OPERATIONAL AMPLIFIER

In addition to this instructions, please read the following chapters in the book 'Basic electronics for scientists and engineers' by D. L. Eggleston:

6. Operational amplifiers, and the following chapters:
   - 6.1. Introduction
   - 6.3. Linear applications
   - 6.4. Practical considerations for real op-amps (chapters 6.4.1 and 6.4.4)

Additional resources:
https://www.electronics-tutorials.ws/opamp/opamp_1.html
https://www.electronics-tutorials.ws/opamp/opamp_2.html
https://www.electronics-tutorials.ws/opamp/opamp_4.html
https://www.electronics-tutorials.ws/opamp/opamp_5.html (first two subchapters, until Wheatstone bridge)
https://www.electronics-tutorials.ws/opamp/opamp_8.html (summary)

Operational amplifier (OA) or op-amp is a DC-coupled high-gain electronic voltage amplifier. OA amplifies DC signals, while AC signals are amplified only in a specific frequency interval (band). OA has differential input (two inputs) and usually a single-ended output.

Operational amplifier was originally used in analogue computing machines as the first large-scale computers in order to perform analogue mathematical operations such as addition, multiplication, differentiation, integration, etc. Today, OA is commonly used in many electronic devices and circuits, and its application is very broad and versatile. It is the main building block of a modern analogue electronic circuit.

Op-amps are built in integrated form, can have very small dimensions, they are cheap, reliable, and temperature stable, have excellent amplifying, frequency and impedance properties, and consequently represent basic components of linear integrated electric circuits used in many devices, systems and instruments.

Operational amplifier is a type of complex differential amplifier with two inputs acting as differential high impedance inputs:

- Inverting input marked with a minus (-) sign, and
- Non-inverting input marked with a plus (+) sign.

Single output U_i is used in most op-amps. Symbol of the operational amplifier used in electric circuit diagrams is shown in figure 1 where A represents amplification factor (gain) of the amplifier. Input voltage $u_u^{(+)}$ is connected to the non-inverting input of the OA, while input voltage $u_u^{(-)}$ is connected to the inverting input of the OA. Output voltage u_i is in-phase with the input voltage $u_u^{(+)}$ and in anti-phase (phase difference is π rad) with the input voltage $u_u^{(-)}$.

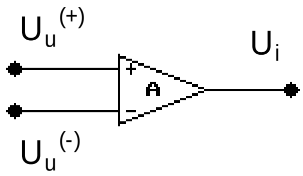


Figure 1. *Symbol of the operational amplifier in electronic circuit diagrams*

Properties of an ideal operational amplifier:

1. Amplifier voltage gain (factor of the voltage amplification) $A \to \infty$,
2. Input impedance $R_u \to \infty$,
3. Output impedance $R_i = 0$,
4. Gain does not depend on frequency (infinite frequency bandwidth),
5. Characteristics are temperature stable,
6. Output voltage is $U_i = 0$ if the input voltages at both inputs are equal $U_u^+ = U_u^-$.

Operational amplifier is a complex type of differential multi-stage amplifier that usually has at least three stages (figure 2):

