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MOSCOW POWER ENGINEERING INSTITUTE
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CIRCUITS WITH OPERATIONAL AMPLIFIERS
Laboratory works

For students dealing with informatics.

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Circuits with operational amplifiers. Laboratory works. Moscow: Publishing House of MPEI, 2000. - 56 pp.

This book contains description of experiments on circuits with operational amplifiers. The offered experiments are executed with real electronic components of operational amplifiers, resistors, potentiometers, capacitors and diodes wired on a special breadboard. Students acquaint with the features and marking of components, with measuring instruments: oscilloscope, multimeter, sine wave generator. The aim of offered experiments: students learn to analyze circuits with operational amplifiers, estimate experiment errors, and work with real electronic components.

The book reflects the experience of teaching foreign students in English at the Moscow Power Engineering Institute (Technical University). The author would be grateful for all remarks and comments concerning contents of this book and language incorrectness as well.

For students dealing with informatics.

Breadboarding

All components are wired on a breadboard. Breadboard contains 32 by 2 sets of 5 electrically connected solderless terminals (1) that straddle both sides of a narrow center groove, and 4 sets of 25 electrically connected terminals (2) along the edges. The center group of 5 electrically connected terminals accommodate the integrated circuit chips and permit 4 additional connections to be made at each pin of the integrated circuit chip. Figure 1 shows electrical interconnection of terminals. Figure 2 shows the example of wire connection. The scheme of voltage follower is wired up.

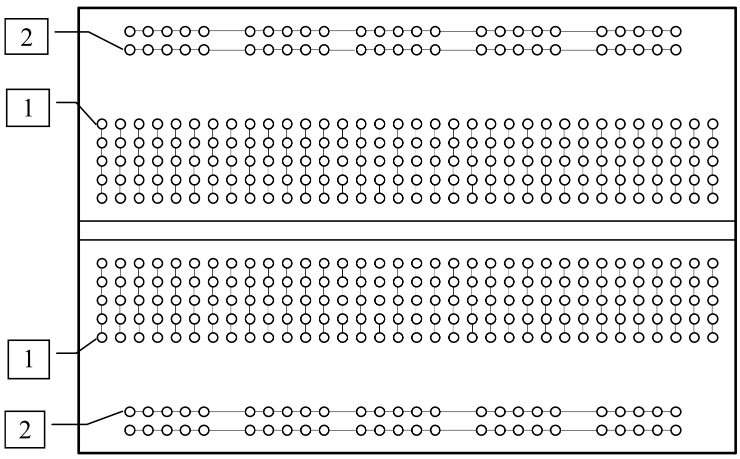


fig. 1. Electrical interconnection of terminals

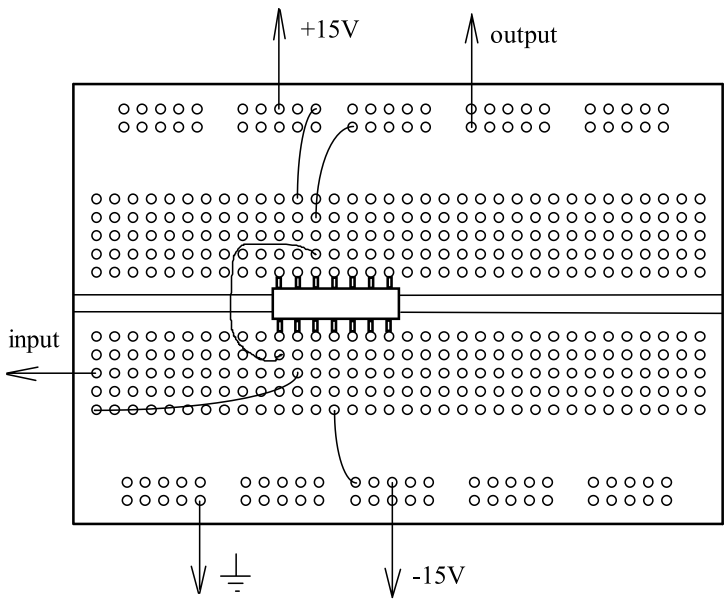


fig. 2. Wire connection for voltage follower

Rules for setting up the experiments

1. Plan your experiment beforehand. Know what types of results you are expected to observe.
2. Disconnect or turn off ***all*** power and signal sources to the breadboard.
3. Clear the breadboard of all wires and components from previous experiment, unless stated otherwise.
4. Check the wired-up circuit against the schematic circuit diagram to make sure that it is correct.
5. Connect or turn on the power and signal sources to the breadboard ***last***!
6. When finished, make sure that you disconnect or turn off all power and signal sources to the breadboard ***before*** you clear the breadboard of wires and components.

Format for the experiments

The instructions for each experiment are presented in the following format.

Schematic diagram of circuit
The description of each experiment begins with the schematic diagram of the completed circuit that you will wire. You should analyze this diagram in an effort to obtain an understanding of the circuit before you proceed further.

Design basics
Under this heading is a brief summary of the equations used for the design of the circuit.

Steps
A series of sequential steps describe the instructions for setting up portions of the experiment. Questions are also included at different points of the section.

Components

Operational amplifiers

The chips КР140УД20А and КР140УД20Б are used in experiments. They are analogous to the well known chip μA747. It is a general purpose duel op-amp. The top view of the chip is shown in fig. 3 and its block diagram in fig. 4.

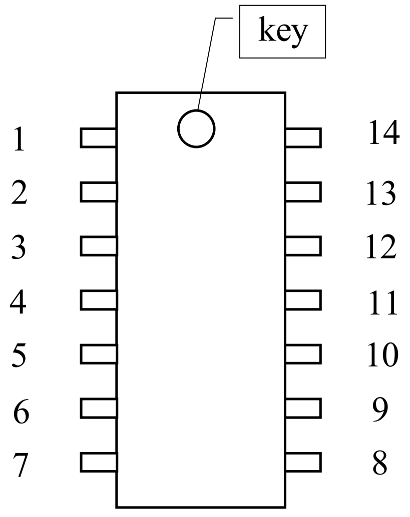


Fig. 3. Top view of КР140УД20А

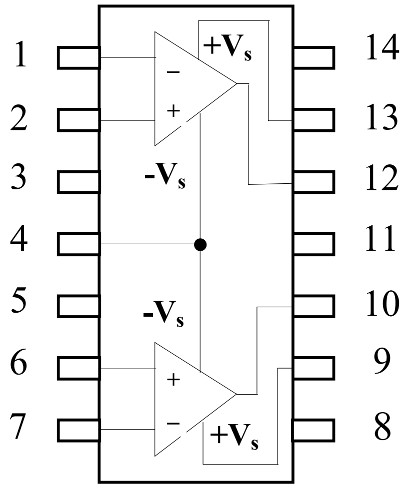


Fig. 4. Block diagram of КР140УД20А

Specifications of КР140УД20А and КР140УД20Б

	КР140УД20Б	КР140УД20А
Open-Loop Voltage Gain (A_o)	25000	50000
Differential Input Impedance (R_d)	300KΩ	500KΩ
Input Bias Current (I_b)	200nA	80nA
Input Offset Current (I_{os}) (Input Difference Current)	50nA	30nA
Input Offset Voltage (E_{os})	6mV	3mV
Common Mode Rejection Ratio (CMRR)	70dB	70dB
Unity-Gain Signal Response (f_T)	0.5MHz	0.5MHz
Slew Rate (SR)	0.3V/μs	0.3V/μs
Output Voltage Swing (V_{omax})	11.5V	11.5V

Maximum output current (I_{omax})	9mA	9mA
Minimum load resistance ($R_{l,min}$)	2 KΩ	2 KΩ
Maximum load capacitance ($C_{l,max}$)	1000pF	1000pF
Supply Voltage (V_s)	+15V, -15V	+15V, -15V
Supply Current (I_s)	2.8mA	2.8mA
Maximum Input Common-Mode Voltage ($V_{cm,max}$)	14.5V	12V
Maximum Input Differential Voltage ($V_{d,max}$)	10V	10V

Resistors

There exist fixed resistors and potentiometers. Fixed resistors have the following features.

Nominal value of resistance
The nominal value is defined as $A*10^n$ Ω, where
widely used set of A is: 1.0; 1.2; 1.5; 1.8; 2.2; 2.7; 3.3; 3.9; 4.7; 5.6; 6.8; 8.2;
widely used meanings of n are: 1; 2; 3; 4; 5; 6; 7; 8; 9 and so on.

The examples of marking
12 or 330 means 12 or 330 Ω;
2K2 or 39K or 560K means 2.2 or 39 or 560 KΩ;
1M0 or 12M means 1.0 or 12 MΩ.

Accuracy
Resistors used for our experiments have accuracy 5%, 10%, 20%. It means that the real resistance of a 100 KΩ and 10% resistor is somewhere between 90 and 110 KΩ.

Power
Working resistors dissipate heat. Resistors used for our experiments can dissipate up to 0.125, 0.25, or 0.5 Watts. Dissipation ability depends on resistor size.

Temperature stability
Relative value of resistance temperature drift depends on resistor type. For cheap resistors typical temperature drift value is 0.075% per degree.

Potentiometers

There exist single turn and multi-turn potentiometers. Figures 5 and 6 show their typical appearance. Nominal value of potentiometer resistance means that potentiometer resistance can be changed from zero to this value.

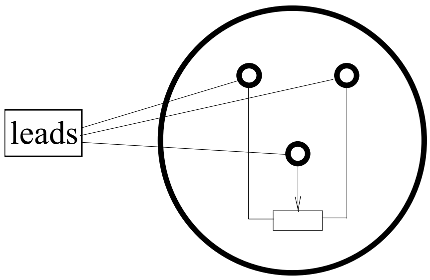


Fig. 5. Single turn potentiometer

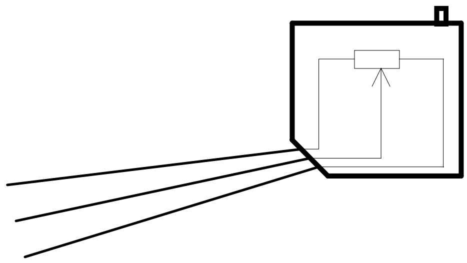


Fig. 6. Multi-turn potentiometer

Capacitors

Capacitors have the following features.

Nominal value of capacitance
The value is defined as $A*10^n$ pF, where
widely used set of A is: 1.0; 1.5; 2.2; 3.3; 4.7; 6.8;
widely used meanings of n are: 1; 2; 3; 4; 5; 6; 7; 8; 9 and so on.

The examples of marking
н13 or 2н2 or 47н means 0.13 or 2.2 or 47 nF;
µ47 or 1µ0 means 0.47 or 1.0 µF.

Accuracy
Capacitors used for our experiments have accuracy 20%.

Temperature stability
Relative value of ñapacitance temperature drift depends on capacitor type. Typical temperature drift values of capacitors used for our experiments are 0.0033% and 0.0075% per degree.

Diodes

In fig. 7 arrow shows forward bias voltage of diode. Under forward bias voltage (about 0.7V) the current flows through the diode in the direction of arrow. In this case diode resistance is low. Under reverse bias voltage of diode its current is 0. In this case diode resistance is usually higher than 100MΩ. Forward and reverse directions for diode can be determined measuring its resistance for both directions.

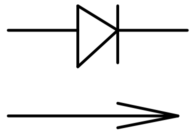


fig. 7. Forward bias voltage of diode

Instruments

Oscilloscopes

C1-68 is a "single trace" device. Vertical dimension of the screen is 6 cm. Vertical sensitivity can be changed from 1 mV/cm to 50 V/cm. Horizontal dimension of the screen is 8 cm. Time sensitivity can be changed from 0,4μs/cm to 2s/cm.

C1-55 is a "dual-trace" device. Vertical dimension of the screen is 8 divisions. Vertical sensitivity can be changed from 10 mV/div. to 20V/div. Horizontal dimension of the screen is 10 divisions. Time sensitivity can be changed from 0,02μs/div. to 2s/div.

