# MARITIME UNIVERSITY OF SZCZECIN

**ORGANIZATIONAL UNIT:**
DEPARTMENT OF MARINE COMMUNICATION TECHNOLOGIES

# INSTRUCTION

**ELECTRICAL ENGEENERING AND ELECTRONICS**
**Laboratory**
**Exercise No 9: Operational amplifiers**

| | |
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# Contents

# 9. OPERATIONAL AMPLIFIER

## 9.1. The purpose and scope of the exercise

The aim of the exercise is to master knowledge of the construction, parameters, characteristics and application of basic operational amplifiers systems.

### Topics

1. Parameters of the ideal operational amplifier.
2. Parameters of the real operational amplifier.

Operational amplifier operation modes
- inverting amplifier
- non-inverting amplifier
- duplicate amplifier
- integration amplifier
- differential amplifier
- diversifying amplifier
- adder amplifier
- comparator

### Control questions

1. What is an operational amplifier?
2. Draw and discuss the graphic symbol of the operational amplifier.
3. Give the parameters of the ideal operational amplifier.
4. Give the parameters of the actual operational amplifier.
5. Specify the use of an operating amplifier.
6. Draw and discuss the operation of the following systems:
   – inverting and non-inverting amplifier,
   – duplicate amplifier,
   – the integration (integrator) and differentiation systems,
   – the sum of two, three, multiple signals,
   – the differential
   – a logarithmic and amplifying amplifier.

## 9.2. Description of the measurement system

A set of instruments:

- two channel function generator,
- ± 15V power supply,
- two-channel oscilloscope,
- test system.

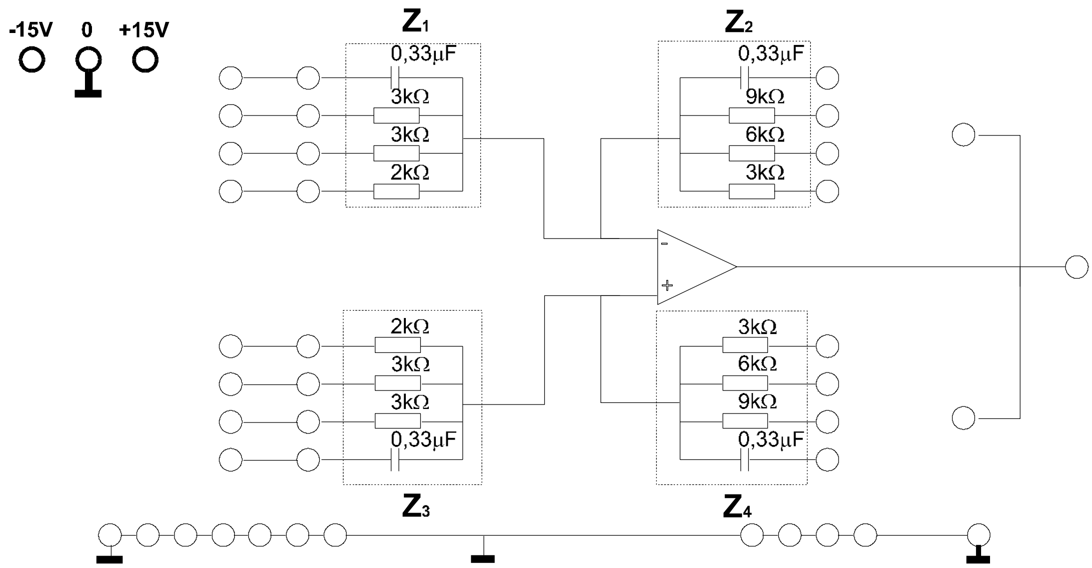



Fig. 9.2.1. Diagram of the tested system.

## 9.3. Execution of the exercise

WARNING!!! DEVICES TO BE INCLUDED FOR THE CONSUMER'S CONSENT AMPLIFY THE AMPLIFIER WITH TURNED POWER OFF AND GENERATOR

Connect the power supply to the operational amplifier circuit (voltage + 15V, ground, -15V).

### 9.3.1. Phase inverter amplifier test

– Connect the measuring system from Fig. 9.3.1, where $R_1$=3 kΩ, $R_2$=6 kΩ $R_3$=2 kΩ. Redraw the diagram of the inverter amplifier. At the input of the amplifier, give the generator a sinusoidal signal with an amplitude $U_{we}$ = 0.5 V and frequencies $f$ =1 kHz.

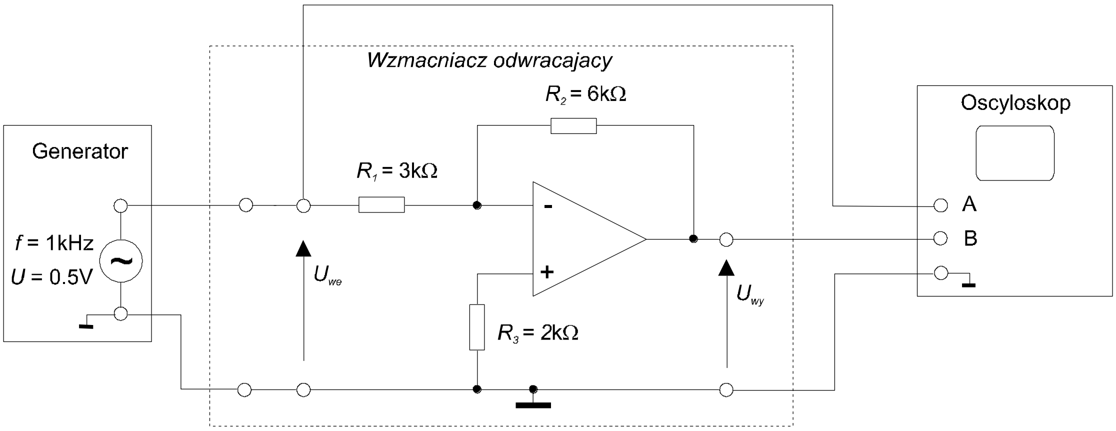



Fig. 9.3.1. A system for testing the inverting amplifier

– Redraw the waveforms of the input and output signals. *(Pay attention to phase shift between signals).* Measure the output voltage amplitude $U_{wy}$ and write to table 9.1. Calculate the amplification based on the observed waveforms..

$$k_u = \frac{U_{wy}}{U_{we}}$$

– Check if the value of the calculated gain is similar to the value of the system gain calculated from the formula:

$$k_u = -\frac{R_2}{R_1}$$

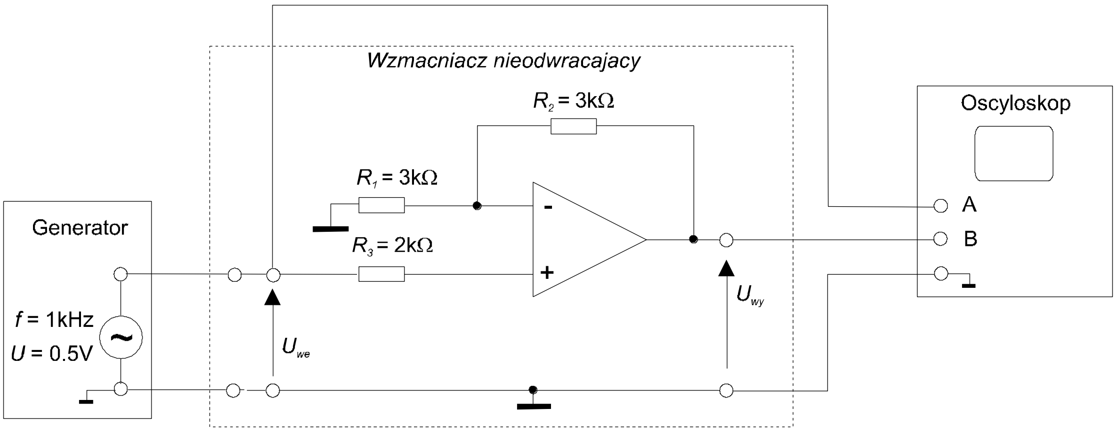
– Change the values of resistors $R_1$ and $R_2$ according to table 9.1. Connect resistor $R_3$ equal to the parallel connection of resistance $R_1$ and $R_2$ (or connect two resistors in parallel with the same values as $R_1$ and $R_2$). Giving at the input of the amplifier a sine signal with an amplitude $U_{we}$ = 0.5 V and frequencies $f$ = 1 kHz measure the amplitudes of the output voltages $U_{wy}$ and write the results in the table.

