Exercise 6.

Testing instrumentation amplifiers

Introduction

It may have many causes why we use analogue amplifier stages in a given measurement environment but it is always important that we can work with the instrumentation amplifier in a constructive way, i.e. we should be aware of the limitations (measurement errors, frequency range etc.) brought into the system by the amplifier stage.

The object of the measurement exercise

To offer practical knowledge to the students in the field of instrumentation amplifiers (measuring their parameters, designing feedback amplifiers etc.).

Theoretical base of the exercise

Analysis of the DC properties of operational amplifiers

Some of the parameters of the integrated operational amplifiers can not be measured directly and precisely, e.g. the open loop gain, the common mode rejection, the input impedance, the offset voltage and current etc. The measuring arrangement of such parameters contains always an auxiliary amplifier, therefore it can be used only for the measurement of the parameters of the operational amplifier itself and it can not be used for the measurement of the resulting parameters of the instrumentation amplifier. These indirect measuring methods are listed below:

- measuring the input offset voltage,
- measuring the operation point input (bias) current and the input offset current,
- measuring the open loop gain,
- measuring the common mode rejection ratio,
- measuring the supply voltage rejection ratio.

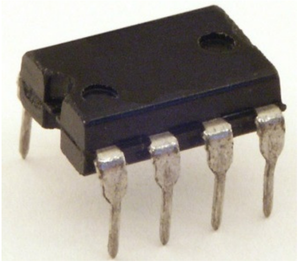
Measurement instruments

Double supply
(±10 V...±20 V)
AGILENT E3630

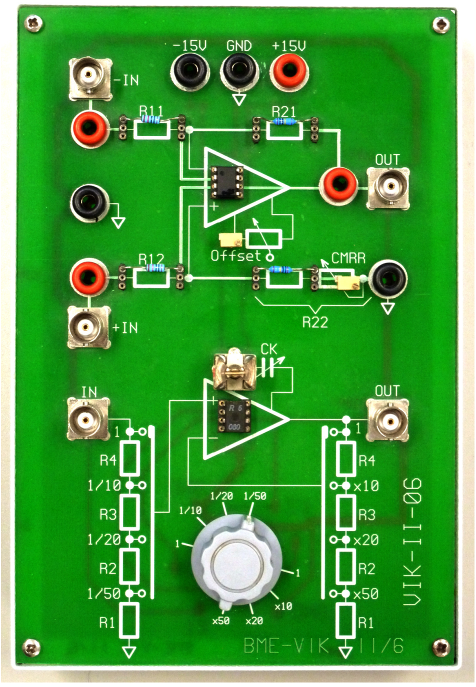
Digital multi-meter
(6½ digit)
AGILENT 33401A

Function generator
(< 20 MHz)
Agilent 33220A

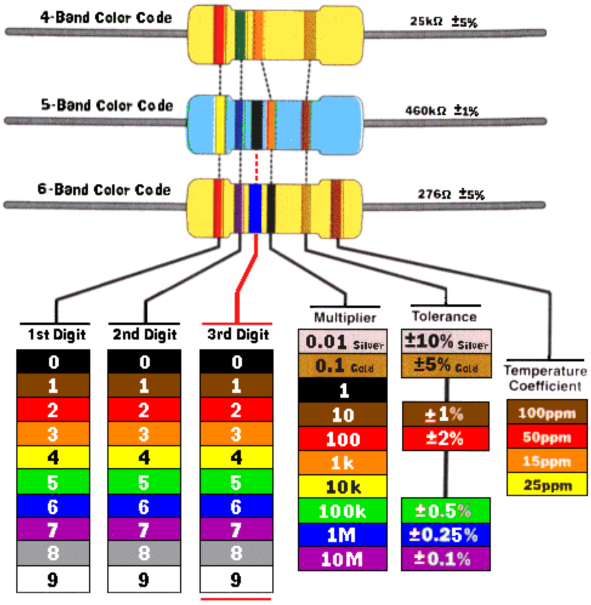
Oscilloscope
(DC - 100MHz)
Agilent 54622A