Digital multimeter

B7-23 is the instrument that can measure:

a) DC voltage with ranges 0.1; 1; 10; 100; 1000 V.
The resolution at 0.1V range is 10 μV.
The relative error $\delta = (0.04 + 0.02(V_{fs}/V_r - 1))\%$

It measures voltage when the button БЛОК is released.
Autoranging when the button АВТО is pushed.

b) Resistance with ranges 0.1; 1; 10; 100; 1000; 10000 KΩ.
The accuracy is
for ranges 0.1; 1; 10; 100; 1000KΩ : $\delta = (0.06 + 0.03(R_{fs}/R_r - 1))\%$;

for the range 10000KΩ : $\delta = (0.15 + 0.05(R_{fs}/R_r - 1))\%$.

It measures resistance when the button БЛОК is pushed.
Autoranging when the button АВТО is pushed.

AC voltmeter

В3-38 is the instrument that can measure AC sine-wave voltage:
at the ranges 1, 3, 10, 30, 100, 300 mV the fiducial error $\gamma = 2{,}5\%$;
at the ranges 1, 3, 10, 30, 100, 300 V the fiducial error $\gamma = 4{,}0\%$.

Sine generator

Г3-109 is the generator that can produce adjustable sine voltage with amplitude 1mV - 15V and frequency 20Hz - 200KHz.

Some formulas for error estimation

V_r - reading value;
V_{fs} - instrument full scale value;
absolute error $\Delta = V_r - V_{ideal}$;
relative error $\delta = \Delta / V_r$;
fiducial error $\gamma = \Delta / V_{fs}$.

If instrument accuracy is specified by relative error $\delta = C + D(V_{fs}/V_r - 1)$, then absolute error of measurement: $\Delta = (C - D)\, V_r + D\, V_{fs}$.
If instrument accuracy is specified by relative error $\delta = A + B(V_{fs} / V_r)$, then absolute error of measurement: $\Delta = A\, V_r + B\, V_{fs}$.
If instrument accuracy is specified by fiducial error γ, then absolute error of measurement: $\Delta = \gamma\, V_{fs}$.

If experiment result $R = a\, b / c$, then relative error of result: $\delta_R = \delta_a + \delta_b - \delta_c$.
If experiment result $R = a + b - c$, then absolute error of result: $\Delta_R = \Delta_a + \Delta_b - \Delta_c$.
The result must be written in the form $(R \pm \Delta)$, where Δ must be written with 2 significant digits. Examples: $V = (3.215 \pm 0.021)$V; $R = (7653 \pm 20)\Omega$.

Experiment №1. Measurement of the input offset voltage

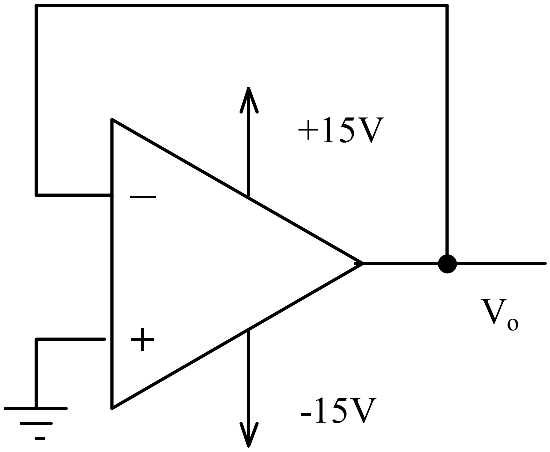


fig. 8. Measurement of the input offset voltage

Design basics

Output voltage: $V_o = E_{os}$

Steps

Step 1
Wire the circuit shown in the schematic diagram. For this experiment, the power supply connections to the op-amp are shown in the schematic diagram. *For the remaining experiments they will be omitted from the diagrams, as these connections are usually implied.*

Step 2
Apply power to the breadboard, and with your voltmeter measure the output voltage. Record your result as

V_o = ________________ mV

Step 3

Using one of the formulas given in the "Error estimation" section calculate the error of the result

Δ = ____ = _________________ mV

Write down the result of your experiment

V_o = _________________ ± _________________ mV

Conclusion

The meaning of V_o must be less than E_{os} given in op-amp specification.

Specified value of E_{os} is _________________ mV, so the measured value is (not) within specified limits.

Note. Since all the experiments use op-amp powered by a dual voltage supply, when you are finished with each experiment, disconnect all the connections to the op-amp except the power. In this way, you won't forget to make these connections when wiring the next experiment, as these power connections are usually omitted from schematic diagrams.

Experiment №2. Measurement of the input offset voltage

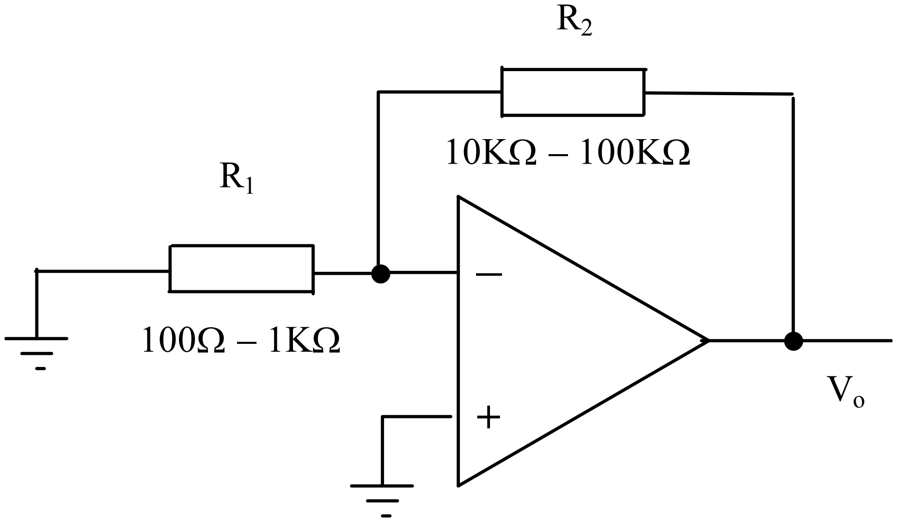


fig. 9. Measurement of the input offset voltage

Design basics

If $R_2\ I_b << E_{os}\ (1+R_2\ /R_1)$, then output voltage: $V_o = E_{os}\ (1+R_2\ /R_1)$.

So, the input offset voltage of an op-amp

$$\mathbf{E_{os} = V_o / (1+R_2 / R_1)}$$

Steps

Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, and with your voltmeter measure the output voltage. Record your result as

V_o = ________________ mV

Step 3

Using one of the formulas given in the “Error estimation” section calculate the error of the result

Δ = ______________________________________ = _________________ mV

Write down the result of your experiment

V_o = ________________ ± ________________ mV

Step 4

Using formulas given in the “Design basics” section, check the inequality and calculate the input offset voltage, recording your results as

$R_2 \; I_b$ = _____________________________________ = _________________ mV

$E_{os} (1+R_2 /R_1)$ = ______________________________ = _________________ mV

$E_{os} = V_o / (1+R_2 /R_1)$ = ___________________________ = ______________ mV

Step 5

Using formulas given in the “Error estimation” section calculate the error of the result

Δ = ____ = ______________ mV

Write down the result of your experiment

E_{os} = ________________ ± ________________ mV

Conclusion

The meaning of E_{os} must be less than E_{os} given in op-amp specification.

Specified value of E_{os} is ________________ mV, so the measured value is (not) within specified limits.

Experiment №3. Measurement of the bias current of inverting input

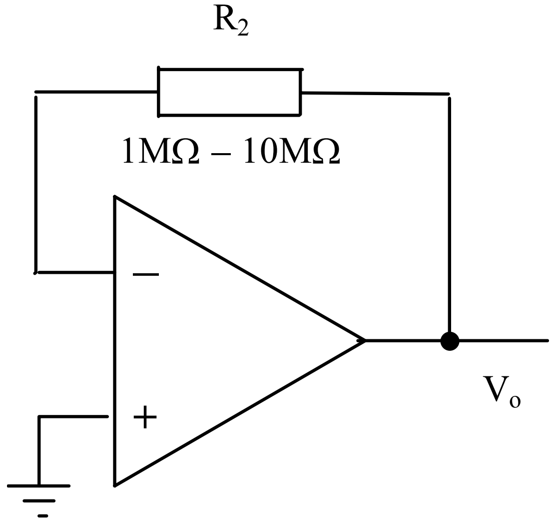


fig. 10. Measurement of the bias current of inverting input

Design basics

If $E_{os} << I_{b-} R_2$, then output voltage: $V_o = I_{b-} R_2$.

So, the bias current of the inverting input of an op-amp $\mathbf{I_{b-} = V_o / R_2}$.

Steps

Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, and with your voltmeter measure the output voltage. Record your result as

V_o = ____________ mV

Step 3

Using one of the formulas given in the "Error estimation" section calculate the error of the result

Δ = ____ = _________________ mV

Write down the result of your experiment

V_o = _________________ ± _________________ mV

Step 4

Using formulas given in the "Design basics" section, check the inequality and calculate the bias current of the inverting input of an op-amp, recording your results as

E_{os} = _______________ << I_{b-} R_2 = __________________________ = ___________

$I_{b-} = V_o / R_2$ = _____________________________________ = _______________ nA

Step 5

Using formulas given in the "Error estimation" section calculate the error of the result

Δ = ____ = _____________ nA

Write down the result of your experiment

I_{b-} = _________________ ± _________________ nA

Conclusion

The meaning of I_{b-} must be less than I_b given in op-amp specification.

Specified value of I_b is _________________ nA, so the measured value is (not) within specified limits.

Experiment №4. Measurement of the bias current of non-inverting input

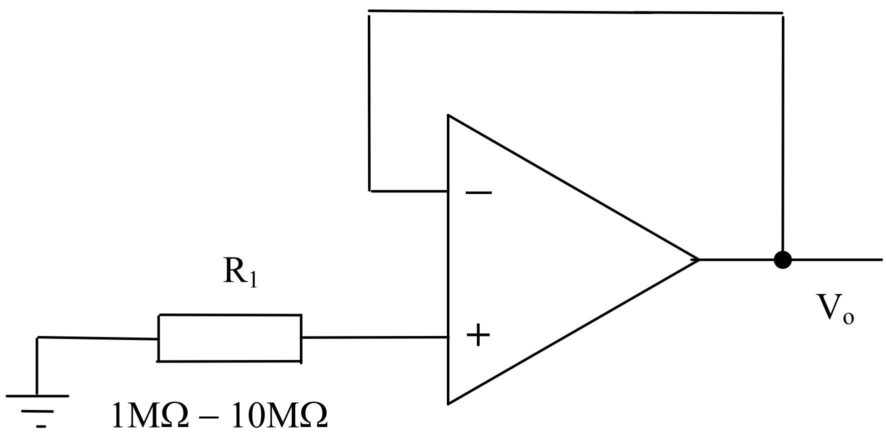


fig. 11. Measurement of the bias current of non-inverting input

Design basics

If $E_{os} << I_{b+} R_1$, then output voltage: $V_o = I_{b+} R_1$.

So, the bias current of the non-inverting input of an op-amp: $\mathbf{I_{b+} = V_o / R_1}$.

Steps

Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, and with your voltmeter measure the output voltage. Record your result as

V_o = _________________ mV

Step 3

Using one of the formulas given in the "Error estimation" section calculate the error of the result

Δ = ____ = ____________ mV

Write down the result of your experiment

V_o = ________________ ± ________________ mV

Step 4

Using formulas given in the "Design basics" section, check the inequality and calculate the bias current of the non-inverting input of an op-amp, recording your result as

E_{os} = ______________ << $I_{b+} R_2$ = _______________________ = ___________

$I_{b+} = V_o / R_1$ = ______________________________________= __________ nA

Step 5

Using formulas given in the "Error estimation" section calculate the error of the result

Δ = ____ = ____________ nA

Write down the result of your experiment

I_{b+} = ________________ ± ________________ nA

Conclusion

The meaning of I_{b+} must be less than I_b given in op-amp specification.

Specified value of I_b is ________________ nA, so the measured value is (not) within specified limits.

