Lodz University of Technology
Institute of Physics

Laboratory of electronics

Exercise E08IFE

Operational Amplifier

Version 1.2 (16 April 2019)

Table of contents:

Before you start to perform an experiment you are obliged to have mastered the following theoretical subjects:

1. Types and mode of action of the feedback [1], [3], [4].
2. Structure, operation and properties of the differential amplifier [1÷5].
3. Properties of the ideal operational amplifier [1÷5].
4. Properties and applications of the practical operational amplifier [1÷5].

1. Purpose of the exercise

To understand and analyze the operations of practical operational amplifier.

2. Hazards

Type	Absence	Low	Medium	High
electrical radiation hazards		+		
optical radiation hazards	+			
mechanical hazards (including acoustic hazards, noise)	+			
electromagnetic radiation hazards (invisible)	+			
biological hazards	+			
ionizing radiation hazards	+			
chemical hazards	+			
thermal hazards (including explosion and fire)	+			

The cables with banana plugs are designed exclusively to used in low-voltage circuits – DO NOT CONNECT THEM TO THE MAINS SUPPLY 230 V.

3. Introduction

3.1. Theoretical basis

A typical operational amplifier (Op-Amp) is made up of three types of amplifier circuit: a differential amplifier, a voltage amplifier, and a push-pull amplifier. The parameters of op-amp is presented in Table 1.

Table 1. – Parameters of operational amplifier (Op-Amp) .

Parameters	The ideal Op-Amp	The practical Op-Amp
Open-loop voltage gain	∞	$10^5 \div 10^6$
Input impedance [Ω]	∞	$10^5 \div 10^8$
Output impedance [Ω]	0	$10 \div 100$
Common-mode rejection ratio (CMRR)	$1: \infty$	$1: 10^3 \div 1: 10^6$ ($60 \div 120$ dB)
Bandwidth [MHz]	$0 \div \infty$	$0 \div 500$
Output voltage [V]	$0 \div \pm \infty$	Limited by supply voltages

3.2. Description of measurement method

The Op-Amp is investigated in systems with negative feedback as inverting and non-inverting amplifier.

Measurements are performed both for DC and AC input voltages. The Adjustable Voltage Source and Function Generator provide the DC an AC signals to the Op-Amp. The kit of DMM's voltmeters shows the DC input and output voltages. For AC voltages the input and output signals are presented on the screen of Oscilloscope, which works in the DUAL mode.

The power supply with serial operating mode is adjusted to the symmetrical voltage ±20V and supplies the Op-Amp.

4. Available equipment

4.1. Experimental module

The experimental module is presented detailed in the chapter 5.

The measurement station includes a set of measuring equipment, which consists of the following devices:

- the laboratory power supply SPD3303D,
- the function generator DF1641B,
- the two-channel analogue oscilloscope GOS-620 or GOS-630,
- the multimeters: KT890, M-3800, M-4650, UT-804 or Protek 506.

The manuals of the above instruments are available on the Website [6].

An important component of measuring station is so-called Adjustable Voltage Source, which enable to apply the inflicted voltages to the input of amplifier.

4.2. Multimeters

DC or AC voltages can be measured using the following multimeters: KT890, M-3800, M-4650, UT-804 or Protek 506.

4.3. Power supply

The experimental module is powered by the laboratory power supply SPD3303D.

4.4. Function generator

As a source of sine signal the function generator DF1641B is used.

4.5. Oscilloscopes

The waveforms of the input and output of amplifiers can be observed on the two-channel analogue oscilloscope GOS-620 or GOS-630. At the request of the students the analogue oscilloscope can be replaced with the digital two-channel oscilloscope type SDS1052DL.

5. Experimental procedure

5.1. The inverting amplifier – basic version

(Connection diagrams are presented in Figures 1a and 1b and the experimental module is presented in Fig 1c).
Explanations: FG – functional generator, OSC – oscilloscope, CH1 and CH2 – channel inputs of oscilloscope.

Switch on the power supply in serial mode, adjust the symmetrical voltage to ±20V and turn off the CH1 and CH2 outputs of power supply.

5.1.1. The transfer characteristic of amplifier

1. Connect the circuit according to the diagrams presented in Figs. 1a and 1c. Set the switches R_3 and R_L to the "∞" position. Set the rotary function switch on DMM's voltmeters to the 20 DCV or 40 DCV (depending on type of multimeter).
2. Set the switches Z_1 and Z_2 to the "2" position (Fig.1c).
3. Set the rotary function switch on the Adjustable Power Supply to the "2" position (Fig. 1a).
4. After checking the system by the supervisor turn on the CH1 and CH2 outputs of the power supply.
5. Increasing the input voltage from –12V to +12V determine the dependence of input voltage on output voltage.
6. Record the obtained result on the data sheet in the Data Table A1.
7. Set the switches Z_1 and Z_2 according to the supervisor's order and repeat the procedure described in previous steps.

Data Table A1 / (A1$^{\#}$) – Inverting amplifier.