Table 9.1. Testing of the inverting amplifier.

| $R_1$ [kΩ] | $R_2$ [kΩ] | $k_u = -\frac{R_2}{R_1}$ | $U_{we}$ [V] | $U_{wy}$ [V] | $k_u = \frac{U_{wy}}{U_{we}}$ |
|---|---|---|---|---|---|
| 3 | 6 | | | | |
| 3 | 3 | | | | |
| 3 | 9 | | | | |
| 2 | 3 | | | | |
| 2 | 6 | | | | |
| 2 | 9 | | | | |

## 9.3.2. Non-inverting amplifier test.

– Connect the measuring system from Fig. 9.3.2 where $R_1$=3 kΩ, $R_2$=6 kΩ $R_3$=2 kΩ. Redraw the diagram of the non-inverter amplifier. At the input of the amplifier, give the generator a sinusoidal signal with an amplitude $U_{we}$ = 0.5 V and frequencies $f$ =1 kHz.




Rys.9.3.2. A system for testing a non-inverting amplifier

– Redraw the waveforms of the input and output signals. *(Pay attention to phase shift between signals).* Measure the output voltage amplitude $U_{wy}$ and write to table 9.2. Calculate the amplification based on the observed waveforms:

$$k_u = \frac{U_{wy}}{U_{we}}$$

– Check if the value of the calculated gain is similar to the value of the system gain calculated from the formula:

$$k_u = 1 + \frac{R_2}{R_1}$$

– Change the values of resistors $R_1$ and $R_2$ according to table 9.2 and $R_3$ should always be 2 kΩ. Giving at the input of the amplifier a sine signal with an amplitude $U_{we}$ = 0.5 V and frequencies $f$ = 1 kHz measure the amplitudes of the output voltages $U_{wy}$ and write the results in the table.

Table 9.2. Testing of non-inverting amplifier.

| $R_1$ [kΩ] | $R_2$ [kΩ] | $k_u = 1 + \frac{R_2}{R_1}$ | $U_{we}$ [V] | $U_{wy}$ [V] | $k_u = \frac{U_{wy}}{U_{we}}$ |
|---|---|---|---|---|---|
| 3 | 6 | | | | |
| 3 | 3 | | | | |
| 3 | 9 | | | | |
| 2 | 3 | | | | |
| 2 | 6 | | | | |
| 2 | 9 | | | | |

### 9.3.3. Duplicate amplifier test

– Connect the measuring system from. Fig. 9.3.3. where $R_2$ = 3 kΩ i $R_3$ = 2 kΩ. Redraw the diagram of the duplicate amplifier. At the input of the amplifier, give the generator a sinusoidal signal with an amplitude $U_{we}$ = 0.5 V and frequencies $f$ =1 kHz

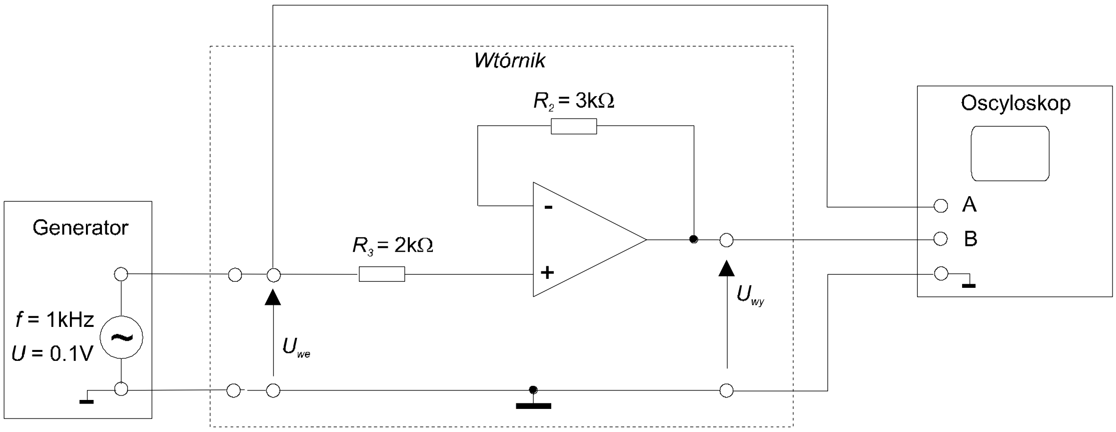



Fig. 9.3.3. A duplicate test system

– Redraw the waveforms of the input and output signals. Measure the output voltage amplitude $U_{wy}$ and write to table 9.3. Calculate the amplification based on the observed waveforms.

$$k_u = \frac{U_{wy}}{U_{we}}$$

– Check if the value of the calculated gain is similar to the value of the system gain calculated from the formula:

$$k_u = \lim_{R_1 \to \infty} \frac{R_1 + R_2}{R_1}$$

– Change the values of resistors $R_2$ = 6 kΩ, 9 kΩ according to table 9.3 with an unchanged input voltage of $U_{we}$ = 0.1 V. Giving a sinusoidal signal with the frequency f = 1 kHz to the input of the amplifier, measure the amplitudes of the output voltages $U_{wy}$ and write the results into the table.

– Set $R_2$ = 3 kΩ. Change the amplitude of the input voltage $U_{we}$ = 0.2V, 0.3V, 0.5V, (according to table 9.3.). Measure the amplitudes of the output voltages $U_{wy}$ and write the results in the table.

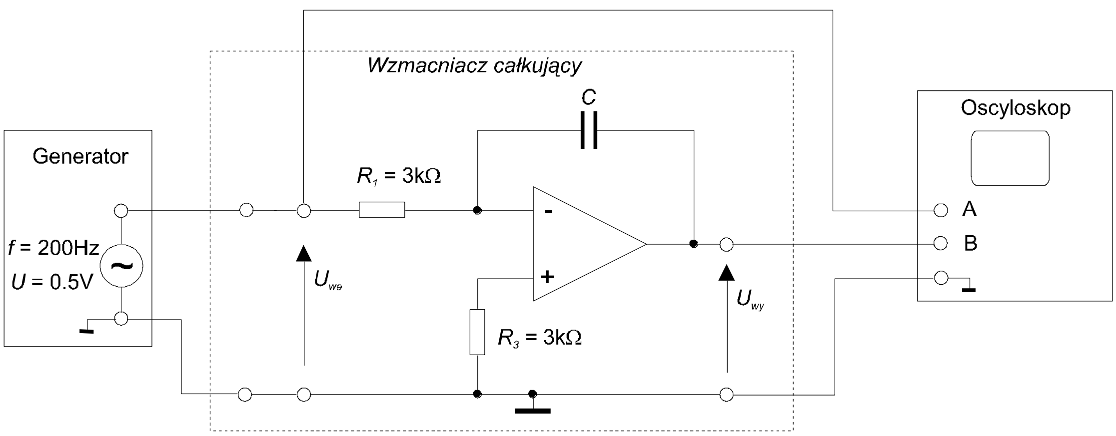
Tabele 9.3. Duplicate amplifier test

| $R_2$ [kΩ] | $k_u = \lim_{R_1 \to \infty}\left(1 + \frac{R_2}{R_1}\right)$ | $U_{we}$ [V] | $U_{wy}$ [V] | $k_u = \frac{U_{wy}}{U_{we}}$ |
|---|---|---|---|---|
| 3 | | 0.1 | | |
| 6 | | 0.1 | | |
| 9 | | 0.1 | | |
| 3 | | 0.2 | | |
| 3 | | 0.3 | | |
| 3 | | 0.5 | | |