Experiment №5. Measurement of the offset current

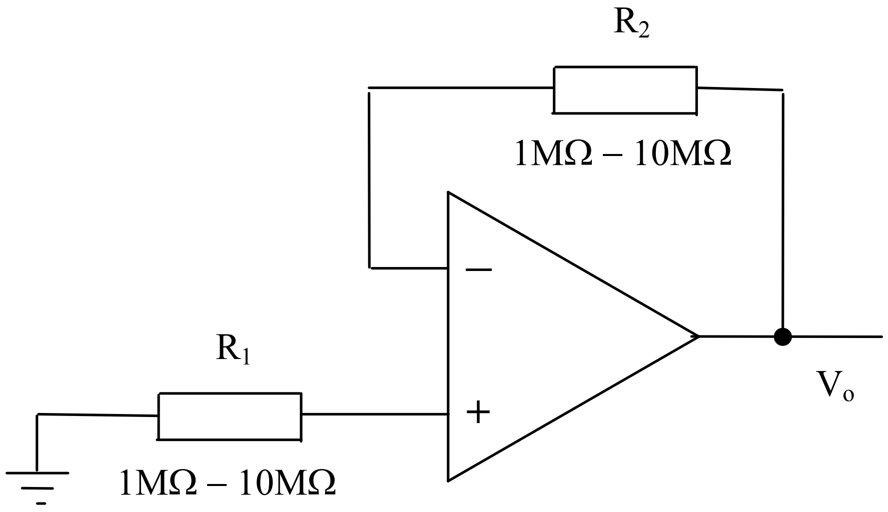


fig. 12. Measurement of the offset current

Design basics

If $E_{os} << I_{b+} R_1 - I_{b-} R_2$, then the output voltage:

$V_o = I_{b+} R_1 - I_{b-} R_2 = I_{os} (R_1 + R_2) / 2 + (R_1 - R_2)(I_{b+} + I_{b-}) / 2$.

If $(R_1 - R_2)(I_{b+} + I_{b-}) / 2 << I_{os} (R_1 + R_2) / 2$,

then the offset current of an op-amp:

$$\mathbf{I_{os} = 2V_o / (R_1 + R_2).}$$

Steps

Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, and with your voltmeter measure the output voltage. Record your result as

V_o = ________________ mV

Step 3

Using one of the formulas given in the "Error estimation" section calculate the error of the result

Δ = ____ = _____________ mV

Write down the result of your experiment

V_o = ________________ ± ________________ mV

Step 4

Using formulas given in the "Design basics" section, check the inequality and calculate the input offset current, recording your results as

E_{os} = ________ $\ll I_{b+} R_1 - I_{b-} R_2$ ____________________________ = ________

$(R_1 - R_2)(I_{b+} + I_{b-})$ = ____________________________________ = ________ mV

$I_{os} (R_1 + R_2)$ = ____ = ________ mV

$I_{os} = 2V_o / (R_1 + R_2)$ = _______________________________ = ____________ nA

Step 5

Using formulas given in the "Error estimation" section calculate the error of the result

Δ = ____ = ____________ nA

Write down the result of your experiment

I_{os} = ________________ ± ________________ nA

Conclusion

The meaning of I_{os} must be less than I_{os} given in op-amp specification.

Specified value of I_{os} is ________________ nA, so the measured value is (not) within specified limits.

Experiment №6. Measurement of the open-loop voltage gain

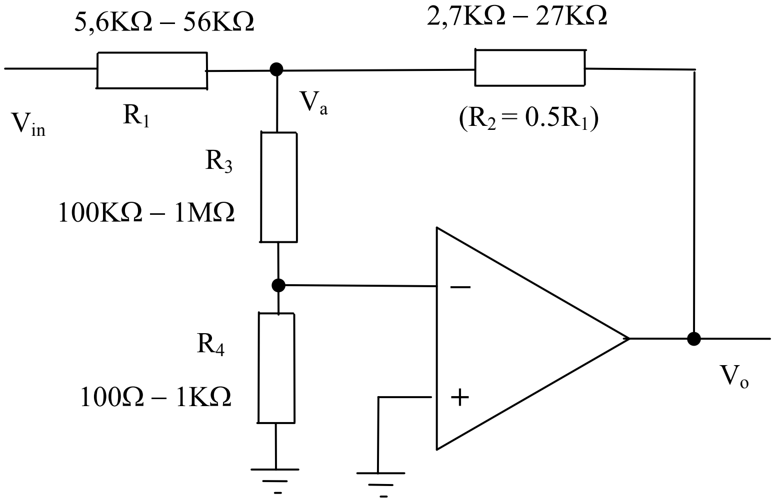


fig. 13. Measurement of the open-loop voltage gain

Design basics

When input voltage V_{in} is V_{in1} , then

$V_{o1} = V_o(E_{os}) + V_o(I_b) + V_o(V_{in1});$ (1)
$V_{a1} = V_a(E_{os}) + V_a(I_b) + (1+ R_3 / R_4)\, V_o(V_{in1})/A_o ,$ (2)

where $V_o (E_{os}) = E_{os} (1+ R_2 / R_1 + R_2 / R_4 + R_3 / R_4 + R_2 R_3 /R_1 R_4);$
$V_o (I_b) = I_b (R_2 + R_3 + R_2 R_3 / R_1);$
$V_o (V_{in1}) = - V_{in1} (R_2 / R_1);$
$V_a (E_{os}) = E_{os} (1+ R_3 / R_4);$
$V_a (I_b) = I_b R_3 .$

When input voltage V_{in} is V_{in2} , then

$V_{o2} = V_o(E_{os}) + V_o(I_b) + V_o(V_{in2});$ (3)
$V_{a2} = V_a(E_{os}) + V_a(I_b) + (1+ R_3 / R_4)\, V_o(V_{in2})/A_o .$ (4)

Subtracting (1) from (3) and (2) from (4) we obtain:
$V_{o2} - V_{o1} = V_o(V_{in2}) - V_o(V_{in1});$

$V_{a2} - V_{a1} = (1+ R_3 / R_4)(V_o(V_{in2}) - V_o(V_{in1}))/ A_o = (1+ R_3 / R_4)(V_{o2} - V_{o1})/ A_o$.

So, the open-loop voltage gain of an op-amp:

$$\mathbf{A_o = (1+ R_3 / R_4)(V_{o2} - V_{o1}) / (V_{a2} - V_{a1})}$$

Steps

Step 1

Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2

Apply power to the breadboard, apply V_{in} = +15V, and with your voltmeter measure the output voltage V_{o1} and the voltage V_{a1}. Record your results as

V_{o1} = ________________ V, V_{a1} = ________________ V

Step 3

Apply V_{in} = -15V, and with your voltmeter measure the output voltage V_{o2} and the voltage V_{a2}. Record your results as

V_{o2} = ________________ V, V_{a2} = ________________ V

Step 4

Using the formula given in the "Design basics" section, calculate the open-loop voltage gain of an op-amp, recording your result as

$A_o = (1+ R_3 / R_4)(V_{o2} - V_{o1}) / (V_{a2} - V_{a1}) =$

= ____ = ________________

Conclusion

The calculated meaning of A_o must be bigger than A_o given in op-amp specification.

Specified value of A_o is ________________ , so the measured value is (not) within specified limits.

Experiment №7. Measurement of the common mode rejection

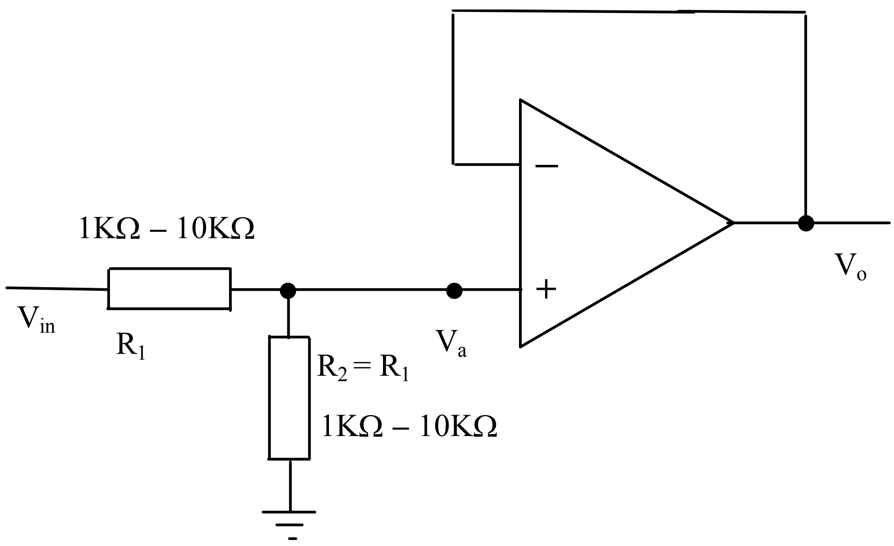


fig. 14. Measurement of the common mode rejection

Design basics

When the op-amp input voltage V_a is V_{a1}, then the output voltage V_{o1} is

$V_{o1} = V_{a1} - V_{a1} / A_o - V_{a1} / CMRR + E_{os}$.

When the op-amp input voltage V_a is V_{a2}, then the output voltage V_{o2} is

$V_{o2} = V_{a2} - V_{a2} / A_o - V_{a2} / CMRR + E_{os}$.

So, $V_{o2} - V_{o1} = (V_{a2} - V_{a1})(1 - 1 / A_o - 1 / CMRR)$.

As $1 / A_o << 1 / CMRR$, then the common mode rejection ratio of an op-amp

$$CMRR = (V_{a2} - V_{a1}) / ((V_{a2} - V_{a1}) - (V_{o2} - V_{o1})) =$$
$$= (V_{a2} - V_{a1}) / ((V_{o1} - V_{a1}) - (V_{o2} - V_{a2})).$$

Usually CMRR is expressed in dB

$$\mathbf{CMR = 20 \log_{10} (CMRR) = 20 \log_{10} ((V_{a2} - V_{a1}) /((V_{o1} - V_{a1}) - (V_{o2} - V_{a2}))).}$$

Steps

Step 1

Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2

Apply power to the breadboard, apply V_{in} = +15V, and with your voltmeter measure the output voltage (V_{o1} - V_{a1}) and the voltage V_{a1}. Record your results as

(V_{o1} - V_{a1}) = ________________ V, V_{a1} = ________________ V

Step 3

Apply V_{in} = -15V, and with your voltmeter measure the output voltage (V_{o2} - V_{a2}) and the voltage V_{a2}. Record your results as

(V_{o2} - V_{a2}) = ________________ V, V_{a2} = ________________ V

Step 4

Using formulas given in the "Design basics" section, check the inequality and calculate the CMR value, recording your results as

$1/A_o$ = _____________ = _________ << 1/CMRR = ______________ = ______

$CMR = 20 \log_{10}((V_{a2} - V_{a1})/((V_{o1} - V_{a1}) - (V_{o2} - V_{a2}))) =$

= ____ = ________ dB

Conclusion

The meaning of CMR must be higher than CMR given in op-amp specification.

Specified value of CMR is ________________ , so the measured value is (not) within specified limits.

Experiment №8. Measurement of the slew rate

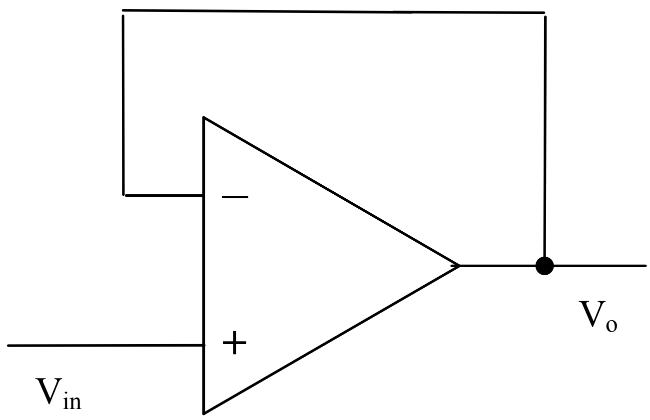


fig. 15. Measurement of the slew rate

Steps

Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, apply input voltage from the sine generator (amplitude $V_m = 4V$, frequency $f = 1kHz$) and with your oscilloscope view the output voltage V_o . It must be sine wave.