I. Differential amplifier at input,
II. Common-emitter transistor amplifier,
III. Voltage follower at output.

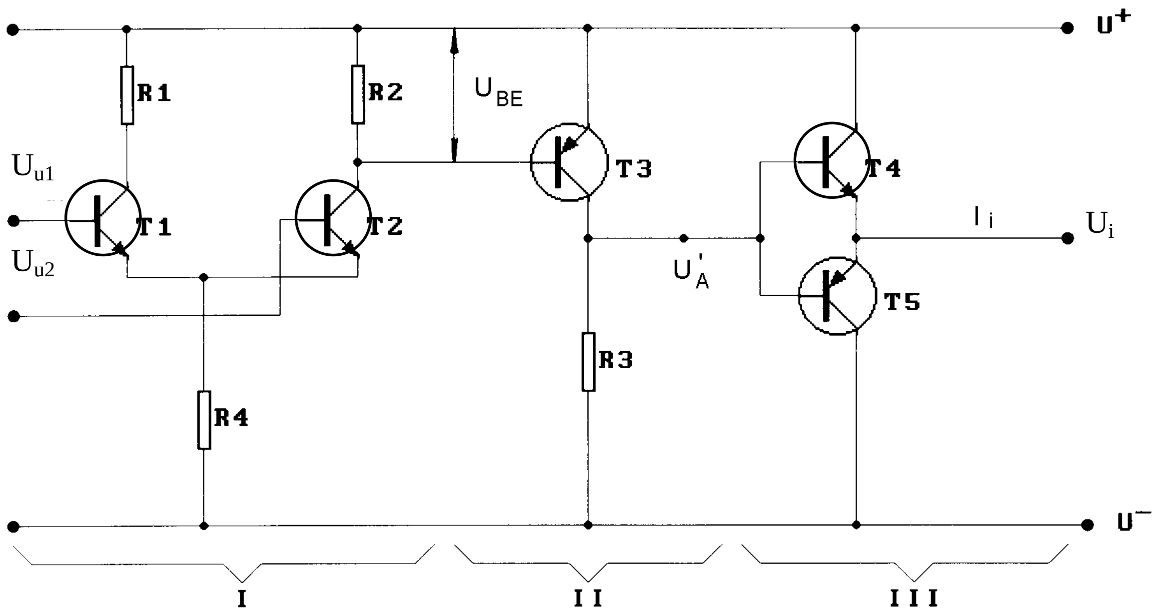


Figure 2. *Structure of the operational amplifier with the three stages*

Input stage of the operational amplifier is a differential amplifier with symmetric input and asymmetric output (see figure 2). Differential amplifier consists of two transistors: T_1 and T_2. Input voltages U_{u1} and U_{u2} are applied to the bases of the two transistors, respectively. Differential amplifier amplify the difference between the two input signals, $U_{u1} – U_{u2}$. Generally, a signal consists of the useful signal that we want to amplify, and noise. If signal is applied to one of the inputs of the differential amplifier, and only noise (grounded input) to the other input, the differential amplifier will amplify the difference between the two inputs, amplifying the useful signal and attenuating (rejecting) the noise.

Transistors T_1 and T_2 in differential amplifier have common emitter. Emitter current in the common emitter should be as constant as possible, which means that the common emitter of the differential amplifier must have high resistance (impedance). So, instead of resistor R_4 in electric circuit shown in figure 2, a current source with very high output resistance (impedance) is typically used. Figure 3 shows one example of the current source used instead of R_4.

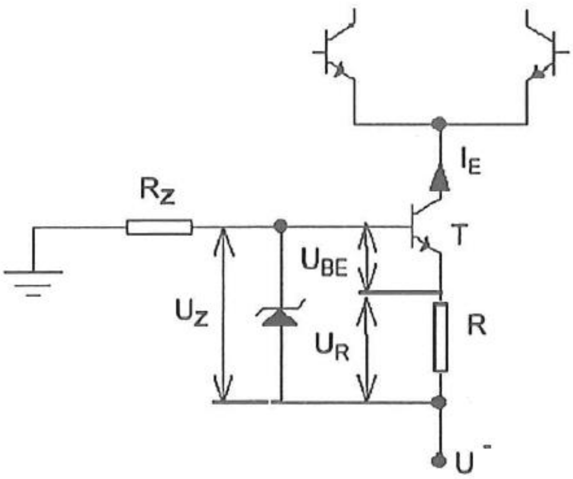


Figure 3. *Current source in differential amplifier*

Current I_E of the common emitter flows through the transistor T, and from Ohmic law we have:

$$I_E = \frac{U_R}{R}$$

According to the circuit diagram on figure 3, it follows:

$$U_R = U_z - U_{BE}$$

and U_z is the voltage drop across the Zener diode. Voltage drop on Zener diode is equal to the breakthrough voltage and almost constant regardless the current through the Zener diode. Voltage drop U_{BE} on forward-biased PN junction between base and emitter is also almost constant (≈ 0.6 V for silicon transistor). So,

$$I_E = \frac{U_z - U_{BE}}{R} = \text{const.}$$

and I_E is constant as required.

Amplified differential signal is further amplified in the common-emitter PNP transistor amplifier T_3. Output signal from the differential amplifier is fed into the base of the transistor T_3. According to the figure 2, base of the transistor T_3 is at the lower potential than the emitter which is connected with the positive terminal of the power supply U^+, so $U_{BE} < 0$. If $|U_{BE}| < 0.6$ V, base-emitter junction in T_3 is reverse-biased, and transistor T_3 is in cut-off conditions (not working, no current is flowing through emitter and collector and there is no voltage drop on R_3), so $U_A' \approx U^-$. If $|U_{BE}| > 0.6$ V, base-emitter junction in T_3 is forward-biased, T_3 enters saturation region where $U_{CE} \approx 0$, current flows through its emitter and collector, and $U_A' \approx U^+$. Consequently, the voltage U_A' at the output of the second stage of the OA can have wide range of the values between U^+ and U^-, i.e.

$$U^- \leq U_A' \leq U^+$$

Variation of the voltage ΔU_{A2} at the asymmetric output of the differential amplifier (output (collector) of the transistor T_2) are strongly amplified in the second stage of OA (in transistor T_3 in common-emitter geometry) so that the variation of the voltage $\Delta U_{A2}'$ at the output of the second stage are:

$$\Delta U_A' = v_u \Delta U_{A2}$$

where v_u is voltage gain (factor of the voltage amplification) of T_3 transistor in common-emitter circuit.

Third stage of op-amp consists of the two complementary transistors T_4 and T_5 of different types (NPN and PNP) in common-collector circuit, also known as *voltage follower*. Voltage follower amplifies the current, but the voltage remains almost constant and unchanged up to the value of 0.6 V (forward-bias voltage of the base-emitter PN junction for a silicate transistor is 0.6 V). This is very important as the op-amp should supply the load at the output with the current large enough to drive that load. At the same time, output voltage should be independent of the output current and remain unchanged for an increased current. This means that the output impedance of the op-amp is small, which is also important in impedance matching with the low impedance load such as a speaker in audio systems or hi-fi. Two common-collector transistors are used and they operate alternately in order to obtain voltage at the output regardless of the polarity of U_A' (U_A' can be positive or negative).

If $U_A' > 0.6$ V, transistor T_4 is in operating condition and $U_i = U_A' - U_{BE}$ (T_4) = $U_A' - 0.6$ V, while T_5 is closed (in cut-off condition).