Z_1 / ($R_{S1}$$^{\#}$)	Z_2 / ($R_L$$^{\#}$)	Input voltage		Output voltage	
[kΩ]	[kΩ]	U_{IN} [V]	ΔU_{IN} [V]	U_{OUT} [V]	ΔU_{OUT} [V]

5.1.2. Measurement of the input impedance of the amplifier

1. Set the input voltage on the value for which the output voltage is near below 12V.
2. Remove the jumper from Input 1 position (Fig. 1c). Put the R_{S1} resistor instead of the jumper.
3. Measure the output voltage of amplifier without changing the input voltage.
4. Record the obtained result on the data sheet in the Data Table A1$^{\#}$.
5. Remove the R_{S1} resistor from input of amplifier.

5.1.3. Measurement of the output impedance of the amplifier

1. Insert the jumper to the Input 1 position (Fig. 1c).
2. Set the input voltage on the value for which the output voltage is near below 12V.
3. Measure the output voltage of amplifier for different positions of switch R_L.
4. Record the obtained result on the data sheet in the Data Table A1$^{\#}$.

5.1.4. Measurement of the bandwidth of amplifier

1. Remove the Adjustable Voltage Source and DMMs.
2. Connect the circuit according to the diagram given in Fig. 1b.
3. Select the sine waveform (without the DC OFFSET) by using the Function Select Switch on the Function Generator (FG) front panel and connect the output of FG to the both CH2 input of oscilloscope and input of amplifier (use T junction to divide the signal from the output of FG) (Fig. 1b and 1c).
4. Connect the output of amplifier to CH1 input of oscilloscope (Fig. 1b and 1c).
5. Set the switches: Z_1 to the "1" position, Z_2 to the "3" position, and R_L to the "∞" position.
6. Set the output frequency of Function Generator to approx. 500 kHz (0.5 MHz).
7. Adjust the output voltage of the generator and the sensitivity of the oscilloscope so that the waveform signal observed at the output of the amplifier was not distorted. Reduce the frequency of the signal from a generator to approx. 300 Hz and read values of the amplitude of input and output signals. The amplitude of the output signal should be taken as a reference value during subsequent measurements.
8. Gradually increase the frequency of the input signal (up to 500 kHz) to find the critical frequencies for which the output amplitude decreases sequentially 2, 3, 4, 5, 6, 8 and 10 times.
9. Every time pay special attention if the output signal is not distorted. Ensure that it is not "cutted off" from the top and from the bottom. Draw the oscillograms with strongly marked oscilloscope settings, type of amplifier and the following values: amplitude level, period, Z_1 and Z_2, voltage gain.

5.1.5. Measurement of AC voltage gain

1. Set again the output frequency of Function Generator to approx. 300 Hz.
2. Measure the input and output amplitudes of signals for various positions of Z_1 and Z_2 switches paying the special attention to non-deforming the signals.
3. Record the obtained results on the data sheet in the Data Table A1 with description "variable signal".