Step 3
Increase the frequency of the input signal until the output voltage becomes triangular wave and its amplitude begins reducing. With the oscilloscope measure the peak-to-peak output voltage ΔV, and record your result

ΔV = ________________ V

Step 4

With the oscilloscope measure the time Δt that it takes for the output voltage to switch either from its minimum to its maximum value, or visa versa, recording your result:

Δt = ________________ μsec

Step 5

Calculate the slew rate ΔV / Δt , and record your result.

ΔV / Δt = ___________________________________ = _____________ V/μsec

Step 6

Set the new amplitude of input sine voltage V_m = 8V retaining the last frequency. With the oscilloscope measure the new meanings of ΔV and Δt.

ΔV = ________________ V;   Δt = ________________ μsec

Calculate the new meaning of the slew rate ΔV / Δt , and record your result.

ΔV / Δt = ___________________________________ = _____________ V/μsec

As the slew rate is the feature of an op-amp, it doesn't depend on the input signal. So, the new measured value must be the same as the value measured at step 5.

Conclusion

The meaning of the slew rate must be higher than the one given in op-amp specification.

Specified value of the slew rate is ________________ V / μsec, so the measured value is (not) within specified limits.

Experiment №9. A two input summing amplifier

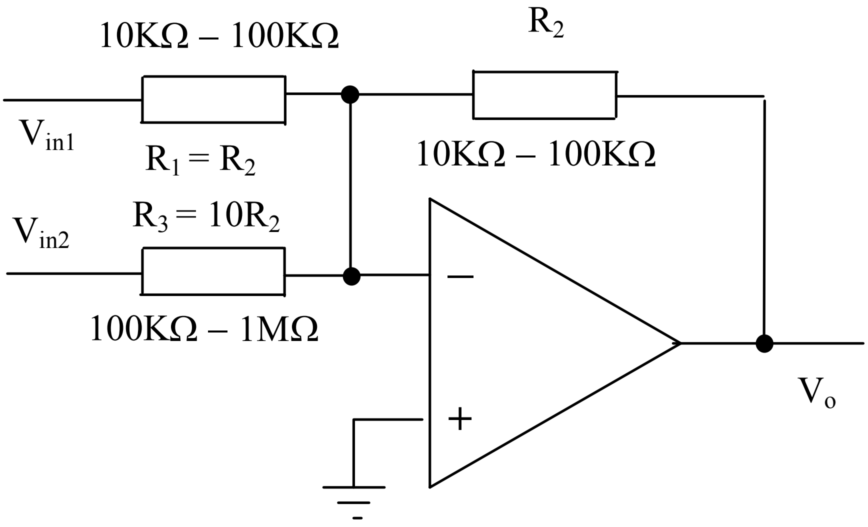


fig. 16. A two input summing amplifier

Design basics

The output voltage:

$$\mathbf{V_o = -\left(V_{in1}\,(R_2/R_1) + V_{in2}\,(R_2/R_3)\right).}$$

Steps

Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, apply input voltage V_{in1} from the sine generator (amplitude $V_m = 4V$, frequency $f = 1kHz$), apply +15V as input voltage V_{in2}, and with your oscilloscope view the output voltage V_o. It must be biased sine wave. The bias must be negative.

Step 3

With your oscilloscope measure the input voltage V_{in1} (peak-to-peak value), the input DC voltage V_{in2} , the average value of output voltage $V_{o,av}$, and the peak-to-peak value of output voltage $V_{o,pp}$.
Record your results as

V_{in1} = __________________ V; V_{in2} = __________________ V

$V_{o,av}$ = __________________ V; $V_{o,pp}$ = __________________ V

Step 4

Calculate the gain A_1 of the first signal and the gain A_2 of the second signal

$A_1 = V_{o,pp} / V_{in1}$ = ___________________________________ = __________________

$A_2 = V_{o,pp} / V_{in2}$ = ____________________________________ = __________________

Step 5

Using the formula given in the " Design basics" section calculate the gain A_1 of the first signal and the gain A_2 of the second signal

$A_1 = R_2 / R_1$ = ______________________________________ = __________________

$A_2 = R_2 / R_3$ = ______________________________________ = __________________

Step 6

Apply input voltage V_{in1} from the sine generator (amplitude $V_m = 4V$, frequency f = 1kHz), apply -15V as input voltage V_{in2} , and with your oscilloscope view the output voltage V_o . It must be biased sine wave. The bias must be positive.

Conclusion

The amplifier sums up two signals. Each channel has its own gain. Each channel inverts its signal.

Experiment №10. Measurement of the frequency response

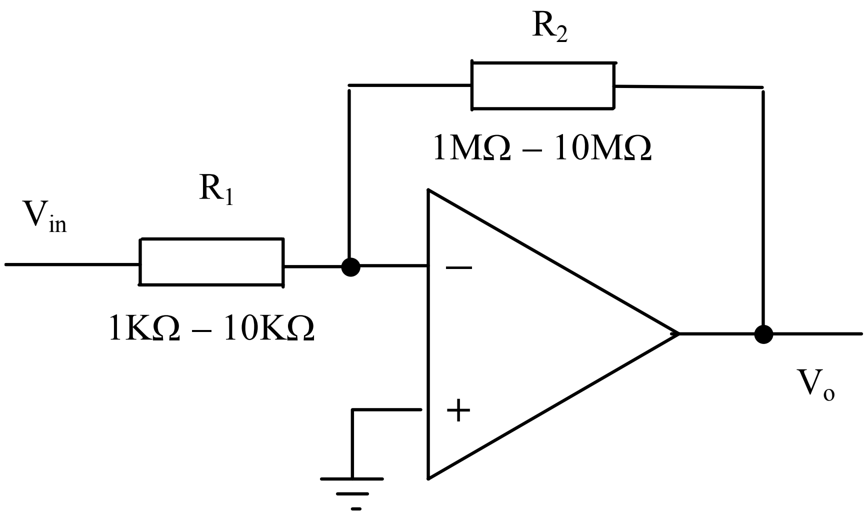


fig. 17. Measurement of the frequency response

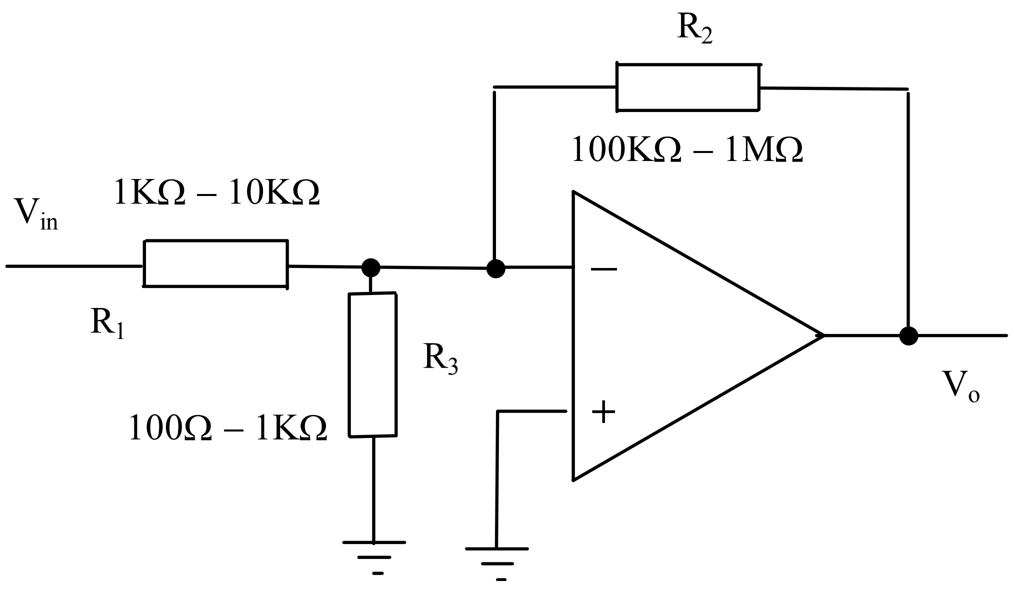


fig. 18. Measurement of the frequency response

Design basics

A_{cl} is the closed-loop gain of op-amp: $A_{cl} = V_o / V_{in}$.
For the schemes in fig. 17 and 18: A_{cl} (f=0) = $- R_2 / R_1$.
f_p is the frequency where approximated curve A_{cl} (f) inflects.
An octave is a doubling of frequency.
A decade is a changing of frequency in ten times.
The "roll-off" of a curve A_{cl} (f) at a rate

$$-6 \text{ dB/octave} = -20 \text{ dB/decade}$$

means inversely proportional dependence of gain A_{cl} (f) and frequency f.

Feedback ratio (β) is the net amount of voltage fed back from the output to the op-amp's input:
for the scheme in fig. 17 $\beta = R_1 / (R_1 + R_2)$;
for the scheme of fig. 18 $\beta = R_1||R_3 / (R_1||R_3 + R_2)$, where $R_1||R_3 = R_1R_3 / (R_1 + R_3)$.

For a closed-loop op-amp: $f_p = f_T \beta$.

Steps

Step 1
Wire the circuit shown in fig. 17. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, apply input voltage from the sine generator (amplitude V_m = 1mV, frequency f = 20Hz), and with your oscilloscope view the output voltage V_o. It must be sine wave. Adjust the input voltage so that the *output voltage* (measured with voltmeter B3-38) is 1V. With B3-38 measure the input voltage V_{in}, and record your result

V_{in} = ________________ mV

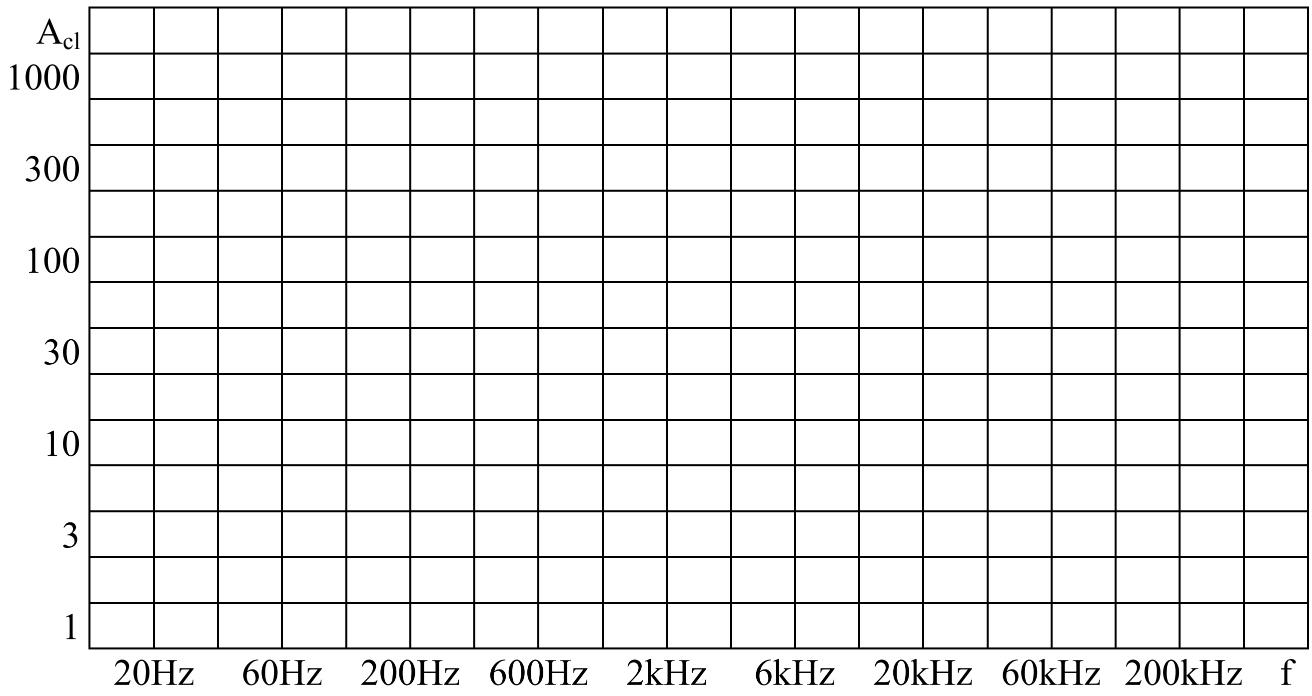
Step 3

Set the frequencies of the input signal in the range 20Hz - 200 kHz keeping the input voltage constant. With the voltmeter B3-38 measure the output voltage V_o and complete the table.

f	20Hz	60Hz	200Hz	600Hz	2kHz	6kHz	20kHz	60kHz	200kHz
V_{in}									
V_o									
A_{cl}									

Step 4

Plot the results on the graph.



