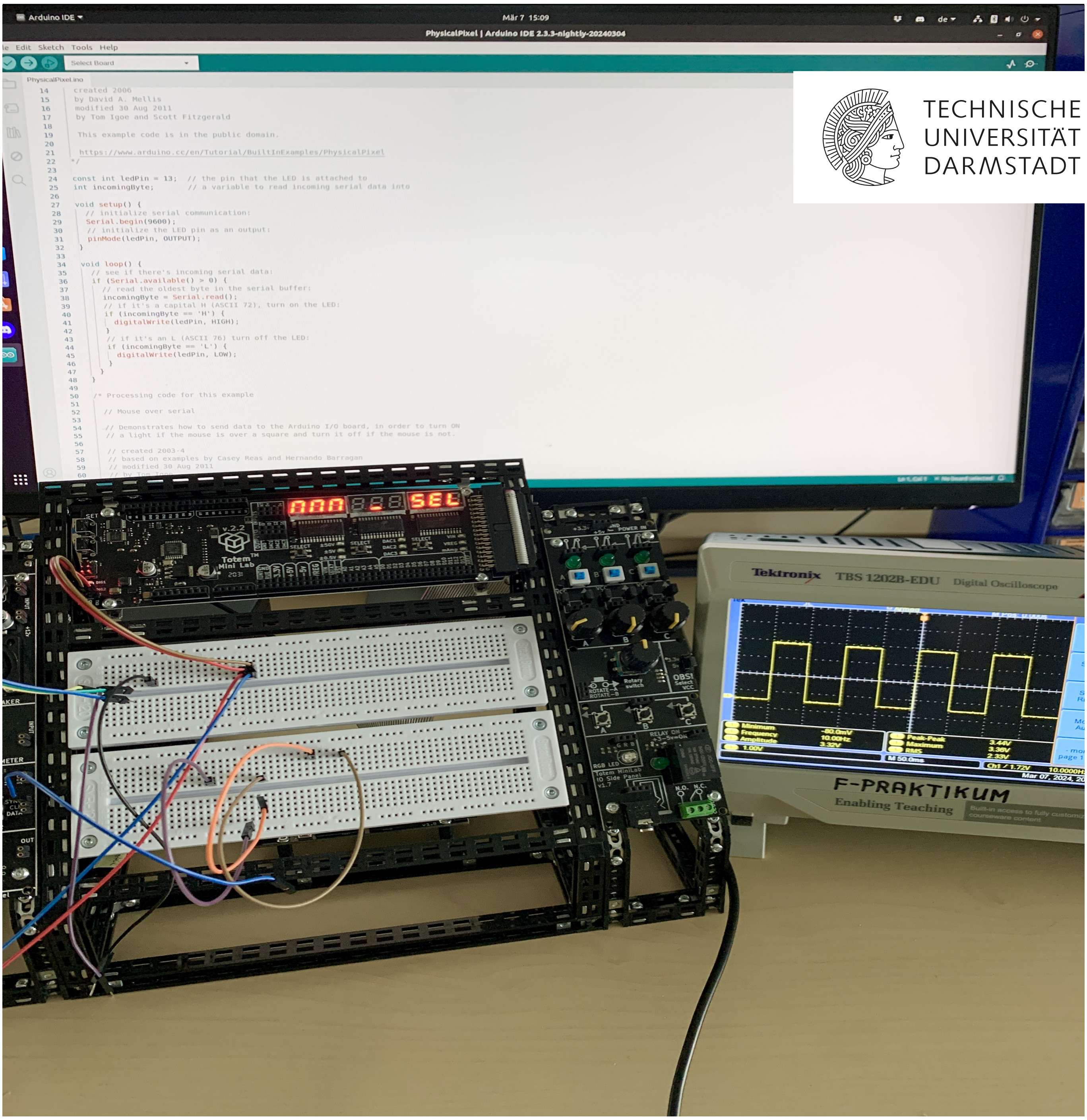
5.1-C: Experiments and simulations of operational amplifier circuit with Arduino



1 Introduction

In experimental nuclear physics, various types of detectors are used to observe physical phenomena: Scintillation detectors, Ionization detectors, etc. These detectors provide a variety of information in the form of electrical signals. In order to extract this information, the signal must be further processed by an electronic system. This experiment should familiarize you with the basic properties and applications of operational amplifiers and should give you an insight into circuit simulation technology with SimulIDE. In the first part of the experiment, several operational amplifier circuits are to be set up and examined. In the second part, the circuits are to be simulated with the PC and the results of the hands-on are to be compared to the results of the computer simulation.