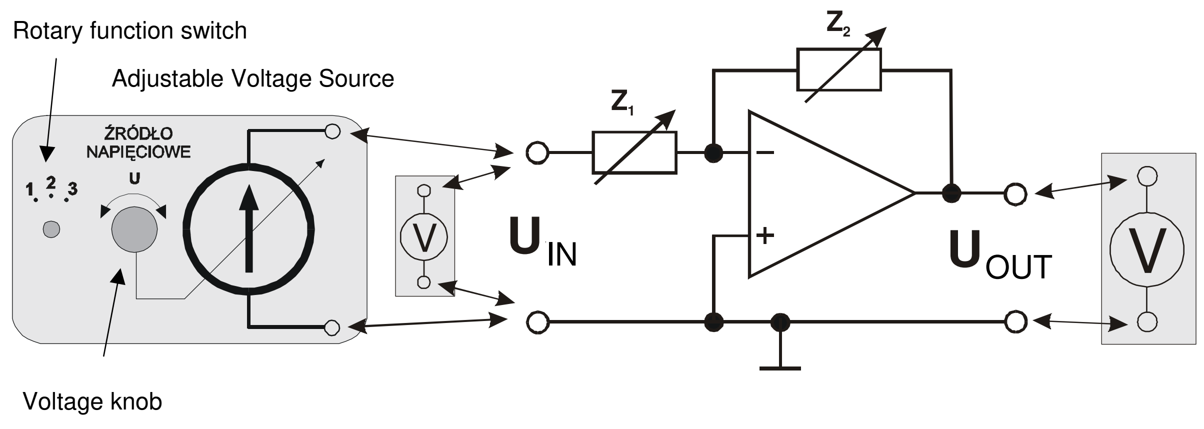
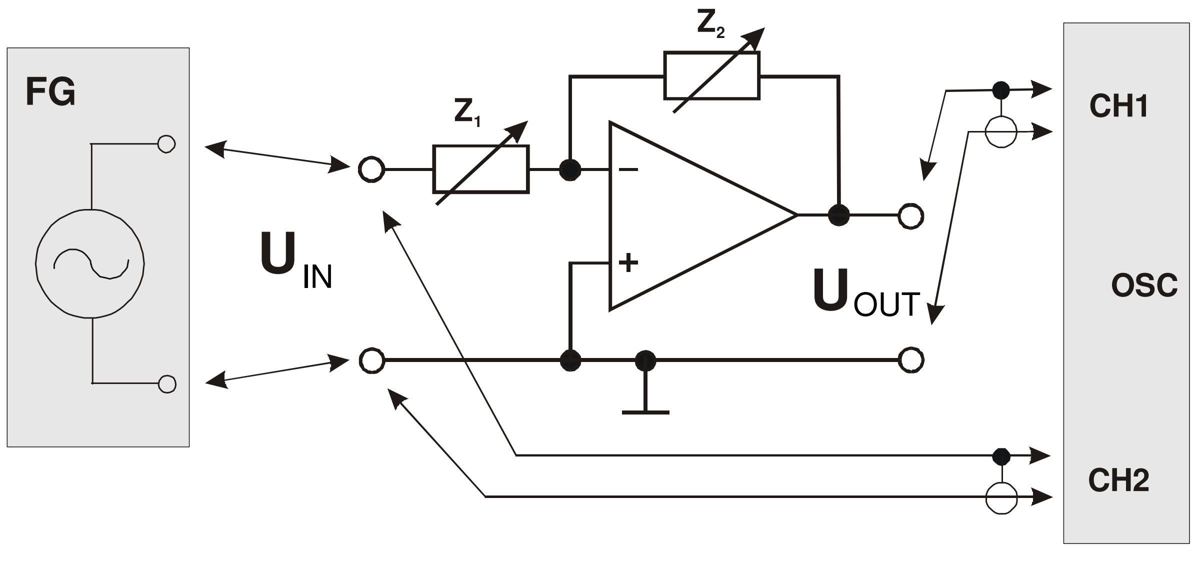
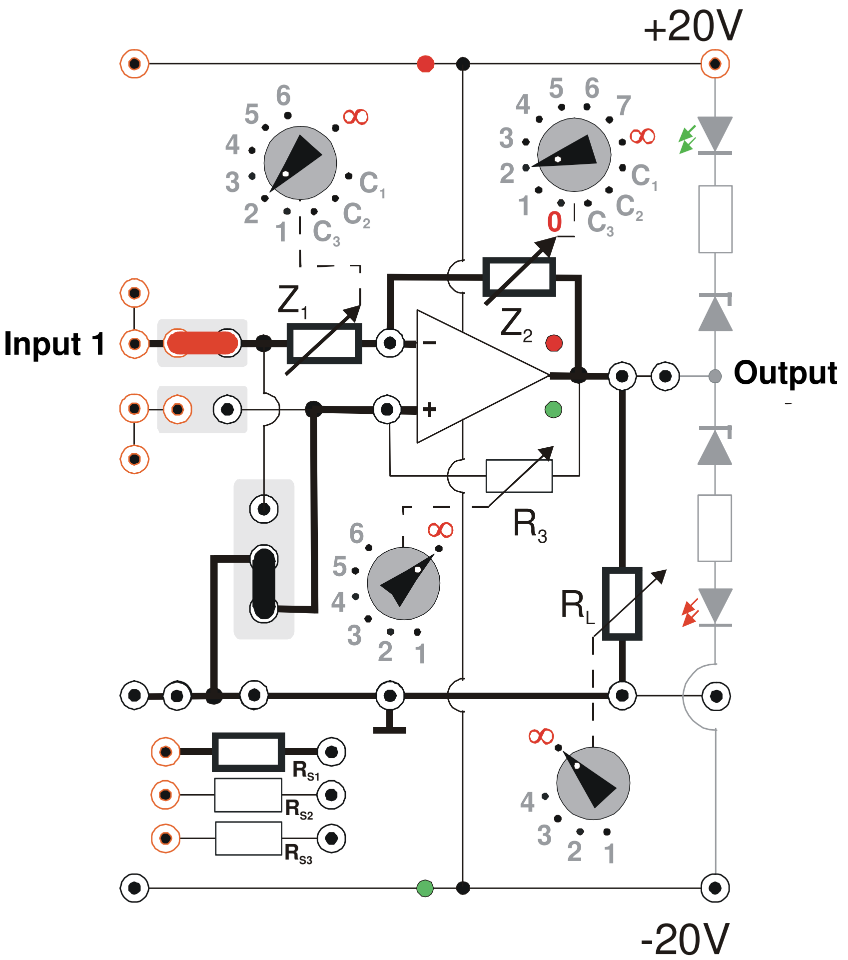


Fig. 1a



FG
Z1
Z2
UIN
UOUT
CH1
OSC
CH2

Fig. 1b



+20V
Input 1
Output
Z1
Z2
R3
RL
RS1
RS2
RS3
-20V

Fig. 1c

5.2. The non-inverting amplifier – basic version

(Connection diagrams are presented on Figures 2a and 2b and the experimental module is presented in Fig. 2c).
Explanations: FG – functional generator, OSC – oscilloscope, CH1 and CH2 – channel inputs of oscilloscope.