**9.3.4. Integrator (integrating system) test.**

– Connect one of the measuring systems from Fig. 9.3.4. (according to the instructor's instructions). Redraw the integral circuit diagram. At the input of the integrator, give the generator a sinusoidal signal with an amplitude $U_{we}$ = 0.5 V and frequencies:
  a) for the integral circuit built on the inverting input $f$ = 200 Hz,
  b) for the integral circuit built on the non-inverting input $f$ = 1000 Hz,

**a)**




**b)**

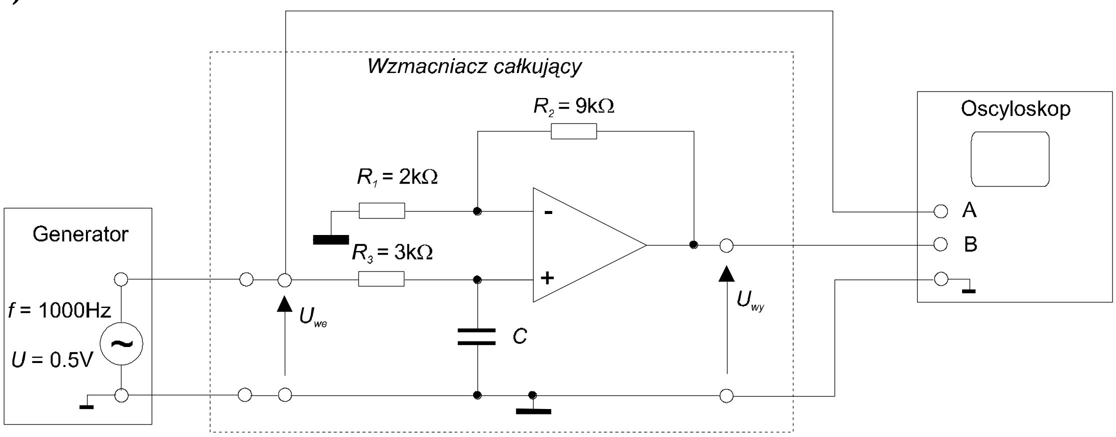



Fig. 9.3.4. The integrator test system a) on the inverting input, b) on the non-inverting input.

– Redraw the waveforms of the input and output signals. Based on the observed waveforms, check if the system is integrating the input signal:

$$U_{wy} = \int U_{we}(t)dt$$

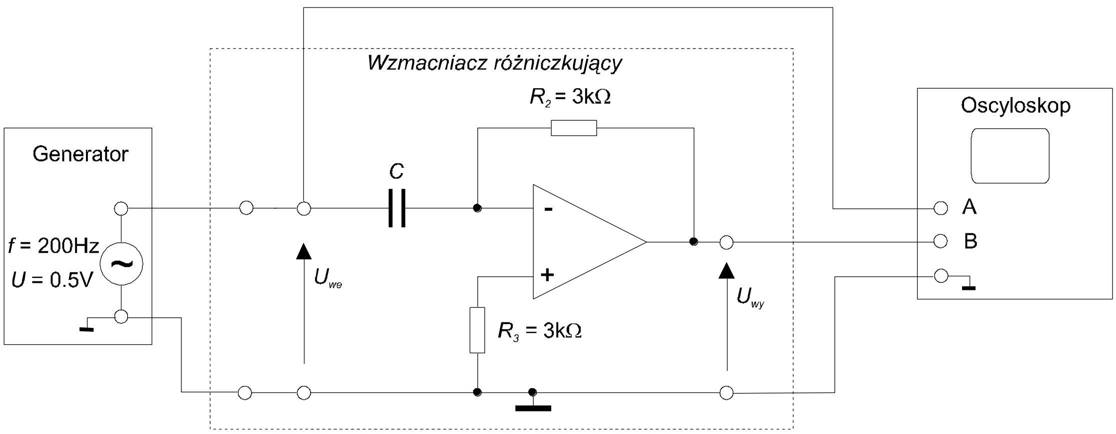
– Change the shape of the input signal in sequence:
  a. Rectangular
  b. Triangular.
– Redraw the input and output signals. Based on the observed waveforms, check if the system is integrating the input signal.

*Note: one period of the rectangular signal and the triangular input voltage should be divided into two sections and saved in the form of a mathematical function. Then compare with equally divided and saved signals on the output of the integral circuit*

### 9.3.5. Testing the differentiate system

– Connect one of the measuring systems from Fig. 9.3.5. (according to the instructor's instructions). Redraw the differentiate circuit diagram. At the input of the differentiate, give the generator a sinusoidal signal with an amplitude $U_{we}$ = 0.5 V and frequencies:
  a) for the differential circuit built on the inverting input $f$ = 200 Hz,
  b) for the differential circuit built on the non-inverting input $f$ = 1000 Hz,

**a)**




**b)**

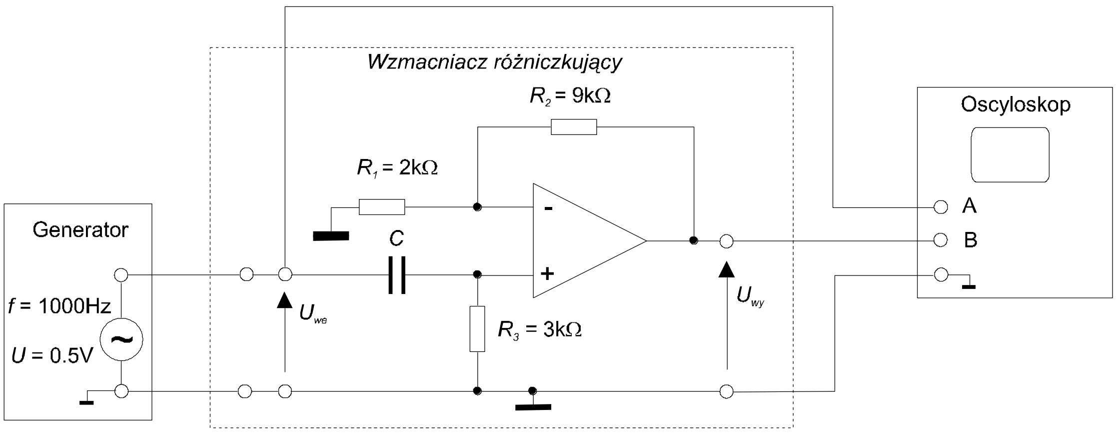



Fig. 9.3.5. System for testing the differentiator: a) on the inverting input, b) on the non-inverting input.

– Redraw the input and output signals. Based on the observed waveforms, check if the system performs differentiation of the input signal:

$$U_{wy} = \frac{dU_{we}(t)}{dt}$$

– Change the shape of the input signal in sequence:
  – a. Rectangular
  – b. Triangular.
– Redraw the input and output signals. Based on the observed waveforms, check whether the system performs differentiation of the input signal.

*Note: one period of the rectangular signal and the triangular input voltage should be divided into two sections and saved in the form of a mathematical function. Then compare with equally divided and saved signals at the output of the differentiator.*

### 9.3.6 The adder amplifier test.

- Connect the measuring system from fig. 9.3.6. where $R_{11}$ = $R_{12}$ = 3 kΩ, $R_2$= 3 kΩ $R_3$ = 2 kΩ. Redraw the sum circuit diagram. At the input of the system, give two sinusoidal signals with frequency from the generator $f$ = 1 kHz and the same amplitudes $U_{we1} = U_{we2}$ = 0.1 V.