If $U_A' < -0.6$ V, transistor T_5 is in operating condition and $U_i = U_A' - U_{BE}$ (T_5) = $U_A' - (-0.6$ V$) = U_A' + 0.6$ V, while T_4 is closed (in cut-off condition).

OPERATIONAL AMPLIFIER IN ELECTRIC CIRCUIT WITH FEEDBACK

Operational amplifier is commonly used in electric circuit with negative feedback (figure 4). Feedback means that a fraction of the output signal (voltage) is ‘fed’ (brought) back to the input through some external circuit. Usually, external circuit consists of a simple feedback resistor (R_2 in figure 4). Feedback in electric circuit with operational amplifier provides very stable system where overall gain of the operational amplifier can be controlled by external electric elements in the circuit. Therefore, overall gain and characteristics of the circuit with the operational amplifier do not depend on the specific characteristics of the operational amplifier, but on the values of external electric elements such as resistors. If the feedback circuit connects output with the inverting input, the feedback is negative. If the non-inverting input is connected to the feedback, than the feedback is positive. These configurations are known as inverting and non-inverting circuits with operational amplifier.

Inverting circuit with an ideal operational amplifier (inverting operational amplifier)

In inverting circuit with OA, input signal is connected to the inverting input (figure 4).

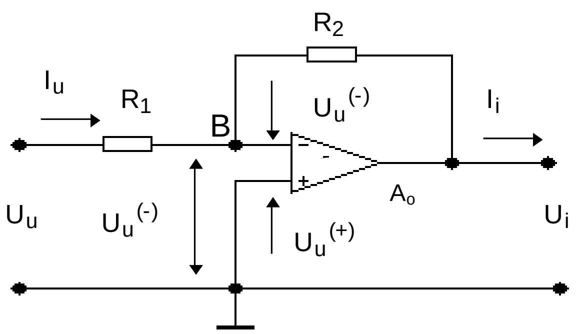


Figure 4. Inverting operational amplifier

Feedback resistor is R_2 and it provides high input and low output resistance (impedance) of this circuit. We can see that

$$U_i = \left(U_u^{(+)} - U_u^{(-)}\right) A_0$$

where A_0 is voltage gain of the operational amplifier. Ideal operational amplifier has infinite voltage gain $A \to \infty$. In order for output voltage U_i to remain constant while $A \to \infty$, the value in brackets must approach zero, $U_u^{(+)} - U_u^{(-)} \to 0$, so

$$U_u^{(+)} = U_u^{(-)} \qquad (1)$$

According to the circuit diagram on figure 4, non-inverting input is grounded, so

$$U_u^{(+)} = 0 \qquad (2)$$

and $U_u^{(-)} = 0$. Therefore, point B in figure 4 is called 'virtual zero'. Ideal operational amplifier has infinitely large input impedance (resistance), $R_u \to \infty$, and therefore input currents vanish:

$$I_u^{(+)} = I_u^{(-)} = 0$$

Input voltage U_u of the inverting OA circuit is equal to the sum of the voltage drop on resistor R_1 and input voltage $U_u^{(-)}$:

$$U_u = I_u R_1 + U_u^{(-)}$$

It follows that

$$I_u = \frac{U_u - U_u^{(-)}}{R_1} \qquad (3)$$

Output current I_i can be obtained from the feedback loop:

$$U_u^{(-)} = I_i R_2 + U_i$$

$$I_i = \frac{U_u^{(-)} - U_i}{R_2} \qquad (4)$$

The input resistance (impedance) of the ideal operational amplifier is infinite, so no current can flow through the OA. Therefore, input current I_u must flow through the feedback loop toward the output, and the current through the feedback resistor R_2 is equal to the input current I_u.

$$I_u = I_i \qquad (5)$$

From relations (3), (4) and (5), it follows

$$\frac{U_u - U_u^{(-)}}{R_1} = \frac{U_u^{(-)} - U_i}{R_2} \qquad (6)$$

If you put (2) into (6), the following is obtained:

$$\frac{U_u}{R_1} = -\frac{U_i}{R_2}$$

Finally, the voltage gain A_0^* of the inverting circuit with ideal operational amplifier (inverting operational amplifier):

$$\boldsymbol{A_0^*} = \frac{\boldsymbol{U_i}}{\boldsymbol{U_u}} = -\frac{\boldsymbol{R_2}}{\boldsymbol{R_1}} \qquad (7)$$

Voltage gain A_0^* of the inverting operational amplifier depends exclusively on the resistors R_1 and R_2 in external circuits and not on the characteristic of the operational amplifier. This means that by simple variation of resistors R_1 and R_2, voltage gain of the circuit can be varied and adjusted. Voltage gain has negative value, which means that the output voltage is phase shifted relative to the input voltage for π rad.

Inverting circuit with a real operational amplifier (inverting operational amplifier)

Real operational amplifier has different characteristics compared to the ideal OA. Among other differences, real OA has finite voltage gain, while ideal OA has infinite voltage gain. Therefore, real inverting operational amplifier will have different voltage gain A^* compared to the voltage gain A_0^* of the ideal inverting operational amplifier (relation 7).