5.2.1. The transfer characteristic of amplifier

1. Turn off the CH1 and CH2 outputs of the power supply.
2. Connect the circuit according to the diagrams presented in Figs. 2a and 2c. Set the switches R_3 and R_L to the "∞" position. Set the rotary function switch on DMM's voltmeters to the 20 DCV or 40 DCV (depending on type of multimeter).
3. Set the switches Z_1 and Z_2 to the "2" position (Fig. 2c).
4. Set the rotary function switch on the Adjustable Power Supply to the "2" position (Fig. 2a).
5. After checking the system by the supervisor turn on the CH1 and CH2 outputs of the power supply.
6. Increasing the input voltage from –12V to +12V determine the dependence of input voltage on output voltage.
7. Record the obtained result on the data sheet in the Data Table A2.
8. Set the switches Z_1 and Z_2 according to the supervisor's order and repeat the procedure described in previous steps.

Data Table A2 / ($A2^{\#}$) – Noninverting amplifier.

Z_1 / ($R_{S2}^{\#}$/$R_{S3}^{\#}$)	Z_2 / ($R_L^{\#}$)	Input voltage		Output voltage	
[kΩ]	[kΩ]	U_{IN} [V]	ΔU_{IN} [V]	U_{OUT} [V]	ΔU_{OUT} [V]

5.2.2. Measurement of the input impedance of the amplifier

1. Set the input voltage on the value for which the output voltage is near below 12V.
2. Remove the jumper from Input 2 position (Fig. 2c). Put the R_{S2} resistor instead of the jumper.
3. Measure the output voltage of amplifier without changing the input voltage.
4. Repeat procedures described above for R_{S3} instead of R_{S2}.
5. Record the obtained result on the data sheet in the Data Table $A2^{\#}$.
6. Remove the R_{S3} resistor.

5.2.3. Measurement of the output impedance of the amplifier

1. Insert the jumper to the Input 2 position (Fig. 2c).
2. Set the input voltage on the value for which the output voltage is near below 12V.
3. Measure the output voltage of amplifier for different positions of switch R_L.
4. Record the obtained result on the data sheet in the Data Table $A2^{\#}$.

5.2.4. Measurement of the bandwidth of amplifier

1. Remove the Adjustable Voltage Source and DMMs.
2. Connect the circuit according to the diagram given in Fig. 2b.
3. Select the sine waveform (without the DC OFFSET) by using the Function Select Switch on the Function Generator (FG) front panel and connect the output of FG to the both CH2 input of oscilloscope and input of amplifier (use T junction to divide the signal from the output of FG) (Fig. 2b and 2c).
4. Connect the output of amplifier to CH1 input of oscilloscope (Fig. 2b and 2c).
5. Set the switches: Z_1 to the "1" position, Z_2 to the "3" position, and R_L to the "∞" position.
6. Set the output frequency of Function Generator to approx. 500 kHz (0.5 MHz).
7. Adjust the output voltage of the generator and the sensitivity of the oscilloscope so that the waveform signal observed at the output of the amplifier was not distorted. Reduce the frequency of the signal from a generator to approx. 300 Hz and read values of the amplitude of input and output signals. The amplitude of the output signal should be taken as a reference value during subsequent measurements.
8. Gradually increase the frequency of the input signal (up to 500 kHz) to find the critical frequencies for which the output amplitude decreases sequentially 2, 3, 4, 5, 6, 8 and 10 times.
9. Every time pay special attention if the output signal is not distorted. Ensure that it is not "cutted off" from the top and from the bottom. Draw the oscillograms with strongly marked oscilloscope settings, type of amplifier and the following values: amplitude level, period, Z_1 and Z_2, voltage gain.

5.2.5. Measurement of AC voltage gain

1. Set again the output frequency of Function Generator to approx. 300 Hz.
2. Measure the input and output amplitudes of signals for various positions of Z_1 and Z_2 switches paying the special attention to non-deforming the signals.
3. Record the obtained results on the data sheet in the Data Table A2 with description "variable signal".