APPLICATIONS: Operational amplifier circuits are used for a variety of tasks. The name "operational amplifier" comes from analog computer technology. The most common applications for operational amplifiers are the amplification and filtering of signals in measurement technology, control and regulation technology and consumer electronics.

The technique of pulse shaping with pole zero cancellation is used in nuclear physics measurements when pulses from counters are evaluated. Without pole-zero cancellation, some of the impulses would not be registered due to superposition effects.

2 Preparation

The basic knowledge of the following contents is required for the advanced study course:

- Kirchhoff's law, Bode plot
- Ideal and real operational amplifiers
- Transmission behavior of passive high, low passes and active filters
- Voltage follower circuit, inverting amplifier
- Programming language: Arduino, Python (or Mathematica)
- Essential electronics of nuclear physics: preamplifier, amplifier, shaper.

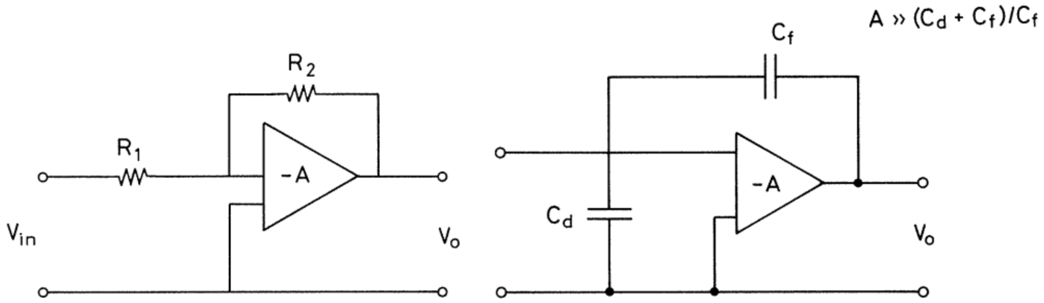


Figure 1: Schematic diagram of a voltage sensitive preamplifier and a charge sensitive preamplifer[1]

3 Equipment

3.1 Operational Amplifier

An operational amplifier (op-amp) is a DC-coupled electronic voltage amplifier. It has two differential input and a one single-ended output. It is operated with external feedback components such as resistor and capacitors to determine the resulting function.

The μA741 device is a general-purpose operational amplifier featuring offset-voltage null capability.

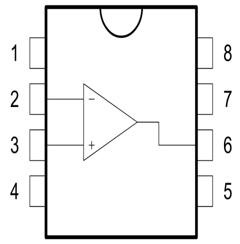


Figure 2: Pin configuration of ua741cn[3]

No.	Name	Description
1	OFFSET	External input offset voltage adjustment
2	IN-	Inverting input
3	IN+	Non-inverting input
4	Vcc-	Negative supply
5	OFFSET	External input offset voltage adjustment
6	Out	Output
7	Vcc+	Positive supply
8	NC	No internal connection

Table 1: Pin functions

3.2 Totem Mini Lab

Totem Mini Lab is a complete toolkit of studying electronics and programming. It consists of Totemduino, which is an improved version of Arduino UNO platform, LabBoard, breadboard and add-on side panels. Mini Lab is designed to be used together with the Totem construction system which allows users to build solid workbenches with integrated breadboards, as well as available expansion boards that can further extend the capabilities of the Mini Lab.

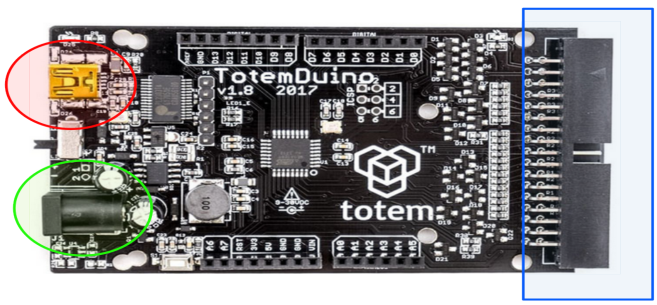


Figure 3: Totemduino board[2]

Totemduino is an one of the main parts of the Totem Mini Lab. It is based on the Arduino UNO board. It has corresponding function as the Arduino board and includes additional features, such as: Output protection, expansion port, powerful 5 V regulator, and selectable microcontroller logic voltage.

