2 $u_a = \pm u$

An output voltage of $\pm u$ can be achieved by setting u_2 to $+u$ and u_1 to Ground. This calculates to $u_a = u_2 - u_1 = u_2 - 0\,\mathrm{V} = u_2$ where u_2 has a voltage of $\pm u$. The simulation can be seen in Fig. 14 where the green curve is $+u$ and the blue curve is the output voltage of the OP-AMP. Since both voltages are identical there is no possibility in showing them in a single plot because one of them would cover the other one. Therefore they are plotted in two separate plot panes. The results confirm the expected behavior.

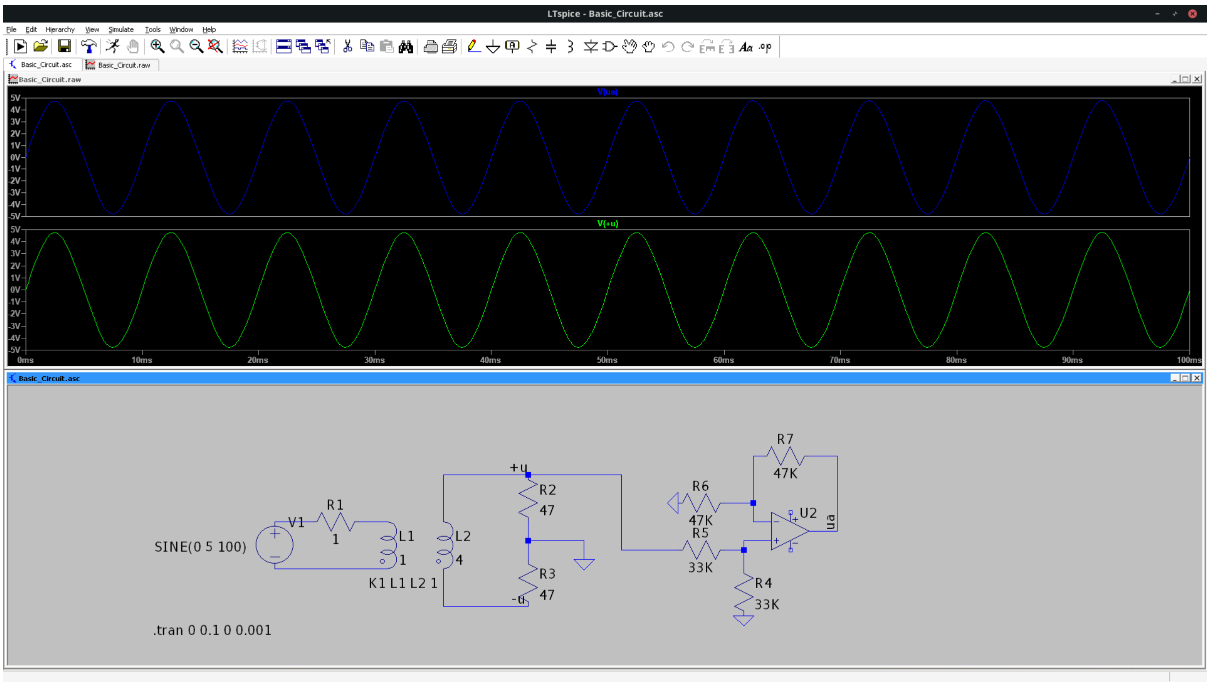

Figure 14: Analog Subtraction resulting in $u_a = \pm u$

2.3 $u_a = \pm 2u$

An output voltage of $\pm u$ can be achieved by setting u_2 to $+u$ and u_1 to $-u$. This calculates to $u_a = u_2 - u_1 = +u - (-u) = 2 \cdot u$. The simulation can be seen in Fig. 15 where the green and blue curves are $\pm u$ and the red curve is the output voltage of the OP-AMP, confirming the expected behavior.

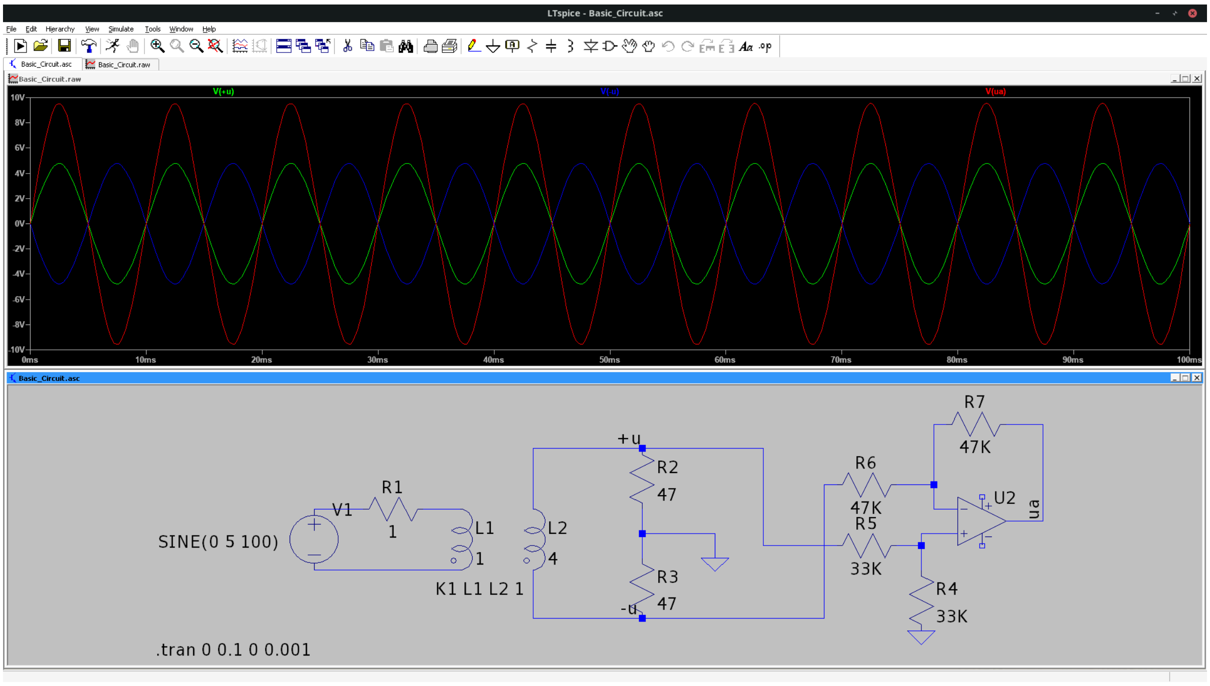

Figure 15: Analog Subtraction resulting in $u_a = \pm 2u$