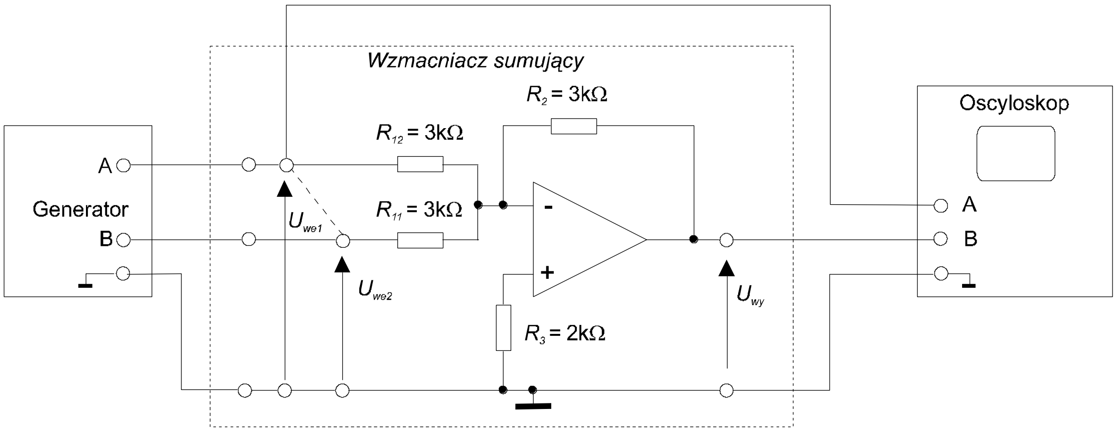



Fig. 9.3.6. A system for analyzing the sumator.

- Redraw the input voltage waveforms $U_{we1}$ i $U_{we2}$ and output voltage waveforms $U_{wy}$. *(Pay attention to phase shift between signals)*. Measure the output voltage amplitude $U_{wy}$ and write to tab. 9.6. Based on the observed waveforms, calculate the amplitude of the output voltage $U_{wy}$ which is the sum of the amplitudes of the input voltages $U_{we1}$ i $U_{we2}$:

$$U_{wy} = U_{we1} + U_{we2}$$

- Check if the value of the calculated gain is similar to the value of the system gain calculated from the formula:

$$U_{wy} = -R_2\left(\frac{U_{we1}}{R_{11}} + \frac{U_{we2}}{R_{12}}\right)$$

- Change the output voltage amplitudes $U_{we1}$ i $U_{we2}$ according to tab. 9.6. Measure input voltage amplitudes $U_{wy}$ and write results to table.
- Set resistor $R_2$= 6 kΩ As in the previous point change the amplitudes of input voltages $U_{we1}$ i $U_{we2}$ according to table 9.6. Measure the output voltage amplitude $U_{wy}$ and write to table.

Table 9.6. Adderr testing

| $R_{11}$ =$R_{12}$ [kΩ] | $R_2$ [kΩ] | $U_{we1}$ [V] | $U_{we2}$ [V] | $U_{wy}$ [V] | $U_{wy} = -R_2\left(\frac{U_{we1}}{R_{11}} + \frac{U_{we2}}{R_{12}}\right)$ |
|---|---|---|---|---|---|
| 3 | 3 | 0.1 | 0.1 | | |
| 3 | 3 | 0.1 | 0.2 | | |
| 3 | 3 | 0.2 | 0.2 | | |
| 3 | 6 | 0.1 | 0.1 | | |
| 3 | 6 | 0.1 | 0.2 | | |
| 3 | 6 | 0.2 | 0.2 | | |

### 9.3.7. The differential system test.

– Connect the measuring system from fig. 9.3.7 where. $R_1$ = $R_2$ = $R_3$= $R_4$ = 3 kΩ. Redraw the differential circuit diagram. At the input of the system, give two sinusoidal signals with frequency from the generator $f$ = 1 kHz and amplitudes $U_{we1}$ = 0.1 V i $U_{we2}$ = 0.2 V.

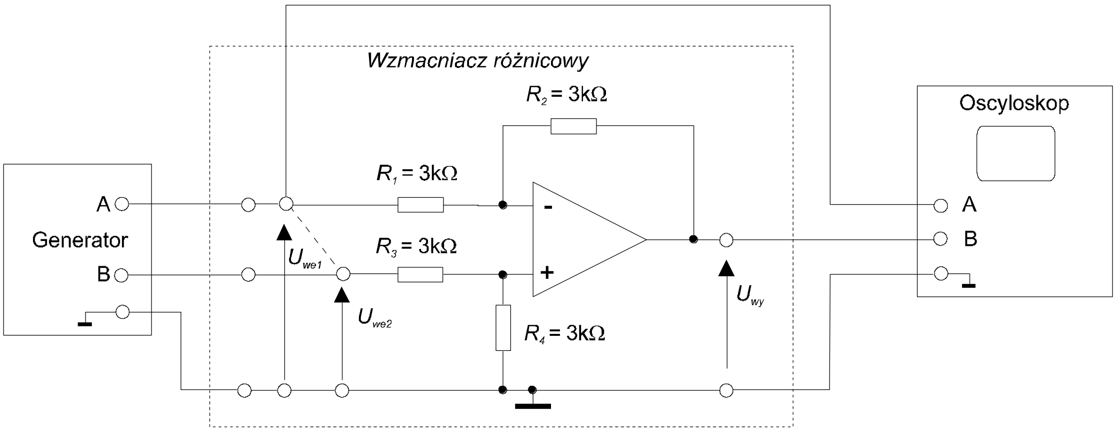



Fig. 9.3.7. System for testing the differential system.

– Redraw the input voltage waveforms $U_{we1}$ i $U_{we2}$ and output voltage waveforms $U_{wy}$. *(Pay attention to phase shift between signals).* Measure the output voltage amplitude $U_{wy}$ and write to tab. 9.7. Based on the observed waveforms, calculate the amplitude of the output voltage $U_{wy}$ being the difference in the amplitudes of the input voltages $U_{we2}$ i $U_{we1}$:

$$U_{wy} = U_{we2} - U_{we1}$$

– Check if the value of the calculated gain is similar to the value of the system gain calculated from the formula:

$$U_{wy} = \frac{R_2}{R_1}\left(U_{we2} - U_{we1}\right)$$

– Change the output voltage amplitudes $U_{we1}$ i $U_{we2}$ according to tab. 9.7. Measure iutput voltage amplitudes $U_{wy}$ and write results to table.
– Set resistors $R_2$ = $R_4$ = 6 kΩ. As in the previous point change the amplitudes of input voltages $U_{we1}$ i $U_{we2}$ according to table 9.7. Measure the output voltage amplitude $U_{wy}$ and write to table.

Table 9.7. Differential system test.

| $R_1$ =$R_3$ [kΩ] | $R_2$ =$R_4$[kΩ] | $U_{we2}$ [V] | $U_{we1}$ [V] | $U_{wy}$ [V] | $U_{wy} = \frac{R_2}{R_1}\left(U_{we2} - U_{we1}\right)$ |
|---|---|---|---|---|---|
| 3 | 3 | 0.2 | 0.1 | | |
| 3 | 3 | 0.2 | 0.2 | | |
| 3 | 3 | 0.2 | 0.3 | | |
| 3 | 6 | 0.2 | 0.1 | | |
| 3 | 6 | 0.2 | 0.2 | | |
| 3 | 6 | 0.2 | 0.3 | | |

## 9.4. 8.4. Assessment conditions

In order to pass the exercise it is necessary to:

- writing a short test at the beginning of the class with a positive result;
- doing the exercise;
- preparing a report according to the instructions below;
- defending the report on the next exercise;
- confirmation of mastering the scope of the exercise during the last final classes;

The report should be included:

- diagrams of all tested operational amplifier circuits.
- a completed measurement sheet.
- input signals which were connected to the tested circuits and signals observed at the outputs of these circuits,
- calculated gains according to given formulas and calculated gains based on exaggerated waveforms,
- mathematical justifications of integration and differentiation of signals,
- own conclusions and observations.