LabBoard is a second key component of the Totem Mini Lab. It is used as an expansion board for Totemduino, also functioning as an additional unit for measuring and testing. (Green box in Figure 4)

Side panel is a collection of basic most commonly used electronics blocks that are used together with Totem Mini Lab (Blue colored box in Figure 4). It consists of a digitally controlled function generator AD9833 chip.

Breadboard is a construction base used to build semi-permanent prototypes of electronic circuits. It includes a perforated block to connect electric components without soldering (Red colored box in Figure 4). Metal strips inside the breadboard are used to make connections between pins. A breadboard consists of two types of areas:

- Terminal strip: holding most of the electronic components
- Bus strip: providing power to the electronic components

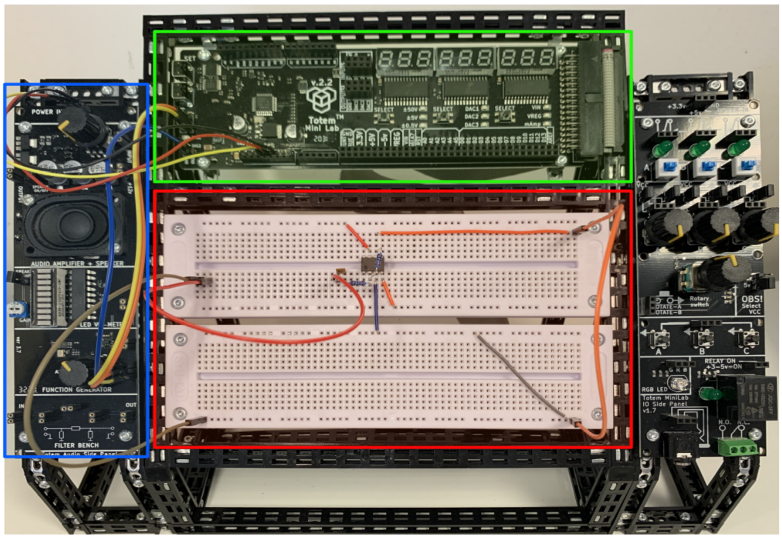


Figure 4: Totem Mini Lab

4 Simulation

SimulIDE is a simple real-time electronic circuit simulator. It supports various components of electronic circuit from passive components (resistors, capacitors, inductors ...), active components (diodes, transistor, op-amp...), microcontroller to Oscilloscope. The components are placed and connected on a central canvas by drag-and-drop.
This will be used to simulate all the electric circuits, which will be introduced later in Chapter 5.3, and to predict and evaluate the results.