Step 5

Approximate the results with two straight lines. Determine the frequencies f_T and f_p. Determine the “roll off” of the characteristic. Record the results:

f_T = ________________ kHz; f_p = ________________ kHz;

“roll off” = ________________________________ = ___________ dB /decade

Step 6

Using the formula given in the “Design basics” section, calculate the frequency f_p based on f_T and β, and the closed-loop amplifier gain A_{cl} (f=0). Record your results as

$f_{p,calc} = f_T \beta = f_T R_1 / (R_1 + R_2)$ = ____________________________________ =

= ___________ kHz

$A_{cl}(f=0) = - R_2 / R_1$ ____________________________________ = __________

Step 7

Switch off the power applied to the breadboard and disconnect the sine generator. Change the resistor R_2 for the new one in the range 100 kΩ - 1MΩ.

Step 8

Apply power to the breadboard, apply input voltage from the sine generator (amplitude V_m = 10mV, frequency f = 20Hz), and with your oscilloscope view the output voltage V_o. It must be sine wave. Adjust the input voltage so that the *output voltage* (measured with voltmeter B3-38) is 1V. With B3-38 measure the input voltage V_{in} , and record your result

V_{in} = ________________ mV

Step 9

Set the frequencies of the input signal in the range 20Hz - 200 kHz keeping the input voltage constant. With the voltmeter B3-38 measure the output voltages V_o , and complete the table. Plot the results on the graph of step 4.

f	20Hz	60Hz	200Hz	600Hz	2kHz	6kHz	20kHz	60kHz	200kHz
V_{in}									
V_o									
A_{cl}									

Step 10

Determine the frequency f_p . Record the result:

f_p = ________________ kHz;

Step 11

Using the formula given in the "Design basics" section, calculate the frequency f_p based on f_T and β, and the closed-loop amplifier gain A_{cl} (f=0). Record your results as

$f_{p,calc} = f_T \beta = f_T R_1 / (R_1 + R_2) =$ ____________________________________ =

= ___________ kHz

$A_{cl}(f=0) = - R_2 / R_1$ ____________________________________ = ___________

Step 12

Switch off the power applied to the breadboard and disconnect the sine generator. Change the resistor R_2 for the new one in the range 10 kΩ – 100 kΩ.

Step 13

Apply power to the breadboard, apply input voltage from the sine generator (amplitude V_m = 100mV, frequency f = 20Hz), and with your oscilloscope view the output voltage V_o. It must be sine wave. Adjust the input voltage so that the *output voltage* (measured with voltmeter B3-38) is 1V. With B3-38 measure the input voltage V_{in} , and record your result

V_{in} = ________________ mV

Step 14

Set the frequencies of the input signal in the range 20Hz - 200 kHz keeping the input voltage constant. With the voltmeter B3-38 measure the output voltages V_o , and complete the table. Plot the results on the graph of step 4.

f	20Hz	60Hz	200Hz	600Hz	2kHz	6kHz	20kHz	60kHz	200kHz
V_{in}									
V_o									
A_{cl}									

Step 15

Determine the frequency f_p of the closed-loop amplifier. Record the result:

f_p = ________________ kHz;

Step 16

Using the formula given in the "Design basics" section, calculate the frequency f_p based on f_T and β, and the closed-loop amplifier gain A_{cl} (f=0). Record your results as

$f_{p,calc} = f_T \beta = f_T R_1 / (R_1 + R_2) =$ ______________________________________ =

= __________ kHz

$A_{cl}(f=0) = - R_2 / R_1$ ______________________________________ = __________

Step 17

Switch off the power applied to the breadboard and disconnect the sine generator. Wire the circuit shown in figure 18. *Don't forget the power supply connections to the op-amp.*

Step 18

Apply power to the breadboard, apply input voltage from the sine generator (amplitude V_m = 10mV, frequency f = 20Hz), and with your oscilloscope view the output voltage V_o. It must be sine wave. Adjust the input voltage so that the *output voltage* (measured with voltmeter B3-38) is 1V. With B3-38 measure the input voltage V_{in}, and record your result

V_{in} = ________________ mV

Step 19

Set the frequencies of the input signal in the range 20Hz - 200 kHz keeping the input voltage constant. With the voltmeter B3-38 measure the output voltages V_o, and complete the table. Plot the results on the graph of step 4.

f	20Hz	60Hz	200Hz	600Hz	2kHz	6kHz	20kHz	60kHz	200kHz
V_{in}									
V_o									
A_{cl}									

Step 20

Determine the frequency f_p of the closed-loop amplifier. Record the result:

f_p = ________________ kHz;

Step 21

Using the formula given in the "Design basics" section, calculate the frequency f_p based on f_T and β, and the closed-loop amplifier gain A_{cl} (f=0). Record your results as

$f_{p,calc} = f_T \beta = f_T (R_1||R_3)/(R_1||R_3 + R_2)$ = ________________________________ =

= _________ kHz

$A_{cl}(f=0) = - R_2 / R_1$ ____________________________________ = __________

Conclusion

1. The meaning of f_T must be higher than the one given in op-amp specification.

Specified value of f_T is ________________ MHz, so the measured value is (not) within specified limits.

2. The "roll off" of op-amp frequency response characteristic is ____ dB/decade.

3. The upper edge f_p of closed-loop amplifier bandwidth is (not) equal $f_T \beta$.

Experiment №11. AC amplifier

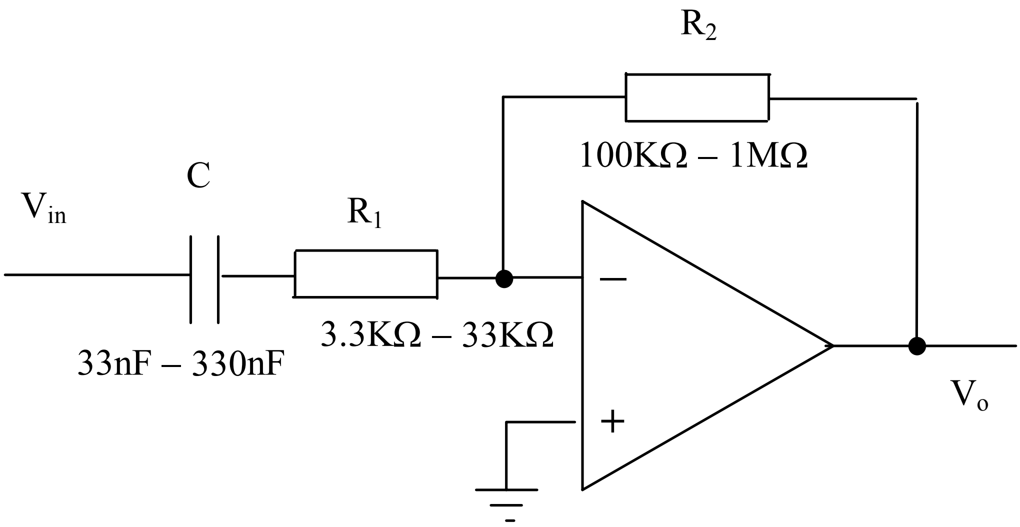


fig. 19. AC amplifier

Design basics

Amplifier gain in the bandpass: $A = -(R_2 / R_1)$
Approximated frequency response curve has two inflections: lower (f_l) and upper (f_p).
The frequency of upper inflection: $f_p = f_T\,\beta$, where $\beta = R_1 / (R_1 + R_2)$
The frequency of lower inflection: $f_l = 1 / 2\pi R_1 C$
The "roll off" of the curve to the left of f_l is +20 dB/decade.
The "roll off" of the curve to the right of f_p is -20 dB/decade.

Steps

Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, apply in turn input voltage +15V, 0V, -15V, and with your oscilloscope view the output voltage V_o. It must be 0V.

Step 3

Apply input voltage from the sine generator (amplitude V_m = 30mV, frequency f = 1000Hz), and with your oscilloscope view the output voltage V_o. It must be sine wave. Adjust the input voltage so that the *output voltage* (measured with voltmeter B3-38) is 1V. With B3-38 measure the input voltage V_{in}, and record your result

V_{in} = ________________ mV

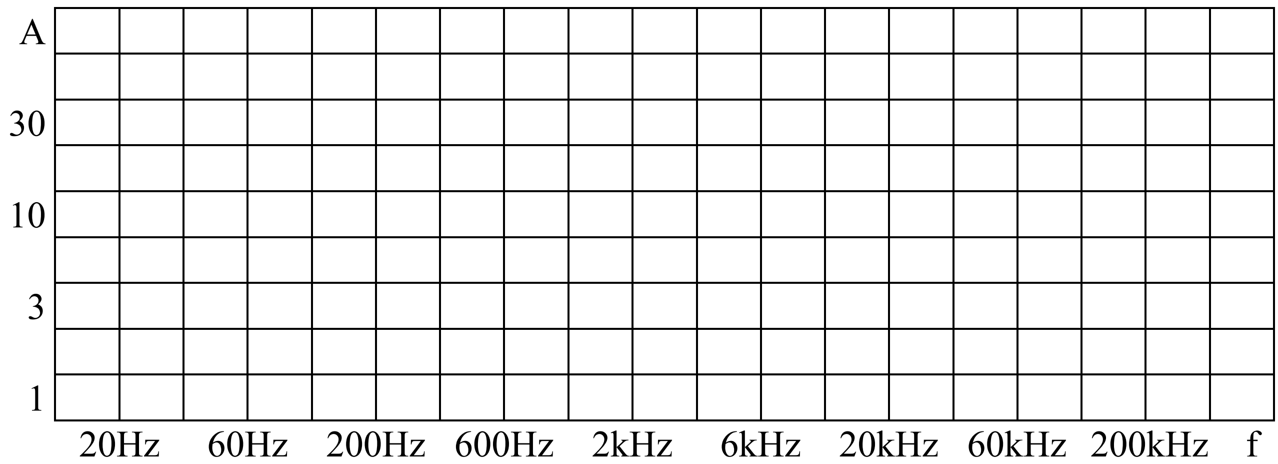
Step 4

Set the frequencies of the input signal in the range 20Hz - 200 kHz keeping the input voltage constant. With B3-38 measure the output voltages V_o, and complete the table.

f	20Hz	60Hz	200Hz	600Hz	2kHz	6kHz	20kHz	60kHz	200kHz
V_{in}									
V_o									
A									

Step 5

Plot the results on the graph.



Step 6

Approximate the results with three straight lines. Determine the frequencies f_T , f_l , f_p . Determine characteristic slopes. Record the results:

f_T = _______________ kHz;

f_l = ________________ Hz;

f_p = ________________ kHz;

the left slope = ____________________________ = +____________ dB/decade;

the right slope = ___________________________ = - ____________ dB/decade.

Step 7

Using formulas given in the "Design basics" section, calculate amplifier gain A in the bandpass, frequency f_p based on f_T and β, and frequency f_l . Record your results as

$A = R_2 / R_1$ = _____________________________________ = ____________

$f_{p,calc} = f_T \beta = f_T R_1 / (R_1 + R_2)$ = ______________________________________ =

= _____________ kHz

$f_l = 1 / 2\pi R_1 C$ = ____ =

= ______________ Hz

Conclusion

The amplifier boosts AC signal and does not conduct DC signal. In the lower part of its frequency response characteristic this amplifier has the roll-off.