### 9.5.1. Basics of operation

The name of the operational amplifier concerned initially the amplification circuits used in electronic analog machines to perform mathematical operations such as addition, subtraction, integration and differentiation of electrical signals. Thanks to its universal application, it is now the basic, most common analog integrated circuit. An increase in interest in operational amplifiers followed the introduction of amplifiers in the form of mass-produced monolithic chips with very good properties, small size and low price (in 2000, the retail cost of one arrangement was at the level of PLN 1).

Currently, the term operational amplifier means an amplifier characterized by a very high voltage gain, and is usually intended to work with an external negative feedback circuit. It is the properties of feedback that determine the properties of the entire system. In the simplest case, feedback is the signal supply through a series of resistors or directly from the output to one of the inputs.

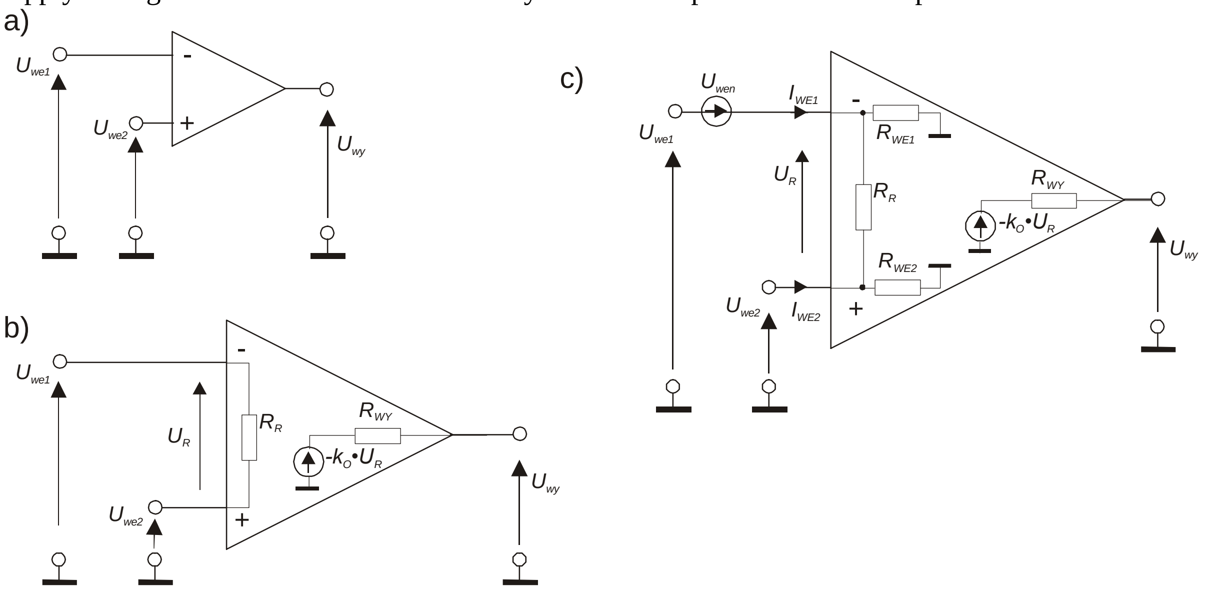



Fig. 9.5.1. Operational amplifier a) graphic symbol, b) the simplest substitute pattern, c) substitute scheme.

The operational amplifier has a symmetrical (differential) input and an asymmetrical output (Fig.9.5.1.a). An input marked with the plus "+" is called the non-inverting (non-inversion) input, and the input marked with the minus "-" is called the inverting (inversion) input. If a sinusoidal voltage is applied to the reversing input "-", the phase shift between the $U_{WE1}$ input and the $U_{WY}$ output signals will be 180°, i.e. the output signal will be "reversed" in relation to the input signal. If the same voltage is applied to the "+" non-inverting input, the phase shift between the signals will be 0, that is, the input signals $U_{WE2}$ and the output $U_{WY}$ will be "compatible" in the phase.

Voltage being the difference of input voltages $U_{WE1}$ i $U_{WE2}$ we call the differential voltage. $U_R$. The voltage at the output of the amplifier is directly proportional to the value of the differential voltage, i.e. to the difference of the input voltages according to the dependence:

$$\boxed{U_{WY} = k_O \cdot (U_{WE2} - U_{WE1}) = k_O \cdot U_R} \qquad (9.5.1)$$

where:

- $U_{WE2}$, - input voltages connected to the non-inverting input „+”
- $U_{WE1}$, - input voltages connected to the inverting input „-”
- $U_R$ - differential voltage,
- $k_O$ - voltage amplification of the operational amplifier,
- $U_{WY}$ - output voltage of the operational amplifier.

### 9.5.2. Parameters of the ideal operational amplifier.

The ideal operational amplifier should have the following properties:
- infinite amplification with an open feedback loop ($k_O \to \infty$),
- an infinitely wide frequency response band (bandwidth),
- infinitely high input impedance, both between the inverting and non-inverting inputs ($R_R \to \infty$) as between each of the inputs and the ground ($R_{WE1} \to \infty$, $R_{WE2} \to \infty$),
- output resistance (impedance) equal to zero ($R_{WY} = 0$),
- output voltage equal to zero at equalisation of input voltages ($U_{WY} = 0$, then $U_{WE1}, = U_{WE2}$),
- infinitely high permissible output current ($I_{WYmax} \to \infty$),
- zero input currents ($I_{WE1max} = 0$, $I_{WE2max} = 0$), also called input polarity currents,
- a perfectly differential amplification, i.e. an infinitely large coefficient of attenuation signal (non-differential), (WTSN $\to \infty$),
- maintaining the above properties when temperature changes.

Explain the concept of the co-current signal attenuation coefficient (also known as undifferentiated). Well, let's assume that the operational amplifier has, for example, a high resistive $R_{WE}$ resistance of approx. 1 MΩ.

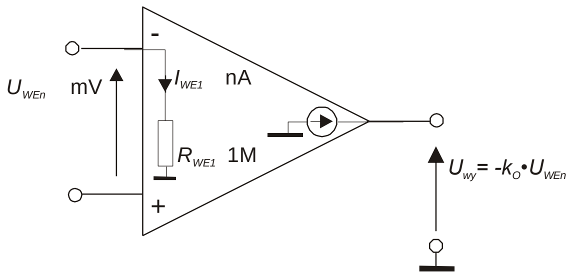



Fig. 9.5.2. Illustration of the impact of voltage imbalance.

The input stages of the operational amplifiers are based on transistors whose zero currents, i.e. those that occur despite the absence of any input signal, are very small with values of several nanoampers. At the input of the amplifier, a voltage will appear called the unbalance voltage $U_{WEn}$, equal to the product of the input resistance $R_{WE}$ and the input polarization current $I_{WE}$ (the zero current of the operational amplifier). The value of this voltage will be approx.0.001V.

$$U_{WEn} = I_{WE} \cdot R_{WE} \approx 0.001\ V \qquad (9.5.2)$$

This low voltage may in many cases overlap with a useful signal fed to the amplifier input. Additionally, amplified by the voltage amplification $k_O$ of the operational amplifier, it can "falsify" the value of the output voltage. Note that such an amplified $k_O U_{Wen}$ unbalance voltage can appear at the output also when we give the same signal to both inputs of the operational amplifier. According to the formula 9.5.1, the output voltage should then be zero, but in practice a small voltage appears. For this reason, in the operational amplifiers, special systems are built to dampen the effect of the voltage of imbalance. The effectiveness of these damping systems is determined by the damping ratio of the non-differential signal (co-current) - WTSN.