Assume that the characteristics of the real operational amplifier are the same as for the real OA, except the voltage gain, which has a finite value A. Under that assumption, input resistance (impedance) of the OA is infinite, so there are no currents through the operational amplifier and input and output currents are the same (relation 5). Therefore, currents through the resistors R_1 and R_2 are the same and the relation (6) still holds. Output voltage is:

$$U_i = A(U_u^{(+)} - U_u^{(-)})$$

But

$$U_u^{(+)} = 0$$

so

$$U_u^{(-)} = -\frac{U_i}{A} \qquad (8)$$

If you put (8) into (6), you find out that:

$$\frac{U_u + \frac{U_i}{A}}{R_1} = \frac{-\frac{U_i}{A} - U_i}{R_2}$$

Multiply the above relation with $\frac{R_1 R_2}{U_i}$ and use the definition of the voltage gain of the OA:

$$A^* = \frac{U_i}{U_u}$$

Finally, the voltage gain of the inverting circuit with the real operational amplifier is:

$$\boldsymbol{A^* = -\frac{R_2}{R_1}\frac{1}{1 + \frac{1}{A}\left(1 + \frac{R_2}{R_1}\right)}} \qquad (9)$$

It can be seen that the voltage gain of the inverting real OA depends on the voltage gain of the OA itself. In the limiting case, when real operational amplifier becomes ideal, $A \rightarrow \infty$, the voltage gain (relation 9) becomes equal to the voltage gain of inverting real operational amplifier (relation 7).

Non-inverting circuit with an ideal operational amplifier (non-inverting operational amplifier)

Input voltage that needs to be amplified is fed to the non-inverting input of the operational amplifier as can be seen in figure 5 of the non-inverting circuit of the OA.

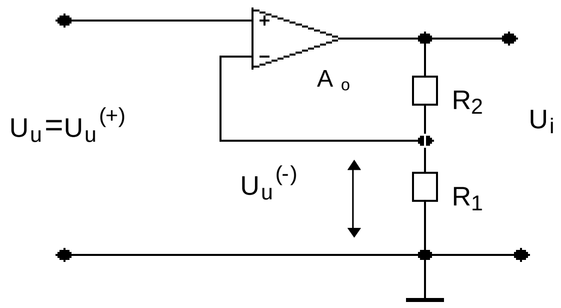


Figure 5. Non-inverting operational amplifier

Output voltage is in phase with the input voltage, and proportional to it. Two inputs of the ideal OA are on the same potential (relation 1) so both inputs have the same voltage U_u.

Resistors operate as output voltage dividers, so:

$$\frac{U_u^{(-)}}{U_i} = \frac{R_1}{R_1 + R_2}$$

In ideal OA:

$$U_u^{(+)} = U_u^{(-)}$$

and

$$U_u = U_u^{(+)}$$

it follows

$$\frac{U_u}{U_i} = \frac{R_1}{R_1 + R_2}$$

Voltage gain of the non-inverting operational amplifier with ideal OA is

$$\boldsymbol{A_0^*} = \frac{\boldsymbol{U_i}}{\boldsymbol{U_u}} = \mathbf{1} + \frac{\boldsymbol{R_2}}{\boldsymbol{R_1}} \qquad (10)$$

Voltage gain of the non-inverting operational amplifier is always larger than 1 and depend on the external elements in the circuit (resistors R_1 and R_2). Output voltage is in-phase with the input voltage.

APPLICATIONS OF THE OPERATIONAL AMPLIFIER CIRCUIT

As have already been mentioned, electric circuits with operational amplifier can be used to perform various operations and functions such as phase inversion, addition, subtraction, derivation, integration, multiplication, taking exponentials and logarithms. They can be applied as comparators, discriminators, voltage followers, memory registers…

The summing amplifier

Summing of the voltages is one of the many possible analogue operations that a circuit with operational amplifier can perform. Such a circuit of the summing amplifier is shown on figure 7 where an arbitrary number of input voltages U_1, U_2, …, U_n can be connected to the inverting input of the OA. Output voltage U_i can be obtained as proportional to the sum of the input voltages. The other, non-inverting input is grounded.

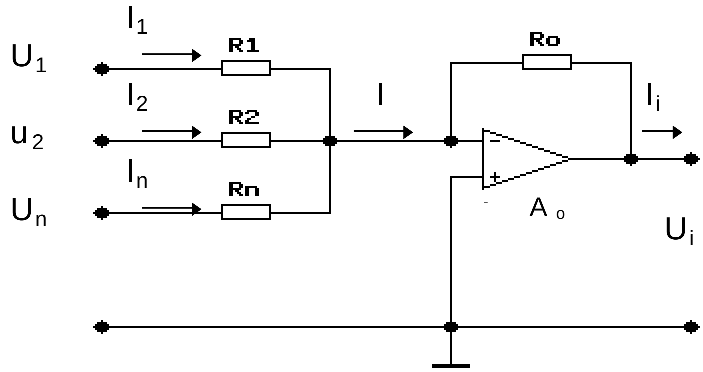


Figure 6. *The summing amplifier*

The total input current I is equal to the sum of the input currents I_1, I_2, …, I_n of individual sources U_1, U_2, …, U_n:

$$I = I_1 + I_2 + \cdots + I_n$$

In approximation of the ideal operational amplifier, operational amplifier has infinite voltage gain and infinite input resistance (impedance), so the 'virtual zeros' are:

$$U_u^{(+)} = U_u^{(-)} = 0$$

and from Ohmic law:

$$I_1 = \frac{U_1}{R_1}, \qquad I_2 = \frac{U_2}{R_2}, \quad \ldots \quad , \qquad I_n = \frac{U_n}{R_n}$$

$$I_i = -\frac{U_i}{R_0}$$

From relation (5) follows that $I_u = I_i$ and:

$$-\frac{U_i}{R_0} = \frac{U_1}{R_1} + \frac{U_2}{R_2} + \cdots + \frac{U_n}{R_n}$$