Experiment №12. Active low-pass first order filter

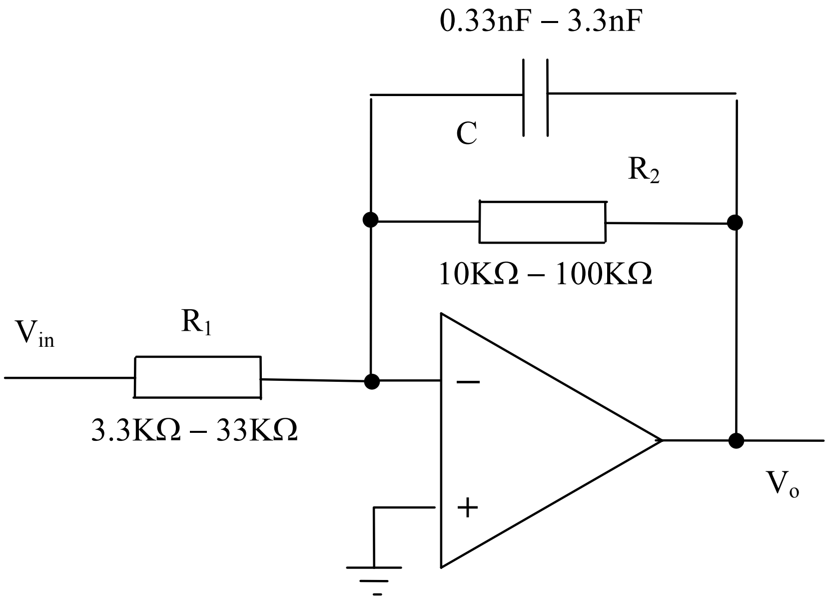


fig. 20. Active low-pass first order filter

Design basics

Filter gain in the bandpass: $A = - R_2 / R_1$.
Approximated frequency response curve has inflection at frequency:

$$f_p = 1 / 2\pi R_2 C$$

The "roll off" of the curve of a first order filter is -20 dB/decade.

Steps

Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, apply input voltage from the sine generator (amplitude V_m = 300mV, frequency f = 100Hz), and with your oscilloscope view the output voltage V_o. It must be sine wave. Adjust the input voltage so that the *output*

voltage (measured with voltmeter B3-38) is 1V. With B3-38 measure the input voltage V_{in} , and record your result

V_{in} = ________________ mV

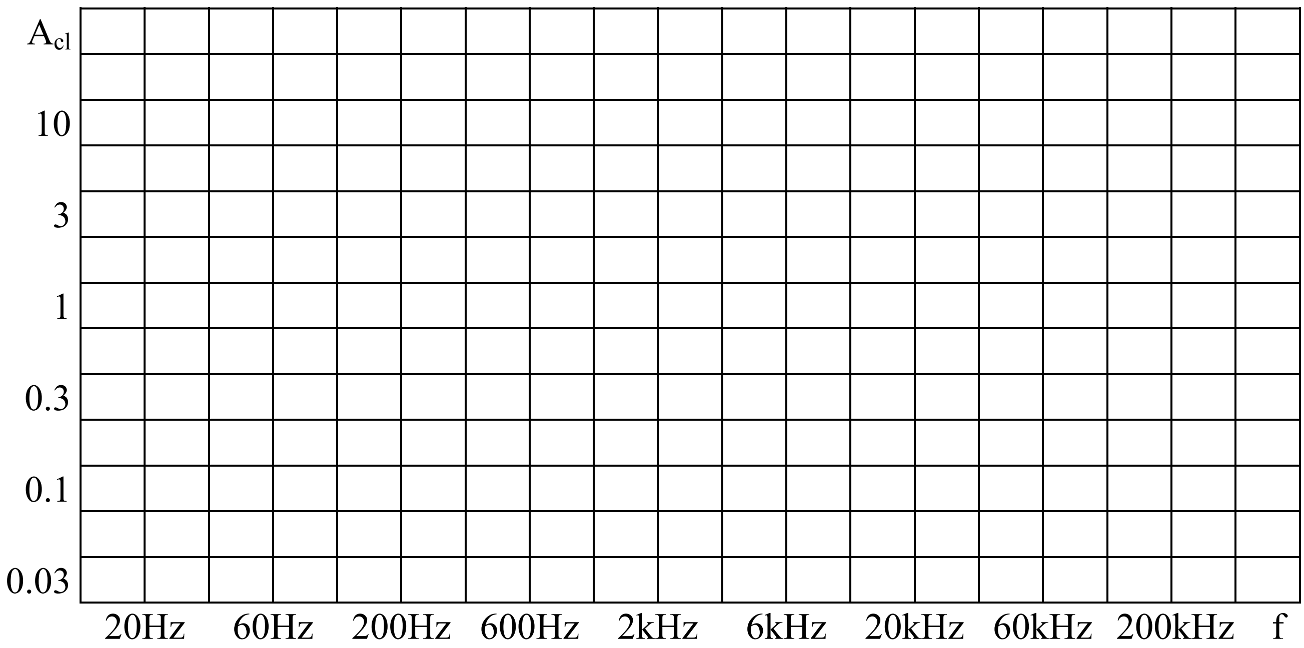
Step 3

Set the frequencies of the input signal in the range 20Hz - 200 kHz keeping the input voltage constant. With B3-38 measure the output voltages V_o , and complete the table.

f	20Hz	60Hz	200Hz	600Hz	2kHz	6kHz	20kHz	60kHz	200kHz
V_{in}									
V_o									
A									

Step 4

Plot the results on the graph.



Step 5

Approximate the results with straight lines. Determine the frequency f_p. Determine characteristic slope. Record the results:

f_p = ______________ kHz;

the slope = ________________________________ = ____________ dB/decade

Step 6

Using formulas given in the "Design basics" section, calculate filter gain A in the bandpass and frequency f_p based on R_1, R_2 and C. Record your results as

$A = R_2 / R_1$ = _____________________________________ = ____________;

$f_p = 1 / 2\pi R_2 C$ = ____ =

= ____________ Hz

Step 7

Switch off the power applied to the breadboard and disconnect the sine generator. Increase the resistance R_2 3 times.

Step 8

Apply power to the breadboard, apply input voltage from the sine generator (amplitude V_m = 100mV, frequency f = 100Hz), and with your oscilloscope view the output voltage V_o. It must be sine wave. Adjust the input voltage so that the *output voltage* (measured with voltmeter B3-38) is 1V. With B3-38 measure the input voltage V_{in}, and record your result

V_{in} = ________________ mV

Step 9

Set the frequencies of the input signal in the range 20Hz - 200 kHz keeping the input voltage constant. With B3-38 measure the output voltages V_o, and complete the table. Plot the results on the graph of step 4.

f	20Hz	60Hz	200Hz	600Hz	2kHz	6kHz	20kHz	60kHz	200kHz

V_{in}									
V_o									
A									

Step 10

Approximate the results with straight lines. Determine the frequency f_p. Record the result:

f_p = _______________ kHz

Step 11

Using the formula given in the "Design basics" section, calculate filter gain in the bandpass A and the frequency f_p based on R_1 , R_2 and C. Record your results as

$A = R_2 / R_1$ = ____ = _____________;

$f_p = 1 / 2\pi R_2 C$ = ____ =

= __________________ Hz

Conclusion

Filter gain is determined by resistors R_1 and R_2. The frequency of inflection is determined by the time constant R_2C.

Experiment №13. Half-wave rectifier

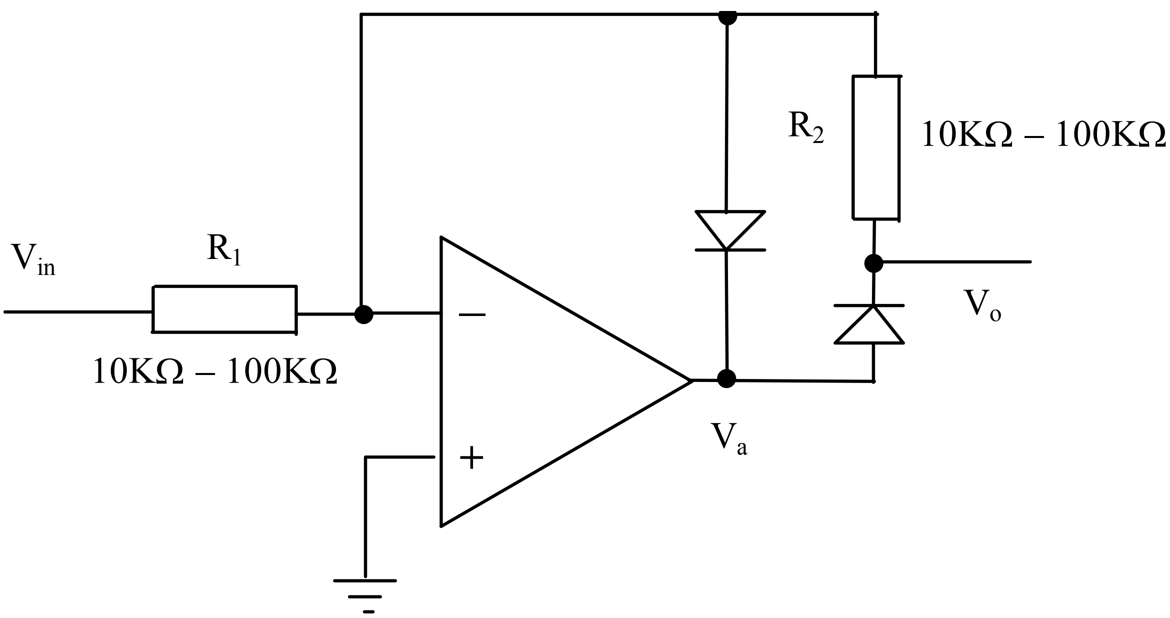


fig. 21. Half-wave rectifier

Design basics

Output voltage:

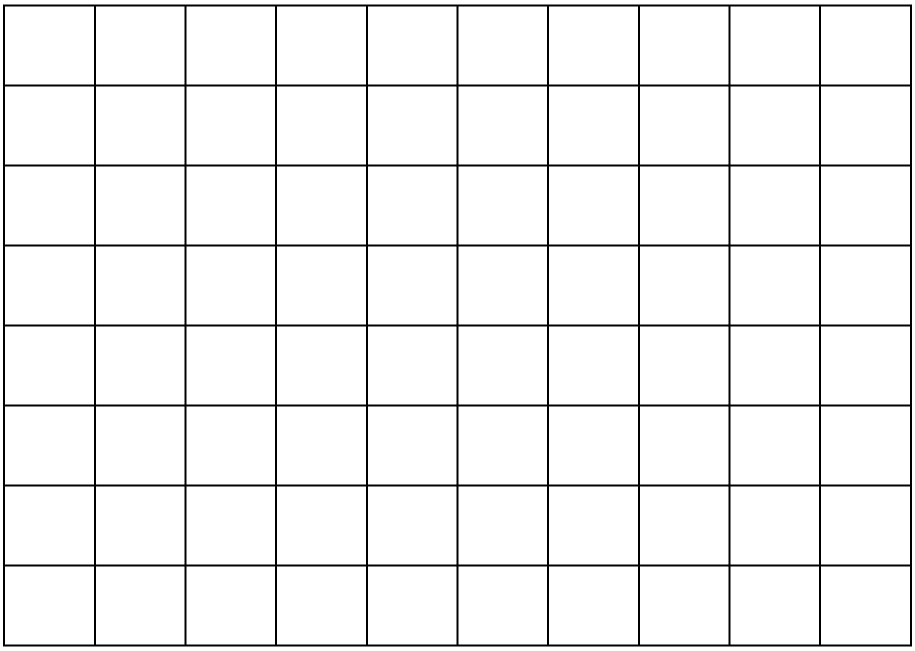
for $V_{in} > 0$: $V_o = 0$,
for $V_{in} < 0$ $V_o = - V_{in} (R_2 / R_1)$.