In today's WTSN amplifiers it is so large that in many systems we can ignore the impact of imbalance.. However, when designing high accuracy systems (eg. measuring amplifiers for small signals) it should be remembered.

In order to analyze many of the amplifier's circuits, two simple rules should be applied:

1. **First, the input current of both inputs is equal to zero, thanks to the input resistance of the amplifier close to infinity. ($R_{WE1}$ ,$R_{WE2}$ $R_R \to \infty$).**
2. **Secondly, the negative feedback will always maintain the voltage difference $U_R = U_{WE2} - U_{WE1}$ close to zero, because with a very large gain $k_U$ at the output of the amplifier should be finalized voltage output $U_{WY}$**

### 9.5.3. Parameters of the actual operational amplifier.

While analyzing the operation of the basic operational amplifier systems, assumptions are made that the properties of the amplifier are ideal. Such idealization is very useful because it allows a simplified analysis of the operation of systems with a relatively small error. In the more precise analysis, however, it is necessary to take into account the limitations resulting from the properties of the actual, non-ideal operational amplifier used in practice.

The basic parameters of the real amplifier are:

1) Differential voltage gain with open feedback loop $k_O$;
2) Differential input impedance $R_R$ ($Z_R$);
3) Input resistances (impedances) (resistance between input "-" and ground, and between "+" input and ground) $R_{WE1}$ i $R_{WE2}$,, ($Z_{WE1}$ i $Z_{WE2}$);
4) Output resistance (impedance) $R_{WY}$ ($Z_{WY}$);
5) Input unbalance voltage $U_{Wen}$, input unbalance current, input polarization currents, their time and temperature drift;
6) No-difference (co-current) attenuation coefficient WTSN;
7) Limit parameters:
– maximum input voltage $U_{WEmax}$,
– maximum differential input voltage $U_{Rmax}$,
– maximum output voltage $U_{WYmax}$;
– maximum output current $I_{WYmax}$;
8) Voltage $U_Z$ and power $P_Z$ supply;
9) Bandwidth $f_g$;
10) Pulse parameters of the amplifier (rise time $t_n$, speed of rise $S$, overshoot $\delta_u$);

One of the most popular operational amplifiers is the amplifier with the symbol μA 741. Table 9.5.1 gives some of its parameters.

Table 9.5.1 Parameters of the operational amplifier μA 741

| Name | Symbol | Value |
|---|---|---|
| Voltage amplification with an open feedback loop | $k_O$ | $2 \cdot 10^5$ [V/V] |
| No-difference signal attenuation coefficient | WTSN | 90 [dB] |
| Differential input resistance | $R_R$ | 2 [MΩ] |
| Output resistance | $R_{WY}$ | 75 [Ω] |
| Input unbalance voltage | $U_{WEN}$ | 1 [mV] |
| Input unbalance current | $I_{WEN}$ | 20 [nA] |
| Temperature coefficient $U_{WEN}$ | A | 7 [μV/K] |
| Maximum input voltage | $U_{WEmax}$ | ± 15 [V] |
| Maximum differential input voltage | $U_{Rmax}$ | ± 30 [V] |
| Maximum output voltage | $U_{WYymax}$ | ± 14 [V] |
| Upper frequencies | $f_g$ | 1 [MHz] |
| Voltage of supply | $U_Z$ | ± 15 [V] |
| Power of supply | $P_Z$ | 45 [mW] |

## 9.5.4. An inverting amplifier.

The inverting amplifier system is shown in Figure 9.5.3. Negative feedback was applied in the system by providing the voltage from the output to the reverting input via the resistance $R_2$. Let us assume that the voltage gain of the amplifier with the open loop has an infinitely large value ($k_O \rightarrow \infty$), the input polarizing currents are equal to zero and the input differential resistance $R_R$. is very big. With these assumptions it is easy to see that the input differential voltage UR is close to zero, because:

$$U_R = \frac{U_{WY}}{k_O} \rightarrow 0 \qquad (9.5.3)$$

if $k_O \rightarrow \infty$.

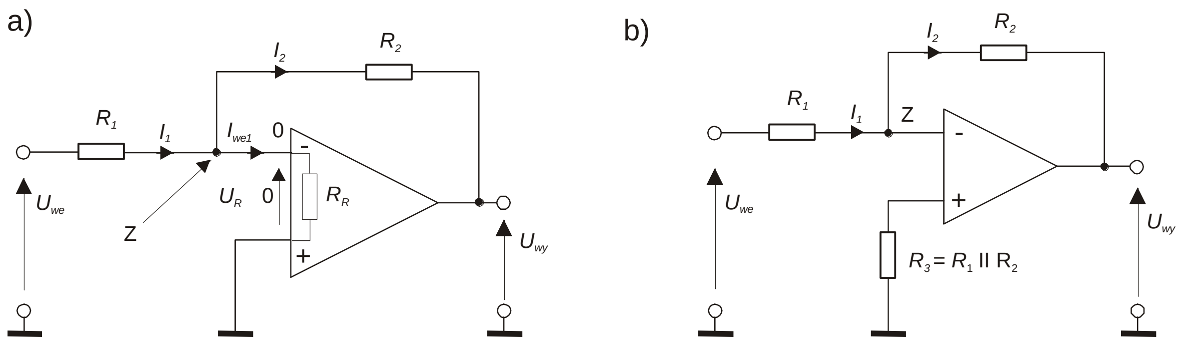



Fig. 9.5.3. Inverting amplifier a) basic system, b) practical system.

The electrical potential at point Z is therefore approximately equal to the potential of the non-inverting "+" to which the ground has been connected, i.e. the potential of 0V. Therefore, the Z point also has a potential approximately equal to 0V. The Z point is often called the point of "virtual ground". Because we assume that the input currents of the amplifier are equal to zero, the current flowing through the resistor $R_1$ flows through $R_2$, i.e.

$$I_2 = I_1 \tag{9.5.4}$$

Taking into account that the potential of the Z point equals zero from Kirchhoff's law, the following equation is obtained:

$$U_{WE} = I_1 \cdot R_1, \quad U_{WY} = -I_2 \cdot R_2 \tag{9.5.5}$$

From the formulas 9.5.4 and 9.5.5 we get the amplification of the entire invert amplifier system:

$$\boxed{k_U = \frac{U_{WY}}{U_{WE}} = -\frac{R_2}{R_1}} \tag{9.5.6}$$

In the case when we choose $R_2 = R_1$, we get an amplifier that repeats the signal at the output but inverted in phase by 180 degrees.

In the general case, when instead of the resistance $R_1$ and $R_2$ we use the impedance $Z_1$ and $Z_2$ we get:

$$k_U = -\frac{Z_2}{Z_1} \tag{9.5.7}$$

Until now, we have considered the case when the non-inverting input "+" was connected directly to the ground. However, in practice, a resistance $R_3$ is connected between the "+" input and the ground, which significantly improves the amplifier's stability. The value of resistor $R_3$ in real conditions is chosen equal to the resistance of the parallel connection $R_1$ and $R_2$:

$$R_3 = R_1 \| R_2 = \frac{R_1 \cdot R_2}{R_1 + R_2} \tag{9.5.8}$$

This results in the best error compensation due to the non-balancing voltage and the error due to the non-zero input currents of the amplifier. Due to the very low value of this current, only the $R_3$ resistance has no significant effect on the parameters of the entire amplification system and the gain formulas remains unchanged.