If all the input resistors are the same, $R_1 = R_2 = \cdots = R_n = R$, we get:

$$U_i = -\frac{R_0}{R}(U_1 + U_2 + \cdots + U_n)$$

If input resistors have the same value as the feedback resistor, $R = R_0$:

$$\boldsymbol{U_i} = -(\boldsymbol{U_1} + \boldsymbol{U_2} + \cdots + \boldsymbol{U_n}) \qquad (11)$$

The output voltage U_i is equal to the sum of all input voltages. If input voltages need to be multiplied by some factor and then summed, different input resistors and feedback resistor can be used. Therefore, such a circuit can be used to perform simple mathematical operations of summation and multiplication by a constant.

The voltage subtractor

The voltage subtractor is a circuit with operational amplifier that differentiate between the two input signals, one connected to the non-inverting input, and one to the inverting input of the OA. Therefore, if the signal is fed to both inputs of the OA, output voltage is proportional to the difference between the two input voltages. Such a circuit with OA is called voltage subtractor (sometimes also differential amplifier) and is shown on figure 7.

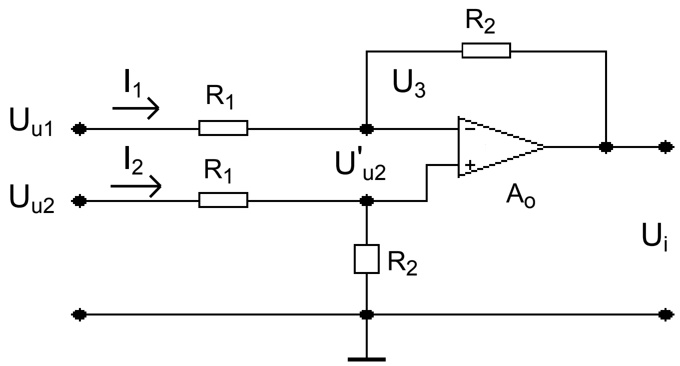


Figure 7. *The voltage subtractor*

Due to the applied input voltage U_{u1}, the current I_1 flows through the resistor R_1 and into the inverting input of the OA. Similarly, due to the applied input voltage U_{u2}, the current I_2 flows through the resistor R_{12} which has the same resistance as R_1, $R_{12} = R_1$, and into the non-inverting input of the OA. Voltage at the non-inverting input of the OA is U_{u2}' and voltage at the inverting input of the OA is U_3. Due to the resistor R_2 between the inverting input and the ground, no 'virtual zeros' are present, although inverting and non-inverting inputs of the ideal operational amplifier are on the same potential. Therefore, voltages on the inverting and non-inverting inputs of the OA must be the same:

$$U_3 = U'_{u2}$$

In accordance with the relation (6), and with $U_u^{(-)} = U_3$:

$$\frac{U_{u1} - U_3}{R_1} = \frac{U_3 - U_i}{R_2} = I_1 \qquad (12)$$

As $U_u^{(+)} = U_u^{(-)} = U_3$, it follows for non-inverting input:

$$\frac{U_{u2} - U_3}{R_1} = \frac{U_3}{R_2} = I_2 \qquad (13)$$

We can get U_3 from relation (12) and put it into (13):

$$\boldsymbol{U_i = \frac{R_2}{R_1}(U_{u2} - U_{u1})} \qquad (14)$$

If all resistors have the same value, $R_1 = R_2$, the output voltage is the difference between the two input voltages:

$$U_i = U_{u2} - U_{u1}$$

Similar to the summing amplifier, this circuit with the operational amplifier can be used to subtract two voltages, or to subtract and multiply by a constant if resistors do not have the same resistance.

The same result can be obtained by a different approach. If we use principle of superposition, output voltage of the OA can be considered as the sum of the two output voltages U_{i1} and U_{i2}, which are results of the amplification of two input signals U_{u1} and U_{u2}.

$$U_i = U_{i_1} + U_{i_2}$$

Relation (7) holds for inverting input:

$$U_{i_1} = -\frac{R_2}{R_1}\, U_{u1}$$

and relation (10) for non-inverting input and for U_{u2}' at the non-inverting input:

$$\frac{U_{i_2}}{U'_{u2}} = \frac{R_1 + R_2}{R_1} \qquad (15)$$

Also

$$\frac{U'_{u2}}{U_{u2}} = \frac{R_2}{R_1 + R_2} \qquad (16)$$

If you put (16) into (15), you get the following:

$$U_{i_2} = \frac{R_1 + R_2}{R_1} \frac{R_2}{R_1 + R_2} U_{u2}$$

$$U_{i_2} = \frac{R_2}{R_1} U_{u2}$$

Voltage at the output of the operational amplifier is:

$$U_i = U_{i_1} + U_{i_2} = -\frac{R_2}{R_1} U_{u1} + \frac{R_2}{R_1} U_{u2} = \frac{R_2}{R_1} (U_{u2} - U_{u1}) \qquad (17)$$