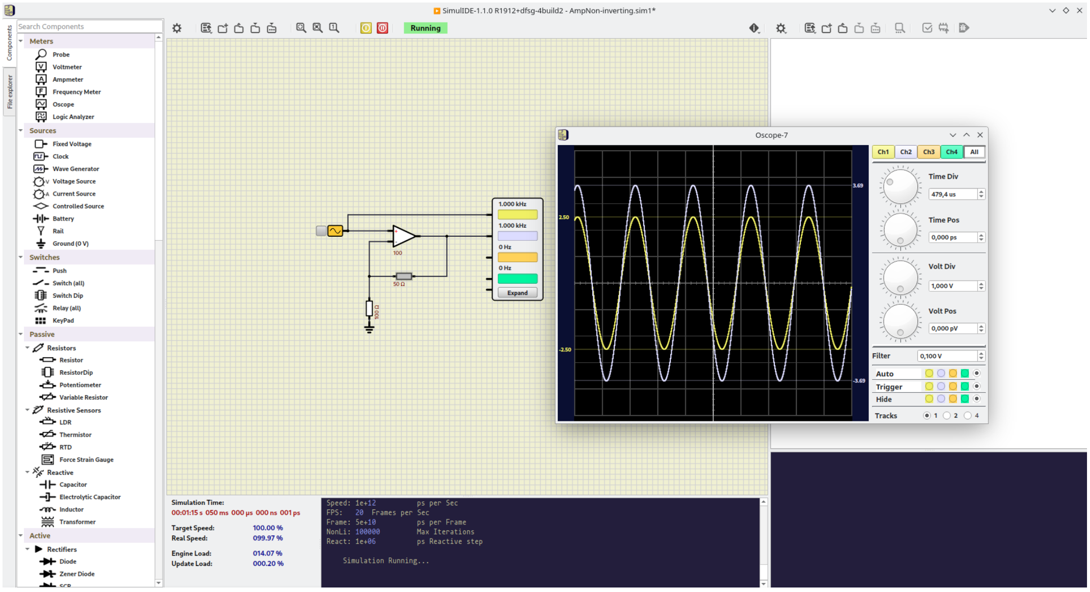


Figure 5: SimulIDE with non-inverting amplifier

5 Experiment execution

5.1 Totem Mini Lab

Connection and communication

Check the connection of Totem Mini Lab and PC (micro USB port on totemduino, red circle in Figure 3). As a first step, copy the script that causes the LED on the totemduino to blink into the Arduino IDE and check the connection by running the script.

```
void setup(){
    pinMode(LED_BUILTIN, OUTPUT);
}
void loop(){
    digitalWrite(LED_BUILTIN, HIGH);
    delay(1000);
    digitalWrite(LED_BUILTIN, LOW);
    delay(1000);
}
```

The connection is valid when the LED of totemduino blinks.

Pulse generator

Make a pulse generator using build-in digital I/O pin (Blue colored box in Figure 3). It needs to be connected to the labboard by flat cable.

i Generate rectangular pulse and check it in oscilloscope.

ii Use two outputs (D13 as a signal, GND as a ground) on labboard

iii Use delayMicroseconds() and digitalWrite() functions to control the period of the pulse.

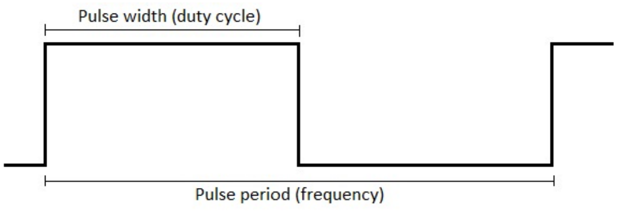


Figure 6: Pulse shape as generated by main board

There is a second method to use pulse generator function on Totem Mini Lab. It use side panel of Totem Mini Lab. It is capable to generate sine, triangle, square wave output signal in up to 12.5 MHz. Generating pulse with two different method and compare it on oscilloscope. And extract the waveform in oscilloscope as a text file and draw graph.

5.2 Connection of power supplies to breadboard

The op-amp operates with DC voltage input(Figure 2). The circuit is powered by a bipolar power supply based on two single-supply power sources connected in series to provide symmetrical +V and -V voltages to the op-amps. In this case, dual output DC power supply is used as a power source.

1. Connect positive output of first channel (V1+) to one bus strip on bread board.
2. Connect negative output of V1 to positive output of V2 and connect second bus strip in bread board. This bus connects in third bus strip on bread board.
3. Connect negative output of V2 to forth bus strip on bread board.

Set the voltages and check with multimeter.

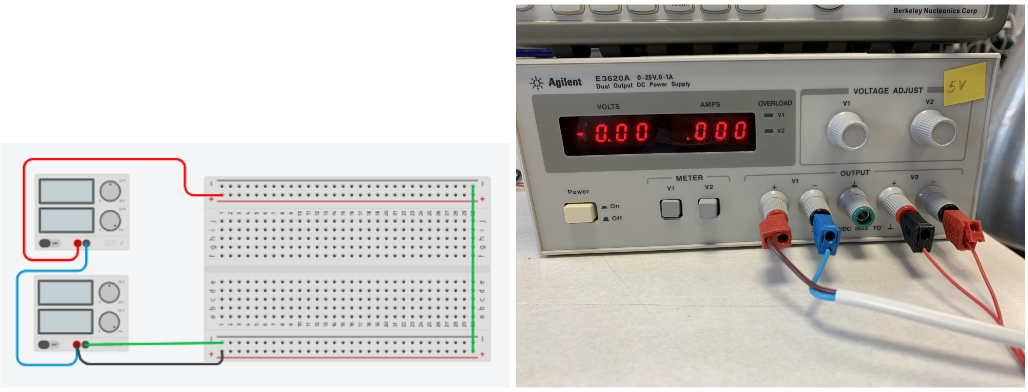


Figure 7: Voltage connection in breadboard with 2-channel DC power supply(left). Dual output power supply(Right)