## 9.5.5. A non-inverting amplifier

In the non-inverting amplifier system (Fig. 9.5.4.a.), the input signal is applied to the non-inverting input through resistor $R_3$, and the output voltage is fed to the input that does not revert through the voltage divider $R_1$ and $R_2$, thus achieving negative feedback. Also in this case, to partially compensate for the unbalance voltage and the input polarization currents, the resistance $R_3$ should be equal to the resistance of the parallel connection $R_1$ and $R_2$

Similarly to the analysis of the previous system, we assume that $U_R$ is approximately equal to zero, the input currents of the amplifier are also equal to zero and the voltage gain $k_O$ is infinitely large. The system has no virtual ground point, the voltage at the "+" and "-" inputs is approximately equal to the $U_{WE}$ input voltage. The Kirchhoff law gives us:

$$U_{WE} = I_1 \cdot R_1$$
$$U_{WE} = I_2 \cdot R_2 + U_{WY} \tag{9.5.9}$$

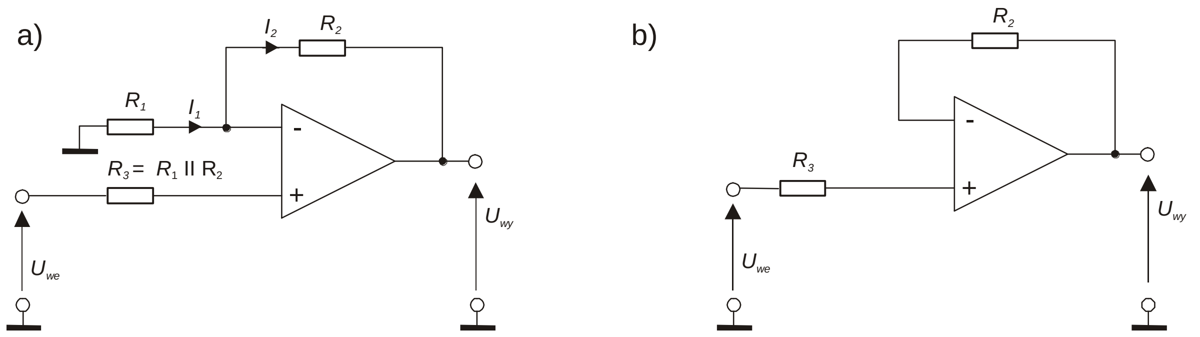



Fig. 9.5.4. a) Non-inverting amplifier, b) Duplicator.

In the case of an ideal amplifier, the $I_1$ and $I_2$ currents are equal. After transformations, we obtain a formula for voltage amplification of non-inverting amplifier:

$$\boxed{k_U = \frac{U_{WY}}{U_{WE}} = \frac{R_2 + R_1}{R_1} = 1 + \frac{R_2}{R_1}} \tag{9.5.10}$$

The gain value depends only on the ratio of the resistance in the feedback system and is always equal to or greater than one.

## 9.5.6. Voltage duplicator.

Consider what will happen if in the non-inverting amplifier system you disconnect the resistances $R_1$, that is, when its value will strive for infinity ($R_1 \to \infty$). gain such a system will be:

$$\boxed{k_U = \lim_{R_1 \to \infty}\left(1 + \frac{R_2}{R_1}\right) = 1} \tag{9.5.11}$$

We get a system that accurately repeats the input signal, hence its name (Fig. 9.4.b.). Voltage duplicator has a very high input resistance similar to the resistance of the operational amplifier and very low output resistance $k_U$ times smaller than the output resistance of the operational amplifier. The duplicator is used in systems where we want to separate the signal source from the system where the signal is used.

## 9.5.7. The integration amplifier.

When in the inverting amplifier we replace the resistance $R_2$ with the capacitor $C$, we get a system called integration amplifier, or integrator Fig 9.5.5.a.

Assuming the ideal properties of the operational amplifier, the Z point is a virtual ground point and the voltage on the capacitor is equal to the inverted output voltage. The current $I_2$ in the capacitor is expressed by the formula:

$$I_2(t) = C \cdot \frac{d(-U_{WY})}{dt} \tag{9.5.12}$$

The current $I_1$ flowing though resistor $R_1$ is

$$I_1 = \frac{U_{WE}}{R_1} \tag{9.5.13}$$

From equality of currents $I_1 = I_2$ it follows that

$$C \cdot \frac{d(-U_{WY})}{dt} = \frac{U_{WE}}{R_1} \tag{9.5.14}$$

By integrating both sides of the above equation, the voltage dependence on the inverter integrator output is obtained from the input signal value:

$$\boxed{U_{WY}(t) = -\frac{1}{R_1 C}\int_0^t U_{WE}(t)dt + U_{WY}(0)} \tag{9.5.15}$$

where $U_{WY}(0)$ is the initial voltage on the capacitor $C$ at the initial moment $t = 0$. As can be seen from the above formula, the system performs integration of the input signal.

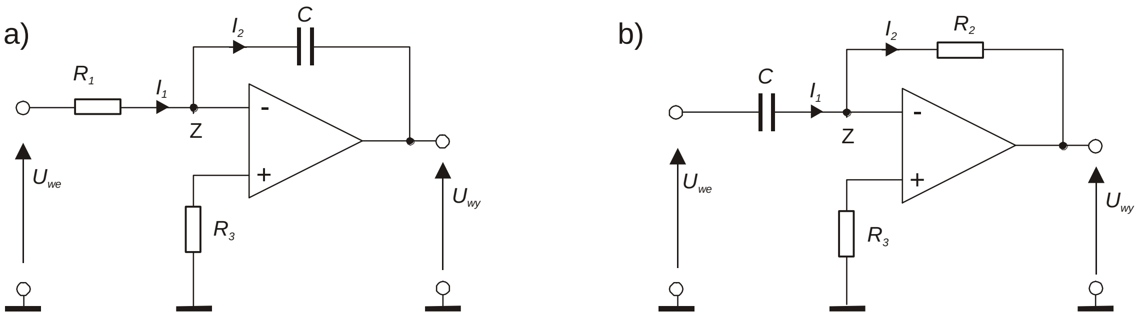



Fig. 9.5.5. Amplifier a) integral (integrator), b) derivative (differential).

### 9.5.8. Differentiate amplifier.

When in the inverting amplifier we replace the resistance $R_1$ with the capacitor $C$, we keep the system called the differential circuit Fig. 9.5.b. The current $I_1$ flowing through the capacitor is expressed by the formula:

$$I_1(t) = C \cdot \frac{dU_{WE}}{dt} \tag{9.5.16}$$

From equality of currents $I_1 = I_2$ it follows that

$$C \cdot \frac{dU_{WE}}{dt} = \frac{-U_{WY}}{R_2} \tag{9.5.17}$$

After simple transformations, we get:

$$\boxed{U_{WY} = -R_2 C \frac{dU_{WE}}{dt}} \tag{9.5.18}$$

The above formula shows that the system performs differentiation of the input signal.

### 9.5.9. Sum amplifier.

By means of an operational amplifier, it is easy to realize the summation of the voltages of many signals by means of the circuit of Fig. 9.5.6





(9.20)

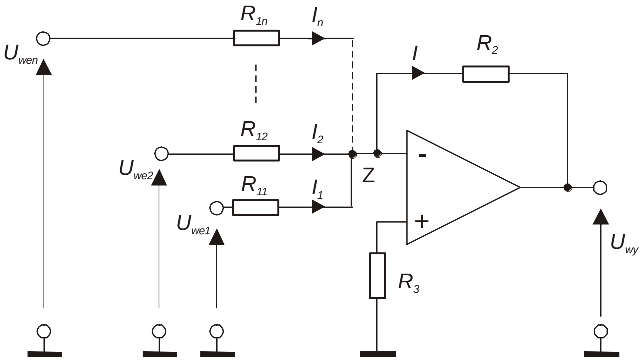



Fig. 9.5.6. Adder amplifier.