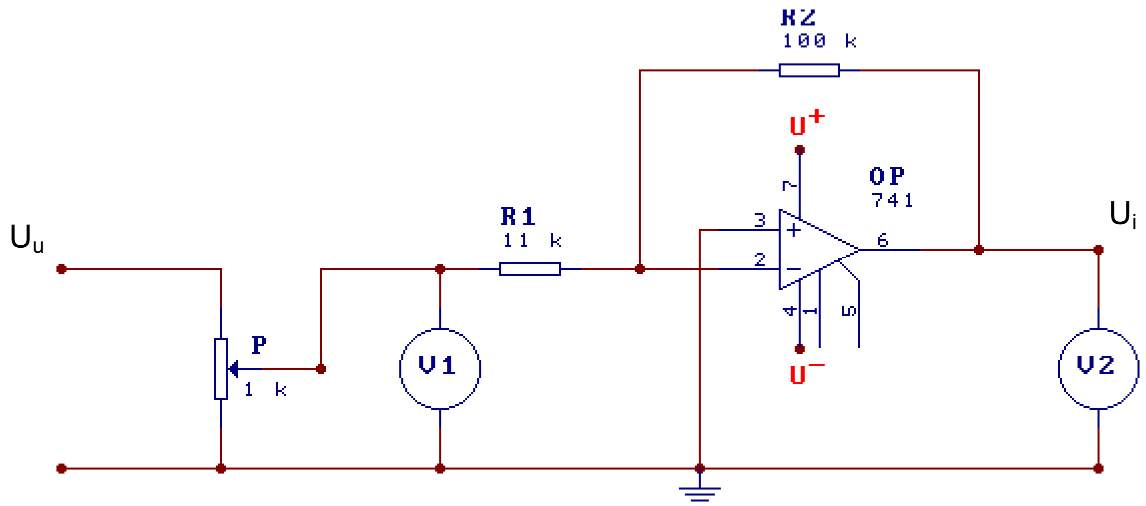
Which is the same as relation (14).

Gain of the difference between the input voltages is determined from relation (17):

$$v_d = \frac{U_1}{U_{u2} - U_{u1}} = \frac{R_2}{R_1} \qquad (18)$$

ASSIGNMENT I:

1. Assembly the inverting circuit with the operational amplifier (inverting operational amplifier) according to the circuit diagram shown below.



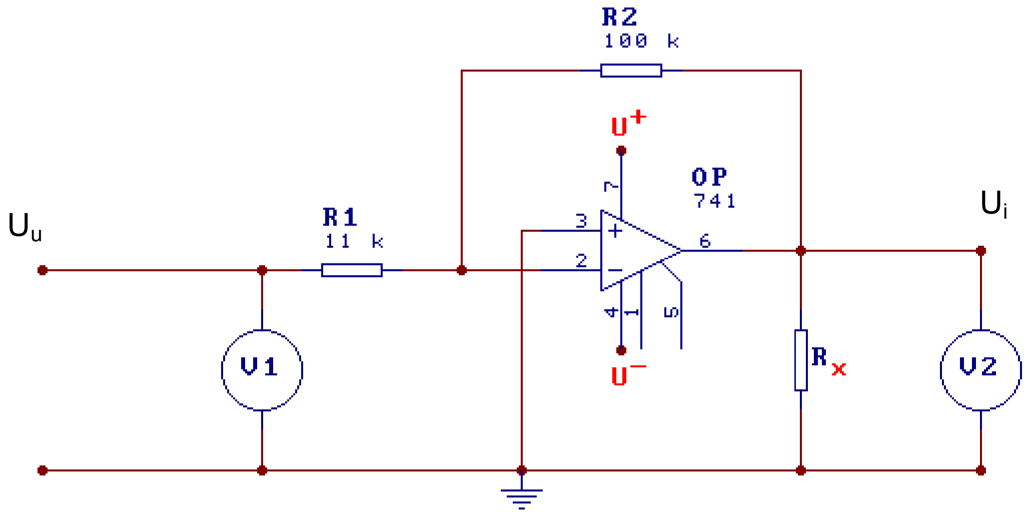
2. Determine voltage gain of the inverting operational amplifier by measuring the dependence of the output voltage on the input voltage and by using the least square method on $U_i = f(U_u)$. Show the measured $U_i = f(U_u)$ on a diagram. Determine uncertainties.
3. Compare the measured voltage gain with the theoretical value calculated from relation (7).