5.3 Electric circuits with an operational amplifier(op-amp)

5.3.1 Amplifier

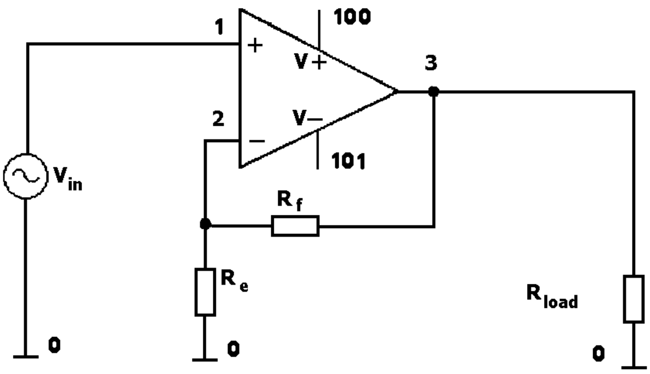


Figure 8: Operational amplifier in non-inverting configuration

Structure with op-amp 1 in non-inverting wiring

i Adjust the offset voltage with grounded inputs and at different values of R_f. Adjust the probe using the square wave signal from the calibration output of the oscilloscope

ii Measure the clipping limit at different amplifications with a triangular signal at the input (in the following process care must be taken that the amplifier is not clipped).

iii Bandwidth measurement. Measure the -3 db cutoff frequency at different gains to calculate the gain-bandwidth product. Use a sinusoidal voltage as input signal. The output voltage should be kept constant. Component values: $R_e = 100\ \Omega$; $R_f = 910\ \Omega$ or 4.7 kΩ or 9.1 kΩ

Structure with op-amp 1 in inverting wiring

i Match the offset voltage with grounded inputs and 10x amplification

ii Measure the voltage between the inverting input (virtual earth) and earth. Use a wide-width square wave as input signal. Sketch the oscillogram and determine the fall time of the signal. Component values: $R_f = 10$ kΩ; $R_e = 10$ kΩ or 100 kΩ.

5.3.2 Filter

Structure with op-amp 2 in inverting circuitry. 1st order low and high pass

i Construction of a first-order low-pass filter. Use a square-wave voltage with $T \ll \tau_0$ as the input signal. Measure and plot the step response. Measure the output amplitude for five different val-

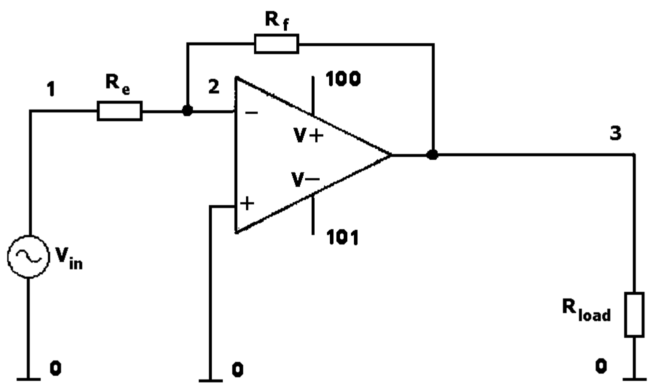


Figure 9: Operational amplifier in inverting configuration

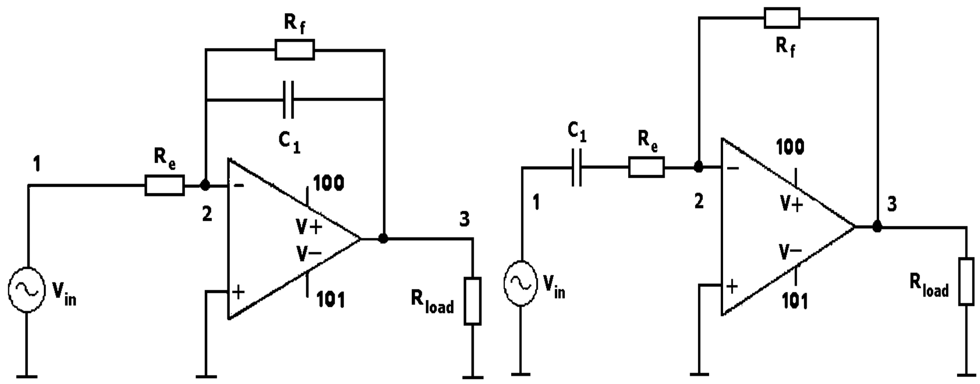


Figure 10: First-order low-pass filter(left). First-order high-pass filter(right).