The different signals $U_{WE1} \div U_{WEn}$ are connect to invert input by resistance $R_1 \div R_n$. The Z point is the virtual ground point. Assuming that the input currents of the operational amplifier are negligible in relation to the currents $I_1 \div I_n$, the current flowing through the resistances $R_2$ is equal to the sum of the currents $I_1 \div I_n$:

$$I = I_1 + I_2 + ... + I_n \tag{9.5.19}$$

Since the potential of the point Z is equal to zero, each of the input currents is expressed by the formula:

$$I_k = \frac{U_k}{R_{1k}} \tag{9.5.20}$$

After similar transformations as in the analysis of the reversing amplifier, we get the formula for the output voltage:

$$\boxed{U_{WY} = -R_2\left(\frac{U_{WE1}}{R_{11}} + \frac{U_{WE2}}{R_{112}} + ... + \frac{U_{WEn}}{R_{11n}}\right)} \tag{9.5.21}$$

Of course, when we use resistances $R_1 \div R_n$ with the same values equal to $R_1$ we get directly the summation of voltages.

$$U_{WY} = -\frac{R_2}{R_1}\left(U_{WE1} + U_{WE2} + ... + U_{WEn}\right) \tag{9.5.22}$$

## 9.5.10. The differential amplifier.

On fig. 9.5.7.a. a system called a differential amplifier is presented.

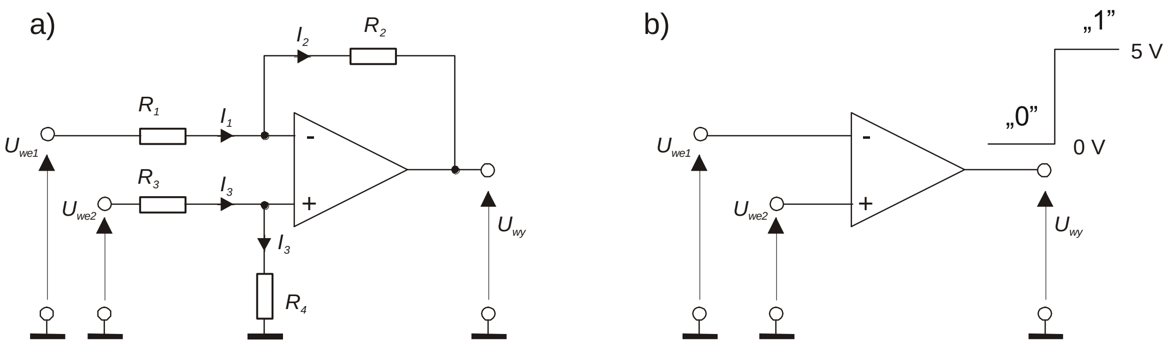



Fig. 9.5.7 a) Differential amplifier b) comparator.

Assuming that the operational amplifier is characterized by ideal properties and by determining $U_+$ and $U_-$ voltage on the inverting and non-inverting inputs, we can write the current balance:

$$I_1 = \frac{U_{WE2} - U_-}{R_1}, \qquad I_3 = \frac{U_{WE1} - U_+}{R_3},$$
$$I_2 = \frac{U_{WY} - U_-}{R_2} \qquad I_3 = \frac{U_+}{R_4} \tag{9.5.23}$$

After transformation we get:

$$U_{WY} = \left(\frac{R_1 + R_2}{R_3 + R_4}\right) \cdot \frac{R_4}{R_1} \cdot U_{WE1} - \frac{R_2}{R_1} U_{WE2} \tag{9.5.24}$$

When we select the resistances so that the condition is met:

$$\frac{R_2}{R_1} = \frac{R_4}{R_3} \tag{9.5.25}$$

we get:

$$U_{WY} = \frac{R_2}{R_1} \cdot \left(U_{WE1} - U_{WE2}\right) \tag{9.5.26}$$

This amplifier realizes the subtraction of signals.

A special case of the differential amplifier is the comparator figure 9.5.7.b. The amplifier has no negative feedback. The $U_{WE1}$ input voltage is fed directly to the inverting input "-". An adjustable reference voltage $U_{WE2}$ is applied to the non-inverting input. At the output of the operational amplifier will appear $U_{WY}$ voltage:

$$U_{WY} = k_O \cdot (U_{WE2} - U_{WE1}) \tag{9.5.27}$$

If we assume that the amplification of the operational amplifier with the open feedback loop tends to infinity $k_O \to \infty$, we will get it on the output of the amplifier:

$$U_{WY} = \infty \quad \text{dla} \quad U_{WE2} > U_{WE1}$$
$$U_{WY} = -\infty \quad \text{dla} \quad U_{WE2} < U_{WE1} \tag{9.5.28}$$

In practice, we will never receive an infinitely great tension. In the case of comparators, the extreme voltages are strictly defined voltages, for example 5V corresponding to $\infty$ and 0V corresponding $-\infty$. If we additionally mark the level 0V as the logic state "0" and the level 5V as the logic state "1", then we will notice that the comparator performs a logic function:

- if $U_{WE1}$ voltage is greater than the reference voltage $U_{WE2}$ ($U_{WE1} > U_{WE2}$ ) we have „0",
- if $U_{WE1}$ voltage is lower than the reference voltage $U_{WE2}$ ($U_{WE1} < U_{WE2}$ ) we have „1".

The comparator detects the "output" of the $U_{WE1}$ input voltage outside the set range (set with $U_{WE2}$ voltage). It is one of the bridges connecting analog and digital electronics.

Comparator applications are very diffrent. They are used in the input circuits of digital voltmeters. They are a basic element of analog-digital converters and systems analyzing pulse amplitudes.

## 9.5.11. Other uses of the operational amplifier.

It is difficult to list all the possible applications of an operational amplifier. Apart from those already mentioned, it is worth mentioning:

***Logarithm amplifier***. If in the invert amplifier system we replace resistance $R_2$ with an element whose current-voltage characteristic is in the form of an exponential function, then we obtain a logarithmic amplifier. The simplest element performing this function is the transistor. At the output a voltage proportional to the logarithmic input voltage appears ($U_{WY} \cong \ln U_{WE}$).

***Exponential (power) amplifier.*** Replacing the resistance of $R_1$ with the transistor in the inverting amplifier, we get a exponential amplifier. Switching the transistor in places, we get a system with the inverse characteristic in relation to the logarithm amplifier ($U_{WY} \cong \exp(U_{WE})$).

***Active filters***. In the inverting amplifier system, replacing resistances R1 and R2 with properly constructed resistance circuits and capacitance we can get filters with very good properties. They are characterized by very good selectivity and additionally they can amplify the filtered signal.

***Generators***. By applying positive feedback, we can cause spontaneous generation of various waveforms, from sinusoidal to complex waveforms of any type.

***Current-voltage converters.*** In the inverter amplifier system, the $I_{WE}$ current signal is fed directly to the "-" input. At the output we get a voltage directly proportional to the current flowing. $U_{WY}=-I_{WE}R_2$.

***Voltage-current converters.*** In the inverter amplifier system, the output of the system is located on the resistance $R_2$. The current flowing through the resistor $R_2$ is $I_{WY} = -U_{WE}/R_1$.

***Transformation systems***. By using a non-linear elements (diodes of various types, non-linear resistances) in the invert amplifier or non-inverting amplifier instead of $R_1 \div R_4$ resistance, we can perform any transformation of the input signals.