Notes:

- Vary input voltage $|U_u|$ between 0.1 and 0.9 V in steps of 0.1 V.
- Obtain measurements with both positive and negative values of the input voltage

ASSIGNMENT II:

1. Assembly the constant voltage source with operational amplifier according to the circuit diagram shown below.



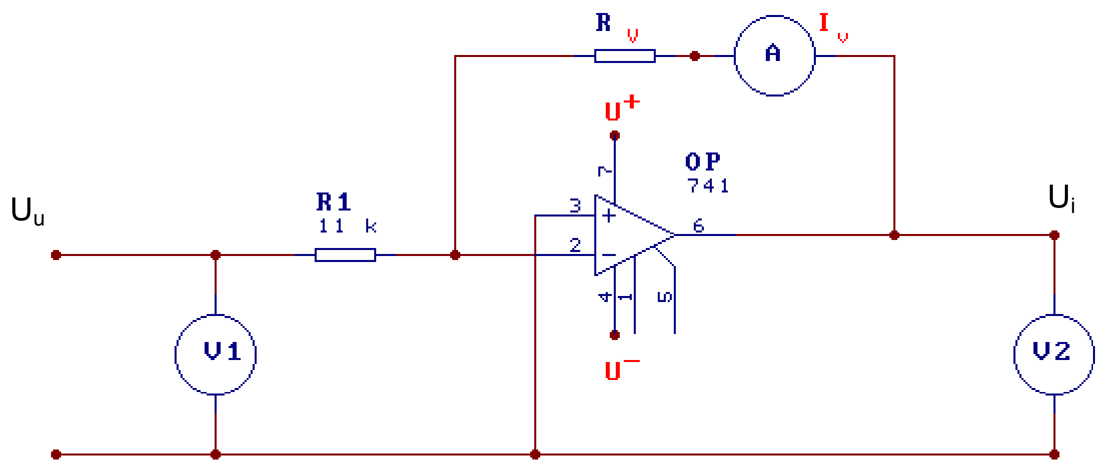
2. Measure the dependence of the output voltage U_i on the output current $I_i = U_i/R_x$ and show it on a diagram U_i = f(I_i)
3. Determine the maximum value of the output current for which this circuit still works as a constant voltage source
4. According to the above results, determine input resistance of the operational amplifier and compare it with the value expected for ideal operational amplifier.

Notes:

- Keep input voltage constant U_u = 0.5 V
- Vary output current I_i by varying the resistance of the resistor R_x, measure the output voltage U_i, then calculate the output current $I_i = U_i/R_x$.
- Use the following values of resistor R_x:
  R_x (Ω) = 9100, 3000, 680, 510, 330, 270, 240, 200, 180, 130, 110

ASSIGNMENT III:

1. Assembly the constant current source with operational amplifier according to the circuit diagram shown below.



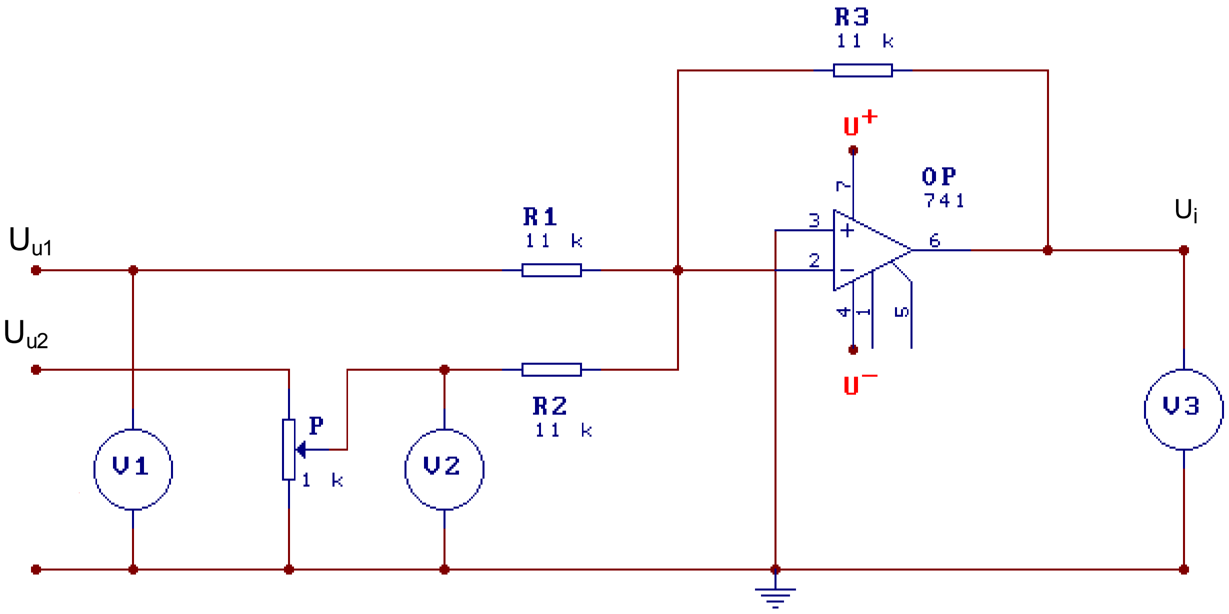
2. Measure the dependence of the output current I_v on the resistance of the feedback resistor R_v and show it on a diagram $I_v = f(R_v)$
3. Determine maximum value of the resistance of the feedback resistor for which this circuit still works as a constant current source
4. According to the above results, determine output resistance of the operational amplifier and compare it with the value expected for ideal operational amplifier.