ues for the input amplitude and two different periods T of the input signal. Component values: $R_e = 10$ kΩ; $R_f = 10$ kΩ; $C_1 = 10$nF.

ii Construction of a first-order high-pass filter. Use a square-wave voltage with $T \gg \tau_0$ as the input signal. Sketch the step response. Find the cutoff frequency of the filter. Component values: $R_e = 10$ kΩ; $R_f = 10$ kΩ; $C_1 = 10$nF.

5.3.3 Other applications

Structure with OP3

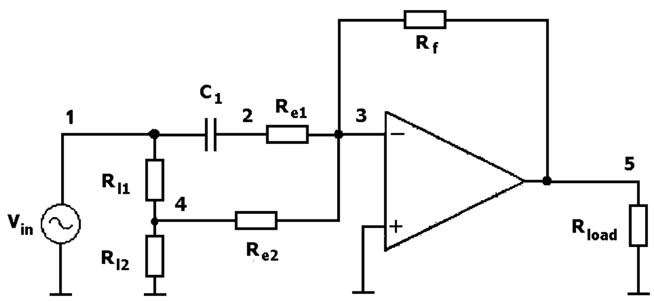


Figure 11: Pole zero cancellation: setting of K (measuring plug)

i Pulse shaping for a radiation detector (see Figure 11 and 12). Measurement with the oscilloscope:

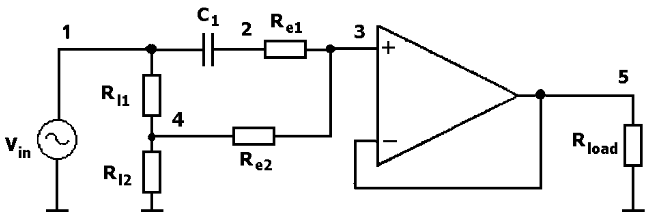


Figure 12: Pole zero cancellation: Determination of K (data connector)

- Use signals from the random pulse generator to display and sketch the so-called ”pile-up” on the oscilloscope.
- Reduce the ”pile-up” by using a first-order high-pass filter. Sketch the ”pile-down” that is now occurring.
- Pulse shaping with pole-zero cancellation. Use the random pulse generator with two different time constants for the exponential drop (τ = 100 μs and 200 μs) and perform the adjustment by varying the fraction K of the input amplitude U_e that can be set on the potentiometer. To do this, use the jumper labeled ”measuring plug” on the breadboard. Then the set value for K is to be determined by using the input-side four-terminal network as an input network in a non-inverting amplifier (voltage follower) (see Figure 12). To do this, the measuring plug on the plug-in board is exchanged for the data plug. Use a square-wave voltage with a large time constant as the input signal. Sketch the pulse shapes.

ii Structure of the 2nd order low-pass filter and examination of the transmission characteristics with sine and square-wave signals (see Figure 13 and 14): The following filters with a fixed gain V_0 = 1 are available: (1) Bessel filter, (2) Butterworth filter, (3) Chebyshev filter with 3 db ripple, (4) variable gain low pass filters. Measure the output amplitude as a function of frequency in the range 100 Hz to 10 kHz with a sinusoidal input signal. Sketch the frequency response with an increased number of measurement points in the area around the cut-off frequency of the filters of 1 kHz. Measure the step response of the filters using a 100 Hz square wave as the input signal.

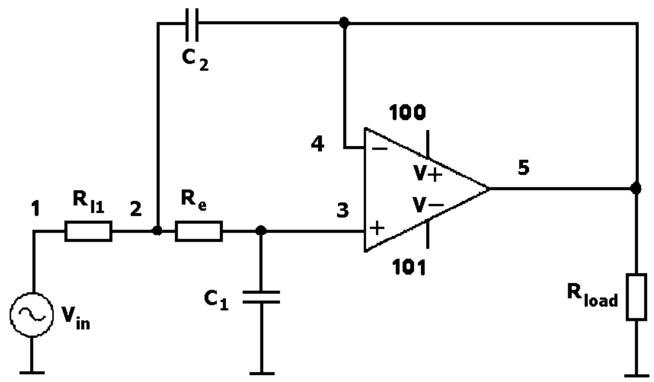


Figure 13: Second-order low-pass filter

5.4 Simulation

1. Simulate the operational amplifier in a non-inverting circuit (see Figure 8). Calculate the gain-bandwidth product from the results.
2. Transfer function and step response of the 2nd order filter. Examine the frequency response and step response of the filters. Create graphs for frequency response, phase response, and step response.
3. Cmpare the properties of the OP model with an idealized OP by simulating a 1st order high-pass filter with both the μA741 model and a voltage-controlled voltage source (ideal OP). Compare the frequency response, step response and signal at the inverting input of the two models.