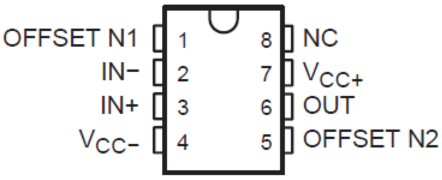


TL071CP



Test board





(Soure: http://www.michaels-electronics-lessons.com/resistor-color-code.html)

RCS-500, Series Resistance & Capacitance Box

Required knowledge (repetition)

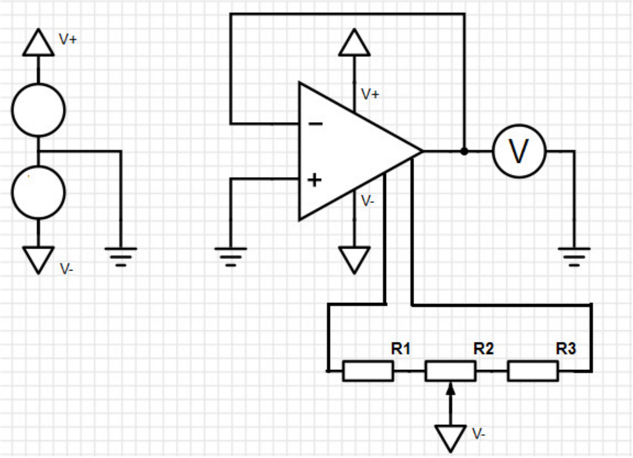
Measuring the input offset voltage (V_{IO})

If you connect 0 V to inputs of the ideal **op**eration **amp**lifier (op-amp), you will measure 0 V on the output. In the real life you usually measure different voltage from 0 V. This voltage deviation is referred as *output offset voltage*.

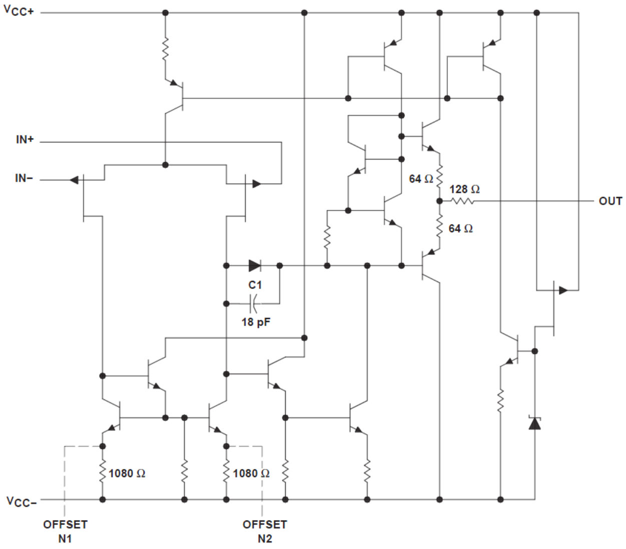
This effect is similar when you connect a DC voltage generator to the input of ideal op-amp, and it results the above-mentioned output offset voltage. The *input offset voltage* is the generator voltage.

Usually the input offset voltage is very small (in our case some µV) value . That's way in the practical application you take advantage of amplifying of the op-amp, and you measure it indirect way at the output of the op-amp.

Elimination of the offset voltage: You connect the non-inverting input to ground, and the inverting input to the output. More op-amp (like TL071CP) has 2 pcs offset inputs to compensate the effect of input offset voltage. On these pins usually are a potentiometer between 2 resistors. The slider of the potentiometer connects to the negative power supply. This circuit is called *Input Offset-Voltage Null Circuit*. You have to adjust the potentiometer to reach the zero output voltage. You must know: the offset voltage depends on the operation point (gain, power supply value and symmetry, temperature, self-heating, etc.). You will see that the output voltage always "crawling" a bit. That's why it is enough to approximate the zero voltage in ±10 µV range.