Steps

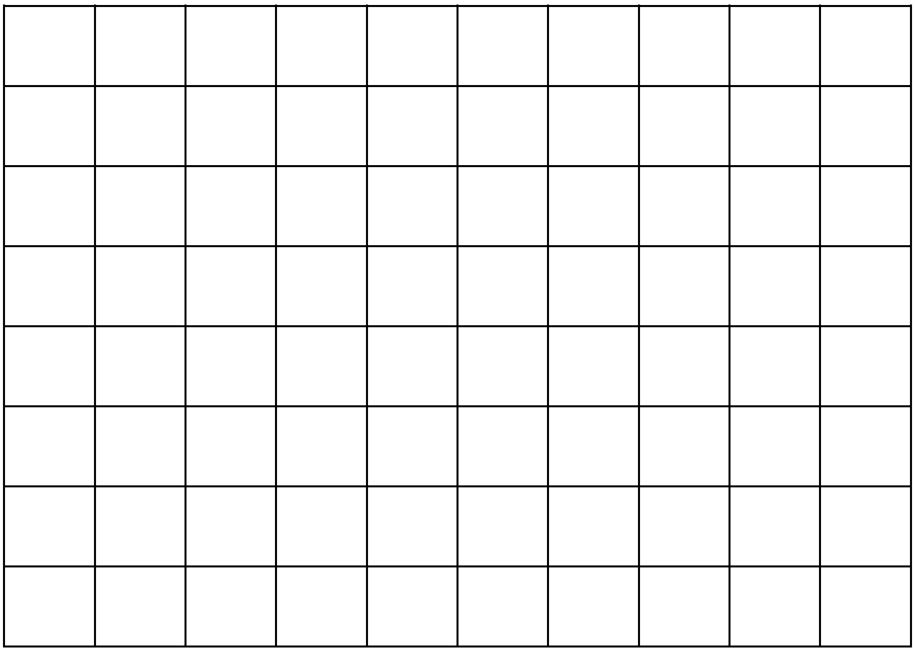
Step 1
Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

Step 2
Apply power to the breadboard, apply input voltage from the sine generator (amplitude $V_m = 1V$, frequency f = 300Hz). Draw down signals V_a , V_o.

Voltage V_a . Oscilloscope settings: __________ V/div. __________ msec/div.



Voltage V_o . Oscilloscope settings: __________ V/div. __________ msec/div.



Step 3

With the oscilloscope measure peak-to-peak input voltage V_{in} and peak-to-peak output voltage V_o , and record your results

V_{in} = _________________ V; V_o = _________________ V

Calculate the rectifier gain basing on experimental data:

$A = 2V_o / V_{in}$ = ____ = __________

Step 4

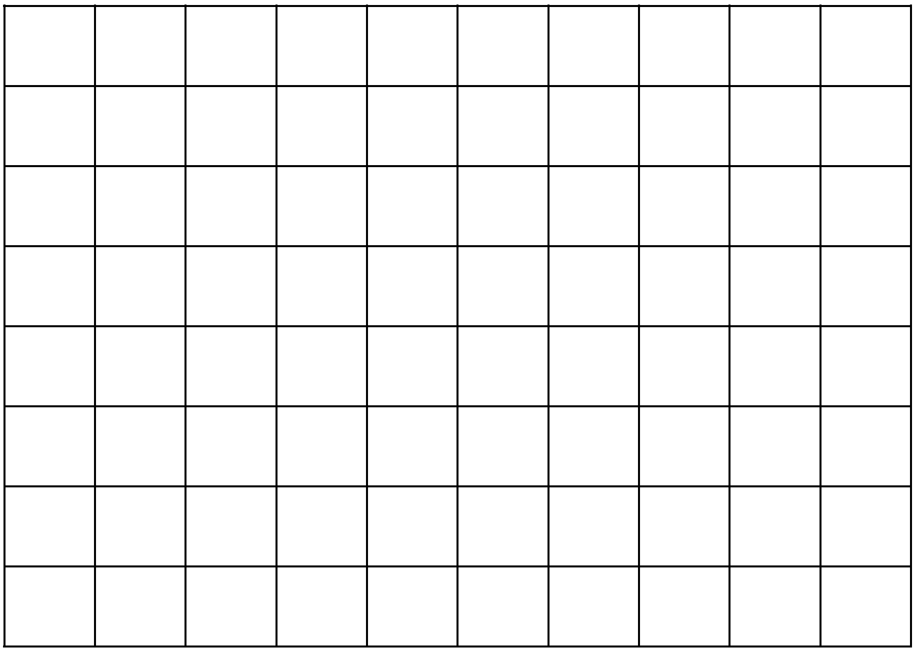
Using the formula given in the “Design basics” section, calculate the rectifier gain:

$A = R_2 / R_1$ = ____ = __________

Step 5

Apply input voltage from the sine generator (amplitude V_m = 1V, frequency f = 30kHz). Draw down signals V_a , V_o .

Voltage V_a . Oscilloscope settings: ___________ V/div. ___________ msec/div.



Voltage V_o . Oscilloscope settings: ___________ V/div. ___________ msec/div.

Conclusion

As it is seen in the drawings of step 2 and 5, the main reason for rectifier error is the slew rate of operational amplifier. The higher is input signal frequency the more slew rate distort output voltage.

Experiment №14. Square wave (relaxation) oscillator

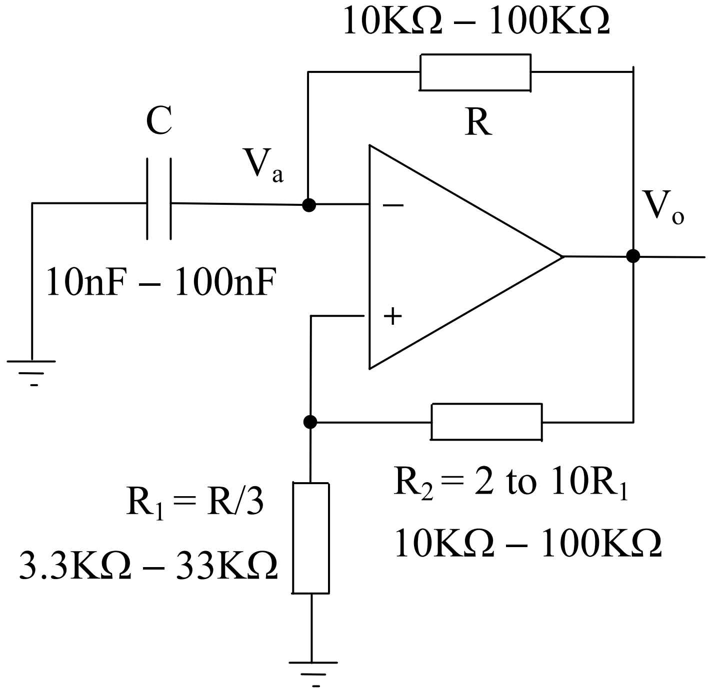


fig. 22. Square wave (relaxation) oscillator

Design basics

Oscillation period: $T_o = 2RC \ln_e (1 + 2R_1 / R_2)$.

Steps

Step 1

Wire the circuit shown in the schematic diagram. *Don't forget the power supply connections to the op-amp.*

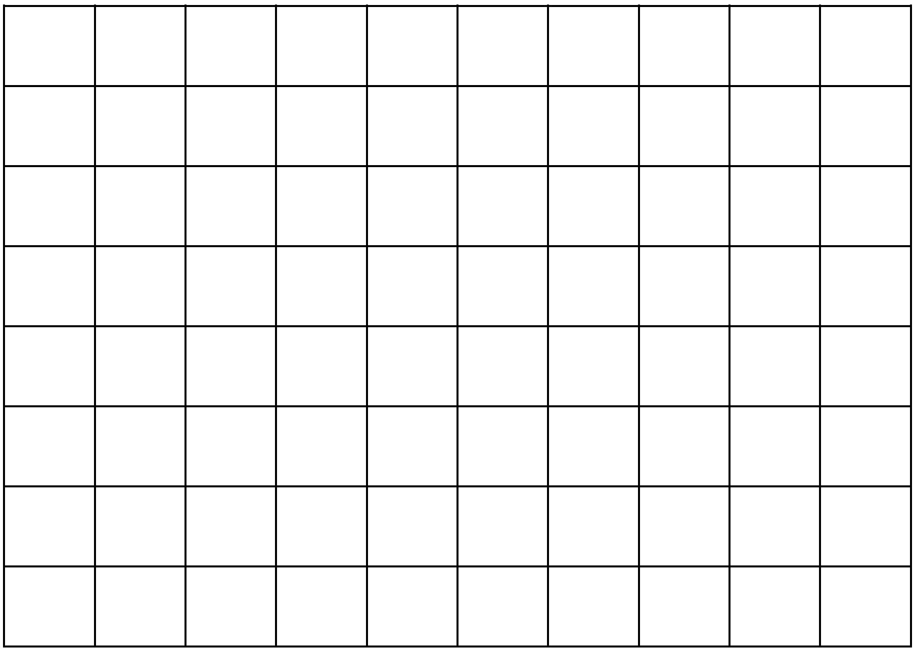
Step 2

Apply power to the breadboard, and with your oscilloscope view the output voltage V_o. It must be square wave.

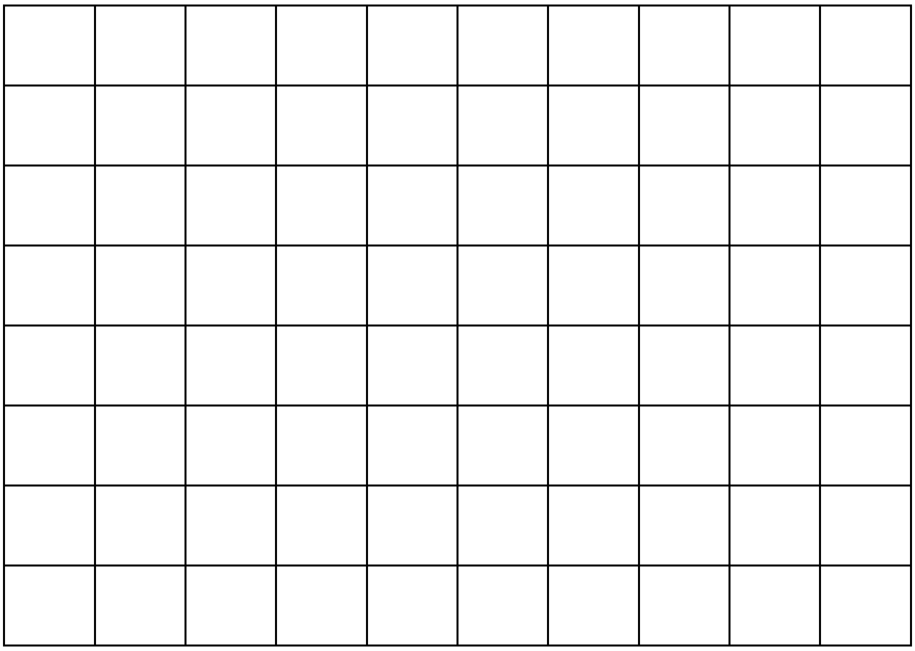
Step 3

Draw down signals V_a , V_o.

Voltage V_a . Oscilloscope settings: __________ V/div. __________ msec/div.



Voltage V_o . Oscilloscope settings: __________ V/div. __________ msec/div.



Step 4

Measure the period of the output voltage and its peak-to-peak value. Record your results as

T_o = ________________ msec; V_{pp} = ________________ V.

Step 5

Using the formula given in the "Design basics" section calculate the output voltage period

$T_o = 2RC\ ln_e (1 + 2R_1 / R_2) =$

= ____ = ____________ msec

Step 6

Switch off the power applied to the breadboard. Reduce the capacitance C 10 times.

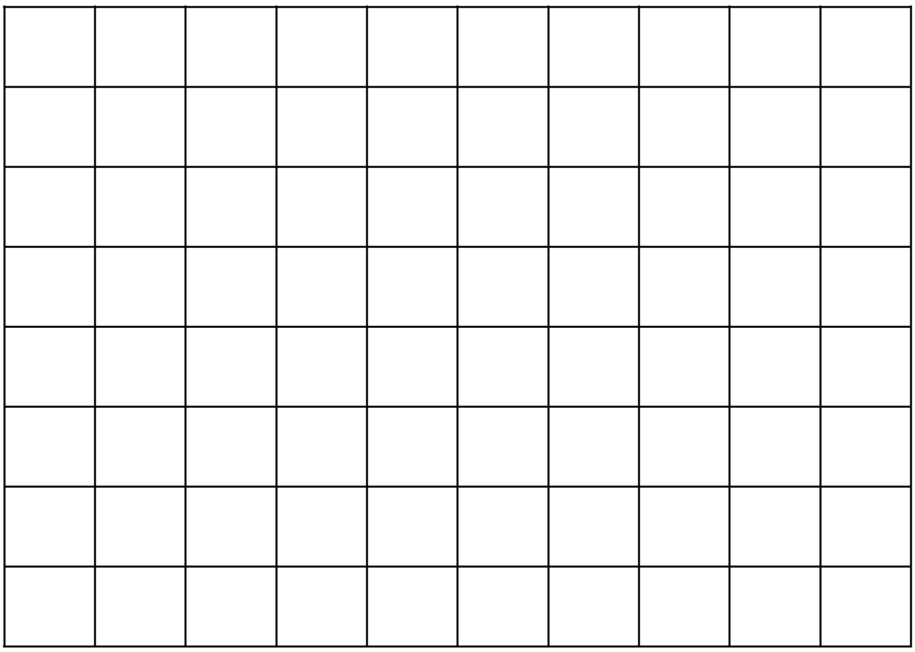
Step 7

Apply power to the breadboard, and with your oscilloscope view the output voltage V_o. It must be distorted square wave.