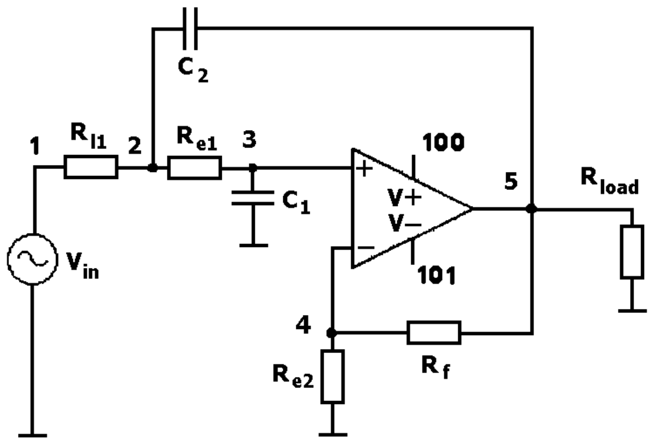


Figure 14: Second-order low-pass filter with variable gain

6 Analysis

6.1 Evaluation of the measurements

For measurement on op-amp 1 in non-inverting circuit

i Explain the effect of the external gain on the offset voltage adjustment. How exactly were you able to set the offset voltage in each case?

ii Sketch the output signal in the overdriven case. Which limitation follows from this measurement for the following test procedure?

iii Compare the measured gain-bandwidth products with the theoretical value. What is the cause of the deviation in gain one? Discuss the possible sources of error of the oscilloscope and the multimeter when measuring AC voltages.

For measurement on op-amp 1 in inverting circuit

i Already treated.

ii Interpret the shape of the signal at the inverting input, derive the expected response signal to a step function on the virtual earth theoretically and compare both the curve shape and the fall time with the experiment.

For measurement with op-amp 2 in inverting circuit

i Derive the transfer function of the circuit and show the integrator behavior for square-wave pulsed with $T \ll \tau$ (Hint: Expand the output signal in a Taylor series in t). Plot the measured output amplitudes over the input amplitude and use this to prove the integrator behavior.

ii Calculate the step response of the circuit and show the differentiator behavior. Compare the measured cutoff frequency with theory.

Regarding the measurements with op-amp 3

i Pulse shaping measurement:
Describe the approach taken in the experiment to shape the output signals in a way that is advantageous for pulse counting(”pile up”, ”pile down”, ”pole zero cancellation”). Derive the transfer function for the circuit used and the pole-zero condition. Calculate with value K has to be set for the pole-zero cancellation and compare with the experiment.

ii Measurements with 2nd order filters:
Discuss the advantages and disadvantages of the different filter types (slope, distortion of signals, ...)

Simulation

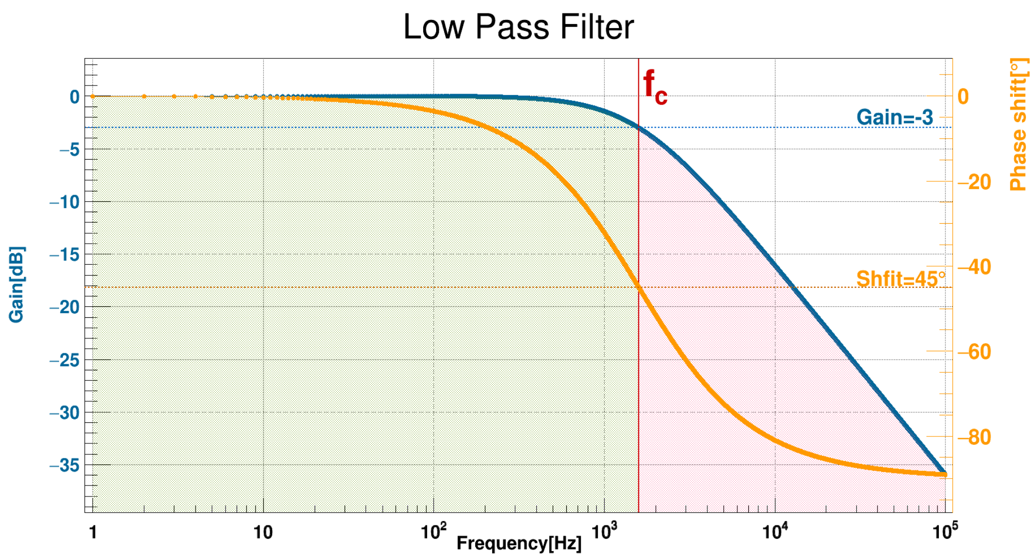
Compare the results of the simulation with those of your measurements. Where are there deviations from the practice and why? What limits the accuracy of the simulation?