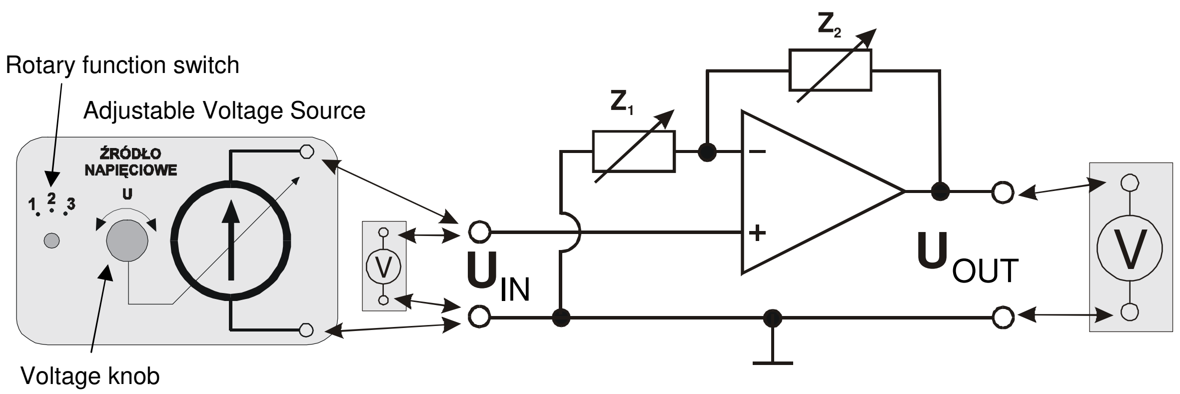
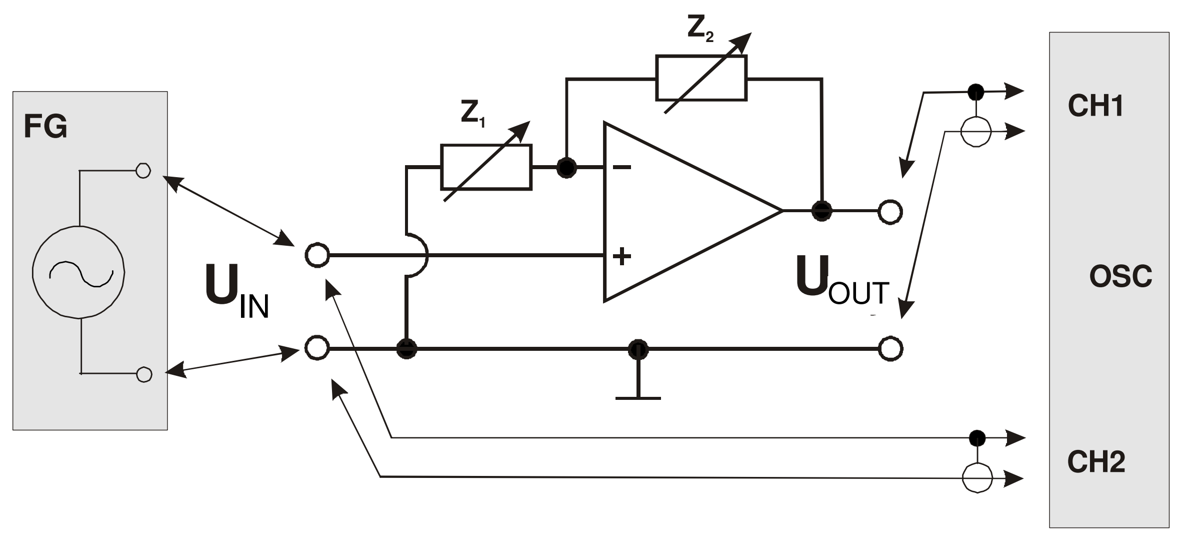
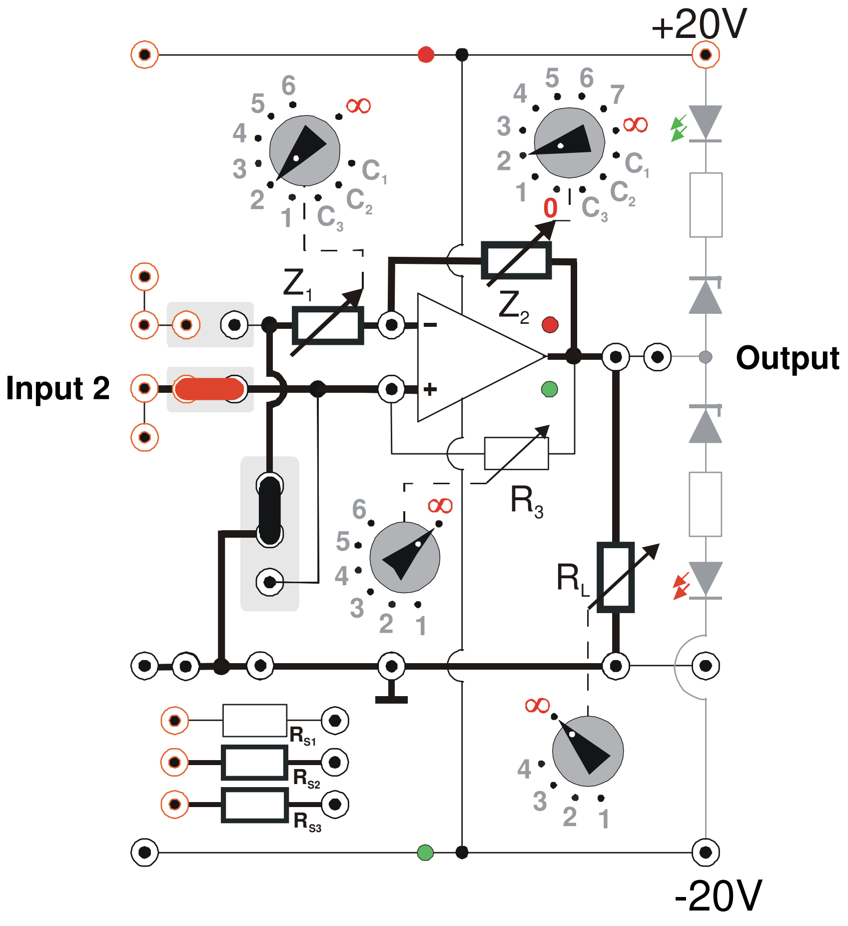


Fig. 2a



FG
Z1
Z2
UIN
UOUT
CH1
OSC
CH2

Fig. 2b



+20V
Z1
Z2
R3
RL
Input 2
Output
RS1
RS2
RS3
-20V

Fig. 2c

5.3. The voltage-follower – extended version

(Connection diagrams are presented in Figures 3a and the experimental module is presented in Fig. 3b).
Explanations: FG – functional generator, OSC – oscilloscope, CH1 and CH2 – channel inputs of oscilloscope.