Additional components and equipment around the op-amp.



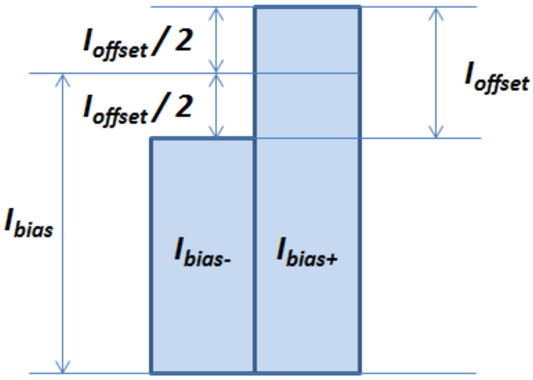
Schematic ot the TL071

Measuring the *operation point input (bias)* current and the *input offset current*,

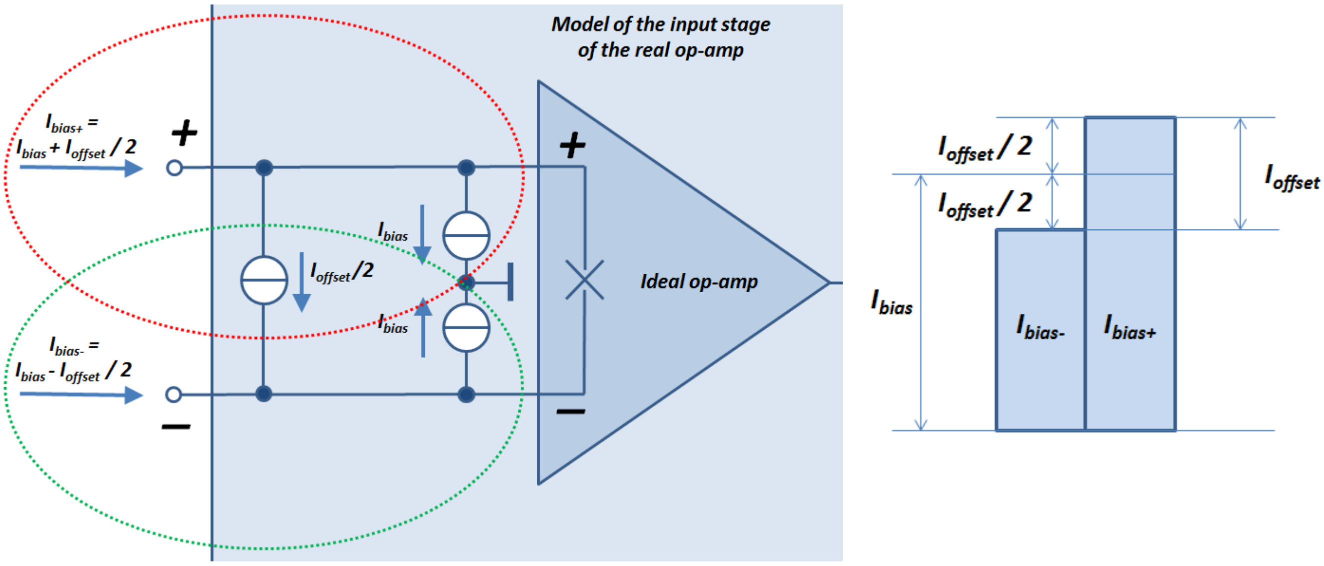
The real op-amp has finite input resistance, and into the both of inputs (+IN,-IN) flow a small current. The difference between the two current is called the *input offset current (I_{offset})*. This current can create the output offset voltage. The *operation point input current (I_{bias})* is the average of the current of the both inputs:

$$I_{offset} = I_{bias+} - I_{bias-}$$

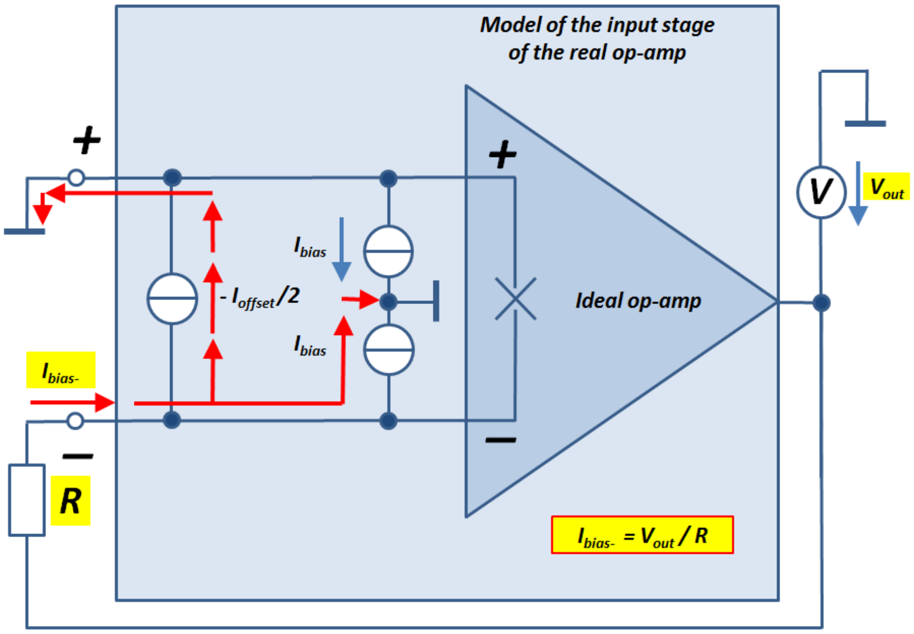
$$I_{bias} = \frac{I_{bias+} + I_{bias-}}{2}$$



These currents are very-very small (around 10 nA)! You are not able to measure it direct way by the standard laboratory equipment. You should apply again **a trick** to do it.



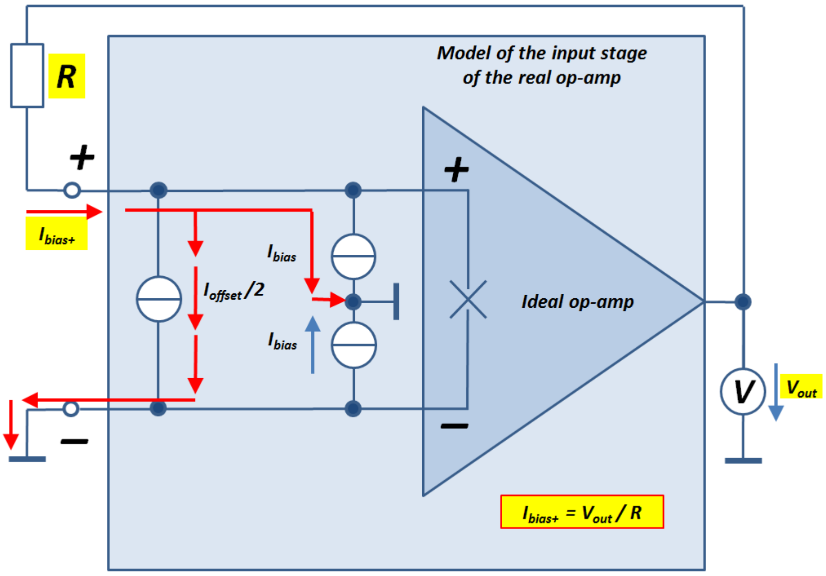
1. You have to eliminate the offset voltage.
2. Connect a known large value resistor (for example 1 MΩ) between the inverting input and the output. The non-inverting input stays on ground. Measure the output voltage, apply the Ohms rule you can calculate the I_{bias-} current.



