5ECA0-TV3: design and build a band-pass amplifier

August 2, 2021

Chapter 1

Preparation

1.1 Disclaimer

Contrary to other years, this lab is performed at home. This means that the supervision for this lab is, due to circumstances, limited. We assume that you follow the steps described in this lab carefully. We do not bear responsibility for events, accidents or material damage caused by experimentation with the lab materials that lie outside the scope and/or instructions of the assignments described here.

This lab is designed to be performed without technician supervision and the TU/e is not able to ensure safety for experiments outside of designated laboratories. By performing the following experiment, we expect you to follow the steps carefully, and to stop and check when unsure how to proceed. If in doubt, powerdown and stop your experiment. These experiments should be performed in groups of at least two students.

1.2 Preface

The hearing range of humans has a frequency range or bandwidth of approximately 20 Hz to 20 kHz. That means that, for example, the sound system on your computer does not have to amplify signals with frequencies outside of this range. Limiting the frequency range of your sound system does not only save power, but it helps to decrease the amount of noise your audio set produces.

With the aid of an amplifier the amplitude of a signal can be increased with a certain gain factor. The frequencies we are interested in can be filtered out by a designed electronic band-pass filter. In this experimental skills (TV) lab you are going to calculate the gain and frequency span of an audio amplifier and build and measure such a system step-by-step.

The knowledge and experience you gain in this lab will be of use if you participate in the upcoming "Rock your baby" project. Furthermore, PRV41 "reflection" is linked to this lab. Regarding the PRV, you will be assessed for your plan and for the quality of your reflection.

1.3 Organization

- Location: Home
- Work load: 10 hours
- Cooperation: It is recommended to perform in groups of two students.
- Supervision: This lab is supported by online Teaching Assistants. You are encouraged to ask questions. Asking questions will not reflect on your grade. Improved experimental outcomes can.

- Grading: You will receive marks for demonstrating a working circuit per subcircuit. Additionally, you will need to provide explanations of your design choices and experimental outcomes in a specially designed canvas quiz. The questions are included as an appendix for your convenience.

1.4 Before starting

- Supply yourself with writing materials such that you can make notes. You will need to explain design choices, and details and calculations are easily forgotten.
- Install the myDAQ readout software ELVIS. It can be downloaded from `https://www.ni.com/nl-nl/support/downloads/drivers/download.ni-elvismx.html#305452` and the installation takes about 10 minutes. Note that ELVIS is unsupported for Linux and Mac.
- Insert the connector into the myDAQ. This is best done by keeping the connector at an angle towards the myDAQ and sliding it in. You can now attach wires to the separate channels of the DAQ by screwing them to the connector.
- Check the components of the box you received to perform this lab at home. It should contain a National Instruments NI myDAQ, a 20-pins connector for the myDAQ, two measurement probes, a screwdriver, a breadboard, a headphone, a bag of capacitors (5 pieces), a bag of resistors (10 pieces), a bag of special components (a potmeter and two LM741 OpAmps) and wires. The resistors should have the following values: $[150\Omega, 680\Omega, 1.0k\Omega, 1.5k\Omega, 3.9k\Omega, 10k\Omega(\times 2), 27k\Omega, 68k\Omega, 82k\Omega, 100k\Omega]$. The capacitors should have the following values: $[10nF, 100nF, 1\mu F, 10\mu F, 100\mu F]$. You can check the values of these components by checking the color codes on the resistors and the inscriptions on the capacitors or by measuring them with the Impedance Analyser of the myDAQ software ELVIS.
- Check whether the headphones work by attaching them to your computer and playing some songs. We would recommend choosing a song with clearly recognizable high and low frequnecy tones like *"First Contact"* from *"DaftPunk"* for this, such that you can easily recognize distortions in the signals when tuning your filters during the rest of the lab.

1.5 Report

Your calculations and measurements will be checked to determine your grade for this lab. For each of the assignments, describe the relevant calculations and possible design choices briefly - just a calculation or graph is sufficient. Additionally, provide short answers showing that you understand where certain distortion e.g. come from for the open questions that are asked. Provide screen shots of the signal generator settings and measurement results to support your answers.

In the graphs you will use a logarithmic scale for plotting power ratios. We will learn more about the reasons for plotting with logarithmic units and logarithmic axes in week 7. For this exercise, be aware that the ratio of power out of a circuit relative to the power into a circuit can be expressed

Power ratio for the circuit = $20 \log_{10} (V_{OUT} / V_{IN})$ dB.