5.3.1. The transfer characteristic of amplifier

1. Turn off the CH1 and CH2 outputs of the power supply.
2. Connect the circuit according to the diagrams presented in Figs. 3a and 3b. Set the switches R_3 and R_L to the "∞" position. Set the rotary function switch on DMM's voltmeters to the 20 DC V.
3. Set the switch Z_1 to "∞" position and switch Z_2 to the "0" position (Fig. 3b).
4. Set the rotary function switch on the Adjustable Power Supply to the "2" position (Fig. 3a).
5. After checking the system by the supervisor turn on the CH1 and CH2 outputs of the power supply.
6. Increasing the input voltage from −12V to +12V determine the dependence of input voltage on output voltage.
7. Record the obtained result on the data sheet in the Data Table A3.

Data Table A3 / ($A3^{\#}$) – The voltage-follower.

Z_1 / ($R_{S2}^{\#}$)	Z_2 / ($R_L^{\#}$)	Input voltage		Output voltage	
[kΩ]	[kΩ]	U_{IN} [V]	ΔU_{IN} [V]	U_{OUT} [V]	ΔU_{OUT} [V]

5.3.2. Measurement of the input impedance of the amplifier

1. Set the input voltage on the value for which the output voltage is near below 12V.
2. Remove the jumper from Input 2 position (Fig. 3b). Put the R_{S2} resistor instead of the jumper.
3. Measure the output voltage of amplifier without changing the input voltage.
4. Repeat procedures described above for R_{S3} instead of R_{S2}.
5. Record the obtained result on the data sheet in the Data Table $A3^{\#}$.
6. Remove the R_{S3} resistor.

5.3.3. Measurement of the output impedance of the amplifier

1. Insert the jumper to the Input 2 position (Fig. 3b).
2. Set the input voltage on the value for which the output voltage is near below 12V.
3. Measure the output voltage of amplifier for different positions of switch R_L.
4. Record the obtained result on the data sheet in the Data Table $A3^{\#}$

5.3.4. Measurement of the bandwidth of amplifier

1. Remove the Adjustable Voltage Source and DMMs.
2. Select the sine waveform (without the DC OFFSET) by using the Function Select Switch on the Function Generator (FG) front panel and connect the output of FG to the both CH2 input of oscilloscope and input of amplifier (use T junction to divide the signal from the output of FG) (Fig. 2b and 3b).
3. Connect the output of amplifier to CH1 input of oscilloscope.
4. Set the switches: Z_1 to the "∞" position, Z_2 to the "**0**" position, and R_L to the "∞" position (Fig. 3b).
5. Set the output frequency of Function Generator to approx. 1500 kHz (1.5 MHz).
6. Adjust the output voltage of the generator and the sensitivity of the oscilloscope so that the waveform signal observed at the output of the amplifier was not distorted. Reduce the frequency of the signal from a generator to approx. 300 Hz and read values of the amplitude of input and output signals. The amplitude of the output signal should be taken as a reference value during subsequent measurements.
7. Gradually increase the frequency of the input signal (up to 1500 kHz) to check if this is affected on the value of the amplitude of the output signal. Specify the maximum reduction in the amplitude of the output signal in the tested frequency range (note that in the case of an ideal follower decrease in amplitude is unmeasurable).
8. Every time pay special attention if the output signal is not distorted. Ensure that it is not "cutted off" from the top and from the bottom. Draw the oscillograms with strongly marked oscilloscope settings, type of amplifier and the following values: amplitude level, period, Z_1 and Z_2, voltage gain.

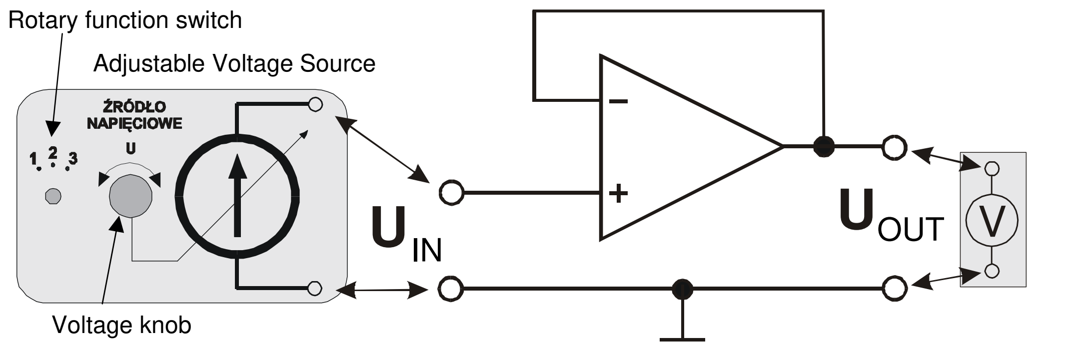

Rotary function switch
Adjustable Voltage Source
ŹRÓDŁO NAPIĘCIOWE
U
1 2 3
U IN
U OUT
V
Voltage knob