Let you see: both connectors of the upper I_{bias} current generator are on the ground potention.

3. This step is similar to the previous one. Connect a wire between the inverting input and the output, and connect a large known value resistor between the non-inverting and ground. Measure the output voltage, and calculate the I_{bias+} current.

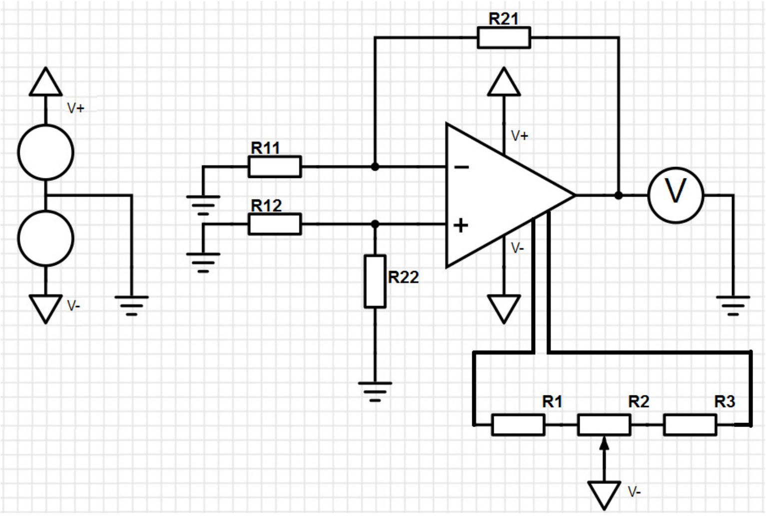
4. Now you can calculate the I_{offset} and I_{bias} too.



Let you see: both connectors of the lower I_{bias} current generator are on the ground potention.

Actual reduced input offset voltages

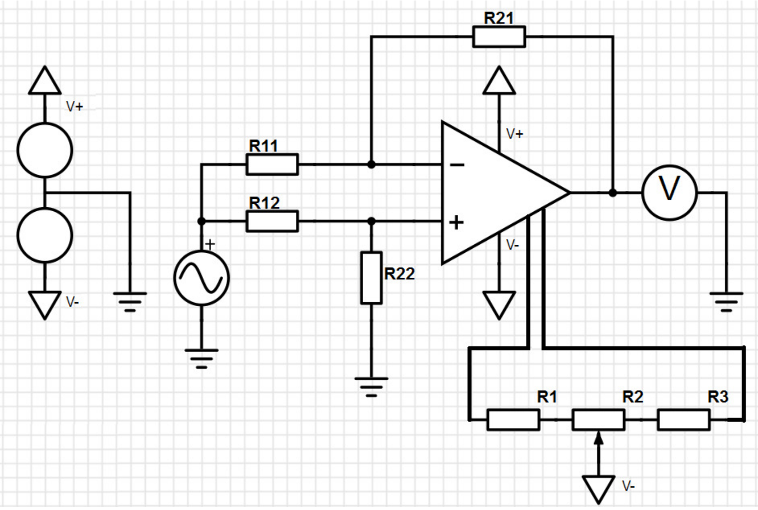
As was mentioned the offset parameters depend on the operation point for example on the gain. In this case you have to connect both of input resistance (R_{11}, R_{12}) to ground, measure the output voltage and divide the measured value by the gain. After all you have to eliminate the output voltage by the potenciometer.



$$V_{reduced\,input} = \frac{V_{out}(all\ input\ resistance\ on\ the\ ground)}{gain}$$