Notes:

- Keep input voltage constant $U_u = 0.5$ V
- Vary output current I_v by varying the resistance of the feedback resistor R_v, and measure the output current I_v for different R_v.
- Use the following values of feedback resistor R_v:
  R_v (kΩ) = 11, 15, 20, 56, 62, 68, 82, 120, 150, 180, 200, 220, 240, 270, 300, 390, 470, 620, 820

ASSIGNMENT IV:

1. Assembly the summing amplifier according to the circuit diagram shown below.



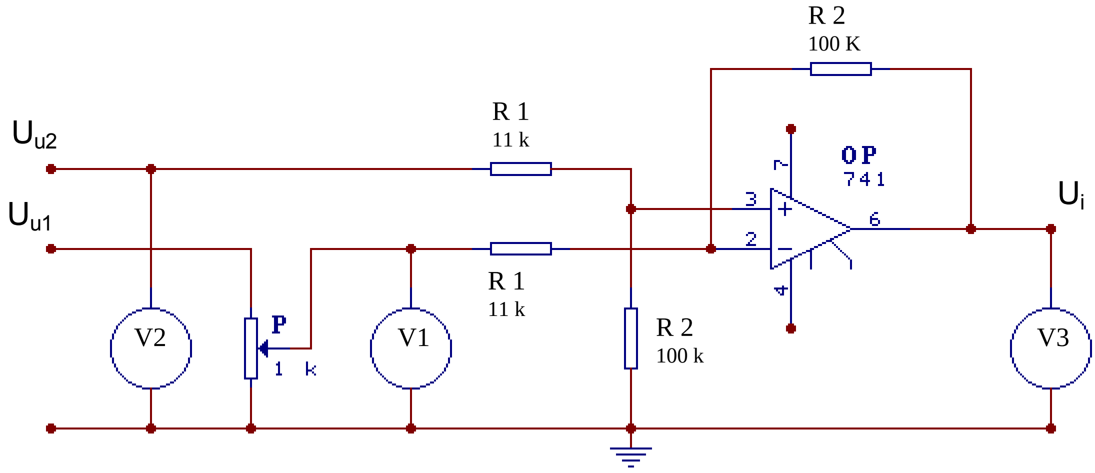
2. Measure the dependence of the output voltage on the sum of the input voltages U_i = f (U_{u1} + U_{u2}). Compare the results with the theoretical values calculated from (11). Show the measured U_i = f (U_{u1} + U_{u2}) on a diagram. Determine uncertainties.
3. Determine gain of the summing amplifier by the least square method and compare it with the theoretical value calculated from (11).

Notes:

- Keep input voltage U_{u1} constant, $U_{u1} = \pm 0.5$ V
- Vary output voltage U_{u2} in the interval ± (0.1 – 1.0) V in the steps of 0.1 V by the use of the potentiometer
- First, make measurements with both input voltages U_{u1} and U_{u2} positive, and then with both input voltages negative

ASSIGNMENT V:

1. Assembly the voltage subtractor according to the circuit diagram shown below.



2. Measure the dependence of the output voltage on the difference of the input voltages U_i = f (U_{u2} – U_{u1}). Compare the results with the theoretical values calculated from (18). Show the measured U_i = f (U_{u2} – U_{u1}) on a diagram. Determine uncertainties.
3. Determine gain of the voltage subtractor by the least square method and compare it with the theoretical value calculated from (18).

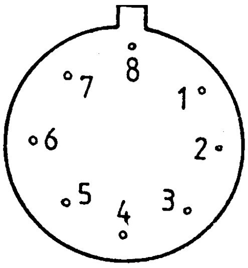
Notes:

- Keep input voltage U_{u1} constant, U_{u1} = 1 V
- Vary output voltage U_{u2} in the interval from 0.1 to 0.9 V and in steps of 0.1 V by the use of the potentiometer
- First, make measurements with both input voltages U_{u1} and U_{u2} positive, and then with both input voltages negative

GENERAL NOTES:

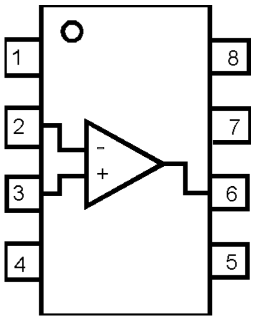
- Operational amplifier μA 741 has eight pins.

Housing: TO-8



(view from below)

Housing: PIN-8

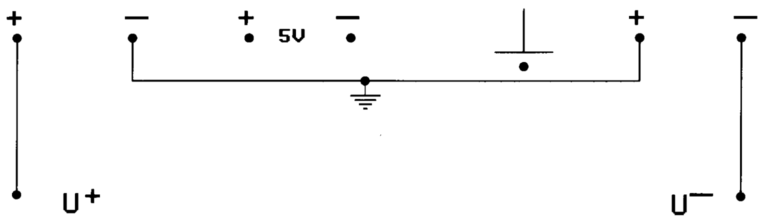


(view from above)

Pin configuration:

1. Frequency compensation at input
2. Inverting input
3. Non-inverting input
4. U^- negative power supply
5. Frequency compensation at output
6. Output
7. U^+ positive power supply
8. NC

- Maximum voltage of the power supply for this OA is $U = \pm 16$ V. Use constant voltage of the power supply $U^+ = +9$ V and $U^- = -9$ V in this assignment. Stabilized power supply has two DC voltage supplies.
- In order to obtain positive and negative voltages of the power supply, connect the terminals according to the diagram below:



Terminals of the stabilized power supply used to supply OA

- When turning on and off the circuit, power supply should be turned on first, and turned off last.
- Turn off all power supplies before modifying the circuit.
- Keep the voltage at the minimum when turning on the source of the input voltage, and then increase it slowly to the desired value.