Fig. 3a

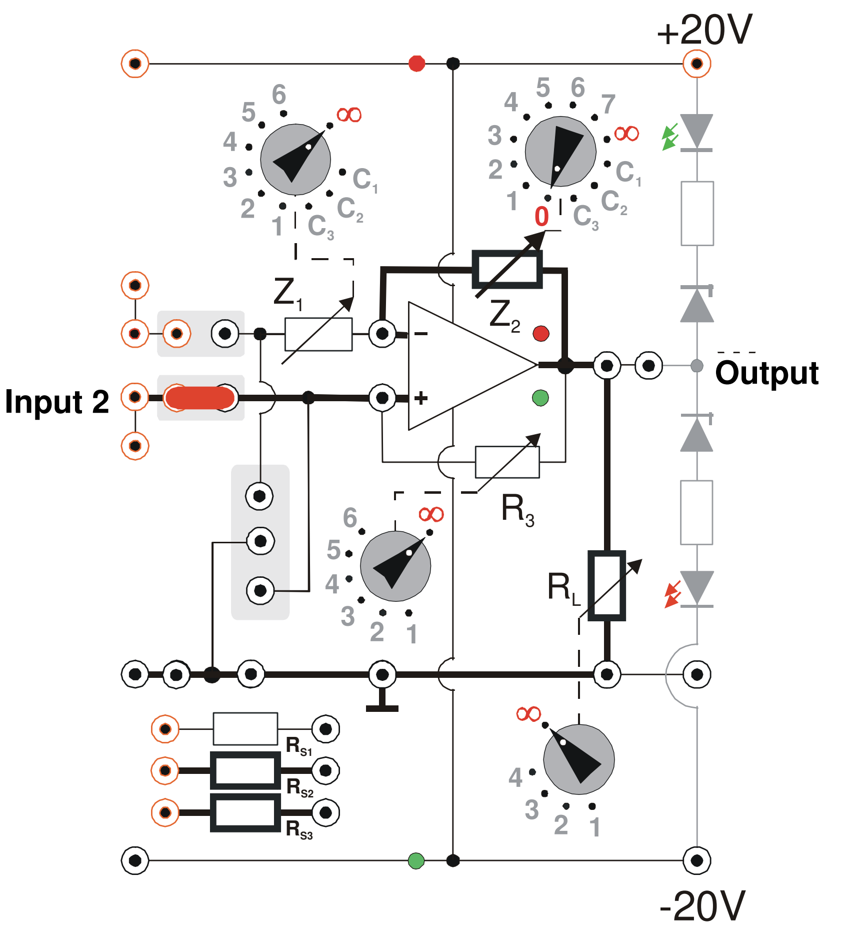

+20V
Input 2
Z1
Z2
R3
RL
RS1
RS2
RS3
Output
-20V

Fig. 3b

5. Report elaboration

1. Plot the transfer characteristic of inverting amplifier $U_{OUT} = f(U_{IN})$.
2. Find the DC voltage gain of inverting amplifier for relevant combinations of Z_1 and Z_2 and compare them with those obtained from equations (1a) or (1b):

$$k_u^{\,t} = -\frac{Z_2}{Z_1} \qquad \text{and} \qquad k_u = \frac{U_{OUT}}{U_{IN}} \,. \tag{1a}$$

$$k_u^{\,tA}[dB] = 20\log\left(\left|\frac{Z_2}{Z_1}\right|\right) \qquad \text{and} \qquad k_u^{\,A}[dB] = 20\log\left(\left|\frac{U_{OUT}}{U_{IN}}\right|\right) \,. \tag{1b}$$

3. Plot the voltage gain coefficient k_u of inverting amplifier versus frequency for different combinations of Z_1 and Z_2 . Apply logarithmic scale for frequency (the sample plot is presented in Fig. 4).
4. Find the input and output impedance of inverting amplifier applying the equations (2):

$$R_{IN} = \frac{R_{S1}}{\dfrac{U_{OUT}}{U_{OUT\,Rs1}} - 1}; \qquad R_{OUT} = R_L\left(\frac{U_{OUT}}{U_{OUT\,RL}} - 1\right). \tag{2}$$

   Derive the relevant formulas and calculate the combined measurement uncertainties ΔR_{IN} and ΔR_{OUT} [7], neglecting the uncertainties of direct measurements ΔR_{S1} and ΔR_L.

5. Based on measurements of input and output amplitudes for inverting amplifier find the AC voltage gains corresponding to relevant combinations of Z_1 and Z_2 and compare them with those obtained from equations (1).
6. Plot the transfer characteristic of noninverting amplifier $U_{OUT} = f(U_{IN})$.
7. Find the DC voltage gain of noninverting amplifier for relevant combinations of Z_1 and Z_2 and compare them with those obtained from equations (3a) or (3b):

$$k_u^{\,t} = 1 + \frac{Z_2}{Z_1} \qquad \text{and} \qquad k_u = \frac{U_{OUT}}{U_{IN}} \,. \tag{3a}$$

$$k_u^{\,tA}[dB] = 20\log\left(\left|1 + \frac{Z_2}{Z_1}\right|\right) \qquad \text{and} \qquad k_u^{\,A}[dB] = 20\log\left(\left|\frac{U_{OUT}}{U_{IN}}\right|\right) \,. \tag{3b}$$