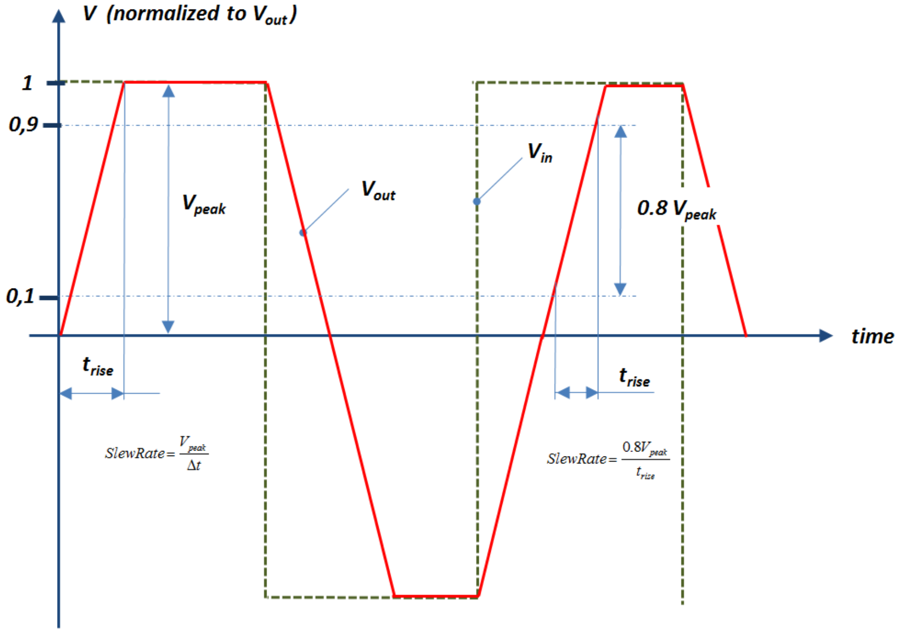
Measuring the common mode rejection ratio

The common mode means to both of input of op-amp get same signal. If you had an ideal op-amp, and applied the common mode, you would measure always zero voltage on the output. But in the real life the input stage is not symmetrical, is not perfect, that’s why you will experience a different voltage from zero. You have to know: when you apply a sine-wave on the common input, then the output voltage waveform can be almost always different form sine-wave due to the nonlinearities of a real amplifier. The amplitude of the input signal is always bigger, then the output one’s, that’s why it is called common mode rejection ratio.



Slew rate

The slew rate is a limit parameter, and it talks about how quick the op-amp can follow the signal changing. When the op-amp is operate above the slew rate limit, you will experience the so called *slewing distortion*. The square-wave signal turns into trapezium-wave.

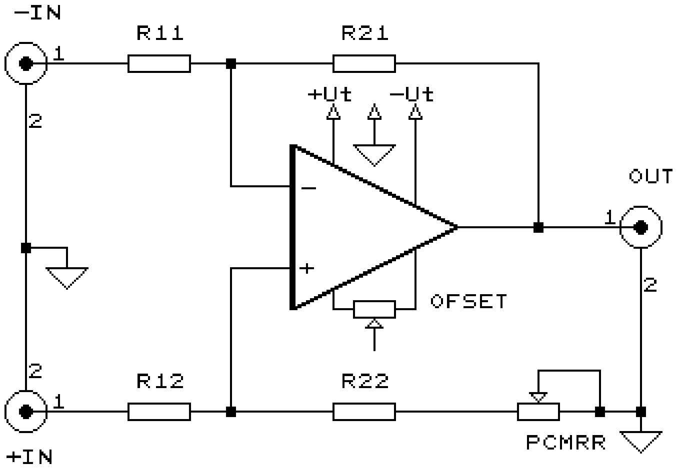


Slope of the trapezium gives the slew rate:

$$SlewRate = \frac{\Delta V_{out}}{\Delta t}, \left[\frac{V}{\mu \sec}\right] \qquad SlewRate = 2\pi \cdot f_{\max} \cdot V_{peak}$$

1. Analysis of the DC properties

1.1. Measuring and setting the input offset.



R_{11} is [,,,] , value, tolerance
R_{12} is [,,,] , value, tolerance
R_{21} is [,,,] , value, tolerance

R_{22} is [,,,] , value, tolerance

1.1.1. Having short-circuited the resistances R_{21} and R_{22}, measure with the DC voltmeter the output voltage of the amplifier, then adjust it by means of the potentiometer POFSET to zero.