Step 8

Draw down signals V_a , V_o.

Voltage V_a . Oscilloscope settings: __________ V/div. __________ msec/div.



Voltage V_o . Oscilloscope settings: __________ V/div. __________ msec/div.

Step 9

Measure the period of the output voltage and its peak-to-peak value. Record your results as

T_o = __________________ msec; V_{pp} = __________________ V.

Step 10

Using the formula given in the "Design basics" section calculate the output voltage period

$T_o = 2RC \ln_e(1 + 2R_1 / R_2) =$

____ = ________________ msec

Conclusion

Oscillation period depends mainly on the time constant RC. Op-amp must have high slew rate.

Appendix

Definitions of op-amp specifications

Input Differential Voltage	(V_d)	The difference between input potentials.
Input Common-Mode Voltage	(V_{cm})	Arithmetical mean of input potentials.
Open-Loop Voltage Gain	(A_o)	The ratio of a change of output voltage to the change of input differential voltage applied to produce the output change. The ideal op-amp has $A_o = \infty$.
Differential Input Impedance	(R_d)	The impedance between the two input terminals. The ideal op-amp has $R_d = \infty$.
Common-Mode Input Impedance	(R_{cm})	The impedance between each input and ground. The ideal op-amp has $R_{cm} = \infty$.
Output Impedance	(R_{oi})	The resistance seen "looking into" the op-amp`s output. The ideal op-amp has $R_{oi} = 0$.
Input Bias Current	(I_b)	The current flowing at either input. The ideal op-amp has $I_b = 0$.
Input Offset Current (Input Difference Current)	(I_{os})	The difference of the two input bias currents. The ideal op-amp has $I_{os} = 0$.
Input Offset Voltage	(E_{os})	The voltage that must be applied to one of the input terminals to give a zero output voltage. The ideal op-amp has $E_{os} = 0$.
Common Mode Rejection Ratio	(CMRR)	The ratio of input common mode voltage to input differential voltage that cause the same change of output voltage. The ideal op-amp has CMRR = ∞.
Unity-Gain Signal Response	(f_T)	The frequency at which the open-loop gain becomes unity.
Slew Rate	(SR)	It defines the maximum rate of change of output voltage for a large input step change. The ideal op-amp has SR = ∞.
Output Voltage Swing	(V_{omax})	Depending on the load resistance, this is the maximum peak output voltage that the op-amp can supply without saturation or clipping.

Supply Voltage	(V_s)	The positive and negative voltage that is used to power the op-amp.
Supply Current	(I_s)	The current that is flowing to an op-amp from the source of supply voltage.
Maximum Common-Mode Voltage	($V_{cm,max}$)	The maximum voltage which can be applied between each input and ground without causing permanent damage to the amplifier.
Maximum Differential Voltage	($V_{d,max}$)	The maximum voltage which can be applied between inputs without causing permanent damage to the amplifier.

English - Russian Vocabulary

7.A1	Absolute error	Абсолютная погрешность	9
7.A2	AC voltage	Напряжение переменного тока	35,37
7.A3	Accuracy	Точность	6,7,8,9
7.A4	Approximate	Аппроксимировать	29,30,35,37,38,40,41
7.A5	Autoranging	Автоматический выбор диапазона	9
7.C1	Capacitance	Емкость	6,7,48
7.C2	Capacitor	Конденсатор	7
7.C3	Common mode rejection ratio	Коэффициент ослабления синфазного сигнала	5,22,50
7.C4	Common-mode input impedance	Синфазный входной импеданс	50
7.C5	Common-mode voltage	Синфазное напряжение	6,50,51
7.C6	Component	Элемент (электронный)	3,4,5
7.C7	Current	Ток	5,6,8,14,15,17,18,19
7.D1	DC voltage	Напряжение постоянного тока	8,27,37
7.D2	Decade	Декада	29,34,35,37,38,40
7.D3	Differential input impedance	Дифференциальный входной импеданс	5
7.D4	Differential voltage	Дифференциальное напряжение	6,50
7.D5	Digital multimeter	Цифровой мультиметр	8
7.D6	Dimension	Размер	8
7.D7	Diode	Диод	8
7.D8	Drift	Дрейф	6,7
7.D9	Dual-trace oscilloscope	Двухлучевой осциллограф	8,11

7.E1	Error	Погрешность	9,11,13,15,17,19,45
7.E2	Estimation	Оценка	9,11,13,15,17,19
7.F1	Feedback	Обратная связь	29
7.F2	Feedback ratio	Коэффициент передачи обратной связи	29
7.F3	Fiducial error	Приведенная погрешность	9
7.F4	First order filter	Фильтр первого порядка	38
7.F5	Forward bias voltage	Прямое напряжение смещения	8
7.F6	Frequency response	Частотная характеристика	28,34,35,37,38,50
7.G1	Generator	Генератор	9,24,26,29,31,38,44
7.H1	Half-wave	Однополупериодный	42
7.I1	Input bias current	Входной ток смещения	5,14,15,16,17,50
7.I2	Input offset current	Разность входных токов смещения	18,19,50
7.I3	Input offset voltage	Входное напряжение смещения	5,10,12,13,50
7.I4	Instrument	Измерительный прибор	8,9
7.I5	Inverting input	Инвертирующий вход	14,15
7.L1	Load	Нагрузка	6,50
7.L2	Low-pass filter	Фильтр низких частот	38
7.M1	Marking	Маркировка	6,7
7.N1	Nominal value	Номинальное значение	8
7.N2	Non-inverting input	Неинвертирующий вход	16,17
7.O1	Octave	Октава	29
7.O2	Open-loop voltage gain	Усиление ОУ без обратной связи	5,20,21,50
7.O3	Operational amplifier	Операционный усилитель	5,45
7.O4	Oscillator	Генератор	46
7.O5	Output impedance	Выходной импеданс	6
7.O6	Output voltage swing	Размах выходного напряжения	6
7.P1	Potential	Потенциал	50
7.P2	Potentiometer	Потенциометр	6,7
7.R1	Range	Диапазон	8,9,30,36,39,40
7.R2	Rectifier	Выпрямитель	42,44,45
7.R3	Relative error	Относительная погрешность	9
7.R4	Resistance	Сопротивление	6,7,8,9,50
7.R5	Resistor	Резистор	6,31,32,41
7.R6	Resolution	Разрешающая способность	8

7.R7	Reverse bias voltage	Обратное напряжение смещения	8
7.S1	Saturation	Насыщение	50
7.S2	Scale	Шкала	9
7.S3	Screen	Экран	8
7.S4	Sensitivity	Чувствительность	8
7.S5	Significant digits	Значащие цифры	9
7.S6	Sine generator	Генератор синусоидальных колебаний	9,24,29,38,40,42,44
7.S7	Slew rate	Скорость нарастания	5,24,25,45,49,50
7.S8	Stability	Стабильность	6,7
7.S9	Supply current	Ток питания	6
7.S10	Supply voltage	Напряжение питания	6,11
7.T1	Terminal	Вывод (зажим)	3,50
7.U1	Unity-gain signal response	Частота единичного усиления	5,50
7.W1	Wire	Проводник	3,4

Русско - английский словарь

7.A1	Абсолютная погрешность	Absolute error	9
7.A5	Автоматический выбор диапазона	Autoranging	9
7.A4	Аппроксимировать	Approximate	29,30,35,37,38,40,41
7.I3	Входное напряжение смещения	Input offset voltage	5,10,12,13,50
7.I1	Входной ток смещения	Input bias current	5,14,15,16,17,50
7.T1	Вывод (зажим)	Terminal	3,50
7.R2	Выпрямитель	Rectifier	42,44,45
7.O5	Выходной импеданс	Output impedance	6
7.G1	Генератор	Generator	9,24,26,29,31,38,44
7.O4	Генератор	Oscillator	46
7.S6	Генератор синусоидальных колебаний	Sine generator	9,24,29,38,40,42,44
7.D9	Двухлучевой осциллограф	Dual-trace oscilloscope	8,11
7.D2	Декада	Decade	29,34,35,37,38,40
7.R1	Диапазон	Range	8,9,30,36,39,40
7.D7	Диод	Diode	8

7.D4	Дифференциальное напряжение	Differential voltage	6,50
7.D3	Дифференциальный входной импеданс	Differential input impedance	5
7.D8	Дрейф	Drift	6,7
7.C1	Емкость	Capacitance	6,7,48
7.S5	Значащие цифры	Significant digits	9
7.I4	Измерительный прибор	Instrument	8,9
7.I5	Инвертирующий вход	Inverting input	14,15
7.C2	Конденсатор	Capacitor	7
7.C3	Коэффициент ослабления синфазного сигнала	Common mode rejection ratio	5,22,50
7.F2	Коэффициент передачи обратной связи	Feedback ratio	29
7.M1	Маркировка	Marking	6,7
7.L1	Нагрузка	Load	6,50
7.A2	Напряжение переменного тока	AC voltage	35,37
7.S10	Напряжение питания	Supply voltage	6,11
7.D1	Напряжение постоянного тока	DC voltage	8,27,37
7.S1	Насыщение	Saturation	50
7.N2	Неинвертирующий вход	Non-inverting input	16,17
7.N1	Номинальное значение	Nominal value	8
7.F1	Обратная связь	Feedback	29
7.R7	Обратное напряжение смещения	Reverse bias voltage	8
7.H1	Однополупериодный	Half-wave	42
7.O1	Октава	Octave	29
7.O3	Операционный усилитель	Operational amplifier	5,45
7.R3	Относительная погрешность	Relative error	9
7.E2	Оценка	Estimation	9,11,13,15,17,19
7.E1	Погрешность	Error	9,11,13,15,17,19,45
7.P1	Потенциал	Potential	50
7.P2	Потенциометр	Potentiometer	6,7
7.F3	Приведенная погрешность	Fiducial error	9
7.W1	Проводник	Wire	3,4

7.F5	Прямое напряжение смещения	Forward bias voltage	8
7.O6	Размах выходного напряжения	Output voltage swing	6
7.D6	Размер	Dimension	8
7.I2	Разность входных токов смещения	Input offset current	18,19,50
7.R6	Разрешающая способность	Resolution	8
7.R5	Резистор	Resistor	6,31,32,41
7.C5	Синфазное напряжение	Common-mode voltage	6,50,51
7.C4	Синфазный входной импеданс	Common-mode input impedance	50
7.S7	Скорость нарастания	Slew rate	5,24,25,45,49,50
7.R4	Сопротивление	Resistance	6,7,8,9,50
7.S8	Стабильность	Stability	6,7
7.C7	Ток	Current	5,6,8,14,15,17,18,19
7.S9	Ток питания	Supply current	6
7.A3	Точность	Accuracy	6,7,8,9
7.O2	Усиление ОУ без обратной связи	Open-loop voltage gain	5,20,21,50
7.L2	Фильтр низких частот	Low-pass filter	38
7.F4	Фильтр первого порядка	First order filter	38
7.D5	Цифровой мультиметр	Digital multimeter	8
7.U1	Частота единичного усиления	Unity-gain signal response	5,50
7.F6	Частотная характеристика	Frequency response	28,34,35,37,38,50
7.S4	Чувствительность	Sensitivity	8
7.S2	Шкала	Scale	9
7.S3	Экран	Screen	8
7.C6	Элемент (электронный)	Component	3,4,5

References

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