8. Plot the voltage gain coefficient k_u of noninverting amplifier versus frequency for different combinations of Z_1 and Z_2 . Apply logarithmic scale for frequency.
9. Find the input and output impedance of noninverting amplifier applying the equations (4)

$$R_{IN} = \frac{R_{S2}}{\dfrac{U_{OUT}}{U_{OUT\,Rs2}} - 1}; \quad \text{and/or} \quad R_{IN} = \frac{R_{S3}}{\dfrac{U_{OUT}}{U_{OUT\,Rs3}} - 1}; \qquad R_{OUT} = R_L\left(\frac{U_{OUT}}{U_{OUT\,RL}} - 1\right). \tag{4}$$

   Derive the relevant formulas and calculate the combined measurement uncertainties ΔR_{IN} and ΔR_{OUT} [7], neglecting the uncertainties of direct measurements ΔR_S and ΔR_L.

10. Based on measurements of input and output amplitudes for noninverting amplifier find the AC voltage gains corresponding to relevant combinations of Z_1 and Z_2 and compare them with those obtained from equations (3).
11. Plot the transfer characteristic of voltage-follower $U_{OUT} = f(U_{IN})$.
12. Find the DC voltage gain of voltage-follower and compare it with this obtained from equations (3) (Z_2=0).
13. Find the input and output impedance of voltage-follower applying the equations (4). Derive the relevant formulas and calculate the measuring errors for R_{IN} and R_{OUT}.
14. Based on measurements of input and output amplitudes for voltage-follower find the AC voltage gain and compare it with this obtained from equations (3)

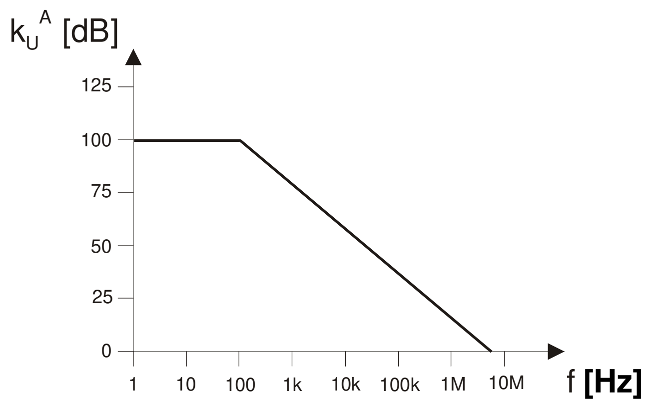


Fig. 4. The sample plot of k_u^A versus frequency. Frequency is presented in logarithmic scale.

6. References

7.1. Basic reference materials

[1] M. Rusek, J. Pasierbiński, *Elementy i układy elektroniczne w pytaniach i odpowiedziach*, WNT, Warszawa, 1999.
[2] M. Nadachowski, Z. Kulka, *Scalone układy analogowe*, WKiŁ, Warszawa, 1985.
[3] P. Horowitz, W. Hill, *Sztuka elektroniki. Cz. 1.*, (tłum. ang.), WKiŁ, Warszawa, 2003.
[4] Z. Nosal, J. Baranowski, *Układy elektroniczne. Cz. I. Układy analogowe liniowe*, Seria Podręczniki Akademickie, (Elektronika, Informatyka, Telekomunikacja), WNT, Warszawa, 2003.
[5] A. Filipowski, *Układy elektroniczne analogowe i cyfrowe*, Seria Podręczniki Akademickie, (Elektronika, Informatyka, Telekomunikacja), WNT, Warszawa, 2005.

7.2. Other reference materials

[6] User guides for multimeters, power supply, function generator, and oscilloscope available on the website:
https://fizyka.p.lodz.pl/pl/dla-studentow/fundamentals-of-electronics/
[7] Ł. Piskorski, *Evaluation of uncertainty in measurements*, TUL Script, Łódź, 2019 (WIKAMP, Pracownia Fizyczna/Physics Lab):
https://ftims.edu.p.lodz.pl/mod/resource/view.php?id=59551

7. Appendixes

A1. Tables of resistances and capacitances

Z_1	
Position	Value
1	5 kΩ
2	10 kΩ
3	15 kΩ
4	20 kΩ
5	25 kΩ
6	30 kΩ
∞	∞ Ω
C_1	0.1 µF
C_2	1.0 µF
C_3	10 µF

Z_2	
Position	Value
0	0 Ω
1	10 kΩ
2	20 kΩ
3	50 kΩ
4	100 kΩ
5	200 kΩ
6	500 kΩ
7	1 MΩ
∞	∞ Ω
C_1	0.1 µF
C_2	1.0 µF
C_3	10 µF

R_3	
Position	Value
1	20 kΩ
2	50 kΩ
3	100 kΩ
4	200 kΩ
5	500 kΩ
6	1 MΩ
∞	∞ Ω

R_L	
Position	Value
1	2 kΩ
2	5 kΩ
3	10 kΩ
4	20 kΩ
∞	∞ Ω

R_{S1}	10 kΩ
R_{S2}	300 kΩ
R_{S3}	10 MΩ