1.1.2. Leave the inputs of the amplifier free and make the measurement with a resolution of at least 10 μV.

1.1.3. Remove the short-circuits on by one and repeat the measurement of the output voltage. From the measured data determine by calculation the input (bias) current and offset current of the amplifier.

Measured values:
When the R_{21} is 1 M Ω, then V_{out} = … mV
When the R_{22} is 1 M Ω, then V_{out} = … mV

I_{bias+} , $I_{bias-\_}$, I_{IO}
…

1.1.4. Set a voltage gain of about A_v=100. Having connected the resistances R_{11} and R_{12} to ground, measure the output offset voltage, calculate the actual reduced input offset voltages of the inverting and the non-inverting amplifiers. Then – using the potentiometer POFSET – adjust the output offset voltage to zero.

Measured values:
When the R_{11} and R_{12} are on the ground, then V_{out} = … mV

$V_{reduced\_input}$ = …

1.2. How the offset voltage depends on the supply voltage?

1.2.1. Change the supply voltages symmetrically an asymmetrically by about ±20%. Determine the offset voltage as a function of the supply voltage.

$V_{Supply+}$ [V]	$V_{Supply-}$ [V]	V_{Offset} [mV]

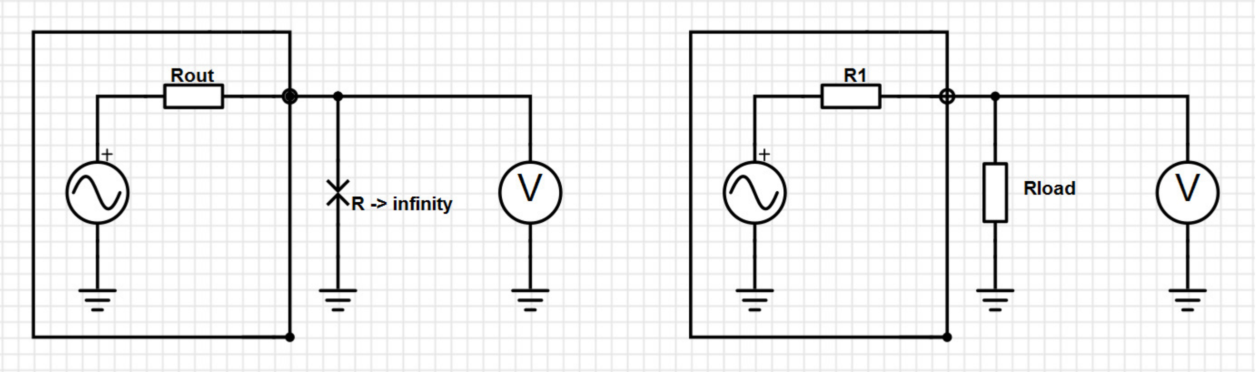
1.3. Determining the Slew Rate and the maximum output voltage

1.3.1. In the case of the gain given in 1.1.4, connect a square-wave signal of 20 kHz on the input of the amplifier and increase it so that the amplifier becomes overdriven. Measure the maximum output voltage swing (V_{outpp} [V]) and the slope of the output signal (SR [V/µs]).

1.4. Determining the limit frequency (and the frequency response) of the maximum output voltage swing 1.4.1. With the value of the Slew Rate determined in the previous paragraph, calculate the limit frequency of the amplifier belonging to the output voltage of V_{out}=10 V_p (7.07 V_{eff}) and measure it also by an oscilloscope.

1.5. Determining the maximum output current and the output resistance of the amplifier **<u>without feedback</u>**.

1.5.1. Load the output of the amplifier with a resistance of R_L=1000 Ω and increasing the input voltage at a frequency of f =1 kHz gradually, measure the maximum output voltage of the feedback amplifier (V_{outmax} [V_p]).