6.2 Bode plot

A Bode plot is a graph of the frequency response of an electric circuit. It is a combination of Bode magnitude plot and Bode phase plot (see Figure 15). The Bode magnitude plot shows frequency dependence of the output gain of a circuit. The frequency is plotted logarithmically and the output gain is given in decibels.

$$\text{Gain} = 20 \cdot \log_{10} \frac{V_{\text{out}}}{V_{\text{in}}}$$

The Bode magnitude plot of the low pass filter (Figure 15,top) shows the frequency response to almost unity for a frequency below the cut-off frequency point(f_c). When the frequency reaches the f_c point, the output signal is attenuated to 70.7% of the input signal value (corresponding to -3 dB of gain).
The Bode phase plot is the graph of the phase. Similar to the magnitude plot, the frequency is plotted logarithmically and the phase is plotted linearly. Due to the filter contains a capacitor, the phase angle of the output signal lags behind that of the input and is -45° out of phase at the -3dB cut-off frequency(f_c).



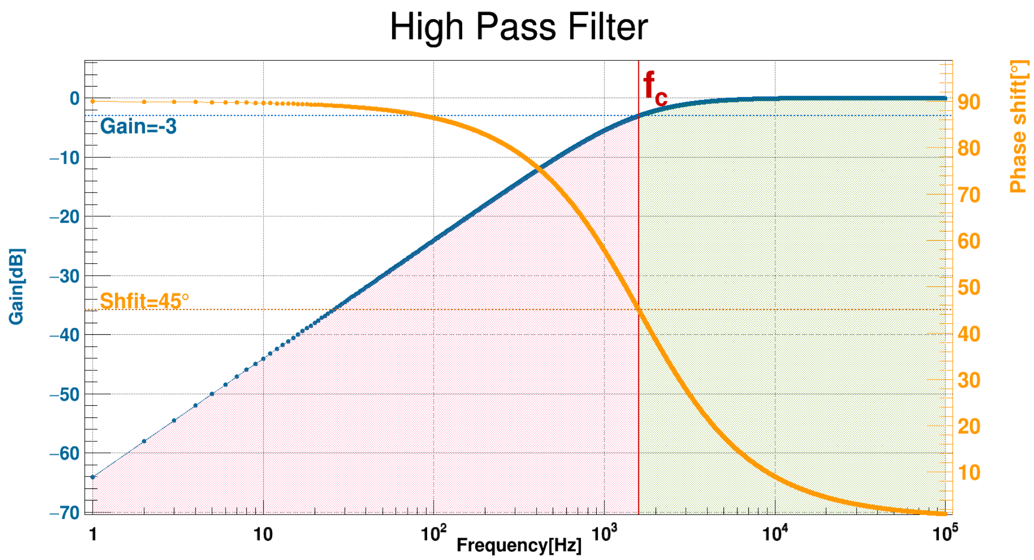


Figure 15: Bode plot of 1st order low pass filter(top)and high pass filter(bottom).Blue lined graph is the Bode magnitude plot and orange lined graph is the Bode phase plot.

References

[1] William R. Leo. *Techniques for Nuclear and Particle Physics Experiments*. Springer Berlin, Heidelberg, 1994.

[2] *MiniLab: totemduino. Totem Documentation*. URL: https://docs.totemmaker.net/totemduino/.

[3] STMicroelectronics. *Data sheet - Production data: uA 741*.