As generally you can calculate the output resistance the next way..

$$V_{out\_loaded} = V_{out\_unloaded} \frac{R_{load}}{R_{out} + R_{load}}, \qquad R_{out} = R_{load} \frac{\left(V_{out\_unloaded} - V_{out\_loaded}\right)}{V_{out\_loaded}}$$

But you have to know, the output resistance of the op-amp depends on the feedback! That's way you have to measure it other way. $R_{out} = \frac{V_{open\_circuit}}{I_{short\_circuit}} = \frac{R_{out\_without\_feedback}}{1 + A \cdot B}$

where AB is the *loop gain*. (A = open-loop gain, B = feedback factor)

1.5.2. Measure the maximum output voltage with open circuit load ($V_{outomax}$ [V_p]). From the results of the two measurements calculate the output resistance of the amplifier without feedback. Check the result in the catalogue.

V_{outmax} = ….V_p Rload = 1000 Ω Rout = …. Ω

Analysis of the dynamic features

2.1. Measuring the Bode plot of an inverting amplifier ($A(f))_v$

2.1.1. Connect the output of the sine-wave generator to the inverting input of the instrumentation amplifier and connect the non-inverting input to ground. Measure input and output voltages and the phase shift of the amplifier with an oscilloscope. Make the measurement in the following way: at a frequency of 1 kHz set an output voltage 7 V_{eff} (0 dB) using the AC voltmeter, then changing the frequency in the range 1 Hz – 1 MHz in 1-2-5-10 steps, measure the effective value of the input and the output voltages and the phase shift. On the base of the measured data calculate and plot the Bode diagram of the inverting amplifier.

2.1.2. Determine the limit frequency of the amplifier belonging to a decrease of -3 dB.

2.2. Measuring the common mode gain of an instrumentation amplifier ($A(f)_{vc}$)

2.2.1. Apply a short circuit between the inputs of the instrumentation amplifier and give a sine-wave of 3 V_{eff} between the short circuit and the ground. Measure the input and output voltages and the phase shift using an oscilloscope and an AC voltmeter.

2.2.2. In the reference branch, by means of the potentiometer PCMRR, which is series connected to the resistance *R22,* set the minimum of the common mode voltage gain at a frequency of f = 10 Hz and measure this common gain.

2.2.3. Take the Bode diagram of the common mode voltage gain of the instrumentation amplifier and plot it in the frequency range of 10 Hz-1 MHz.

2.3. Measuring the Bode diagram of a non-inverting instrumentation amplifier ($A(f)_v$)

2.3.1. Connect the output of the sine-wave generator to the non-inverting input of the instrumentation amplifier and connect the inverting input to ground. Measure the input and output voltages and the phase shift of the amplifier by means of an oscilloscope and an AC voltmeter.

2.3.2. Take the Bode diagram of the non-inverting amplifier at the same frequencies and input amplitudes, which were used in case of the Bode diagram measurement of the inverting amplifier. Plot the results of the measurement in a common diagram with the Bode diagram of the inverting amplifier.

Test questions

1. What is called offset voltage and offset current?
2. What is called operation point input (or bias) current?
3. What is called open loop gain?
4. What is called loop-gain?
5. What is called common mode rejection ratio?
6. What is called maximum output voltage swing?
7. What is the relation among the following parameters of an operational amplifier: A_{vd}, A_{vc} and $CMRR$?
8. Why is not possible to measure directly A_{vd} and A_{vc}?

9. When is it reasonable to use an internally or an externally compensated operational amplifier?
10. What determines the slew rate of an operational amplifier?
11. What is called amplitude and phase margin?
12. How is modified the frequency response of an amplifier by a negative feedback?
13. What is called maximally flat magnitude (or amplitude) response?
14. What kind of methods do you know for the frequency (or phase) compensation of feedback amplifiers?