This means that when $V_{OUT} = 1/2\ V_{IN}$, the power ratio is $20 \log_{10} (1/2) = 6$ dB.

Chapter 2

Assignment

You will desing a low-pass filter and a high-pass filter, tune an amplifier circuit and combine these subcircuits into a band-pass filter. This is a filter which you will learn about in week 7. Finally, you will adjust your band-pass circuit for audio input and output, after which you can listen to a filtered version of your playlist.

2.1 Low-pass filter

You will design a low-pass filter (LPF) and build a circuit that will filter out the high frequencies. A so-called LPF is shown in Figure 2.1.. Simple low-pass (and high-pass) filters reduce the output voltage by a factor of two at a cut off frequency fc which is defined as (2π RC)$^{-1}$.

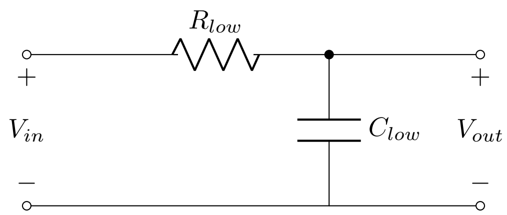


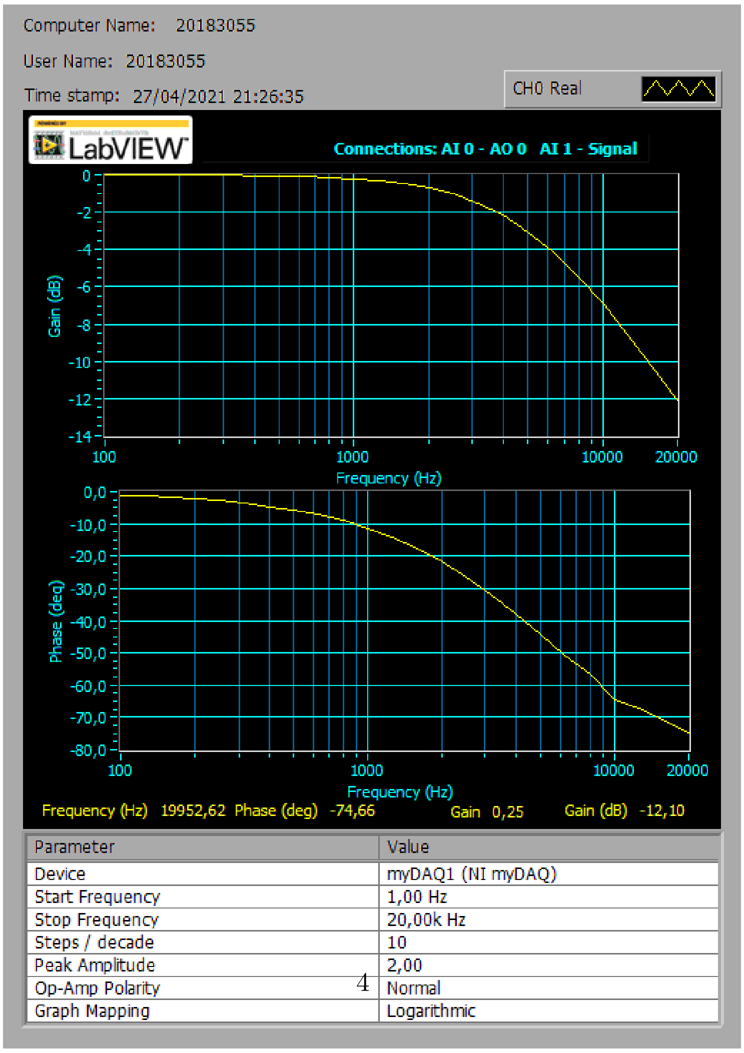
Figure 2.1: A low-pass filter which filters the input voltage V_{in} to output voltage V_{out} through resistor R_{low} and capacitor C_{low}.

Assignment 1

Given that $C_{low} = 3.2nF$, calculate R_{low} such that frequencies above 5 kHz are attenuated. We call this the cutoff frequency $f_{c,LPF}$. Draw a Bode plot with the logarithmic frequency on the x-axis and the gain on the y-axis. You can do this by calculating the gain (in dB) at frequencies $f = [0.1, 1, 5, 10, 20]$ kHz from the transfer function of the filter and connecting these points.

Now validate your design by building it on your Breadboard Breakout. Connect your myDAQ to your PC and start ELVIS. Start the function generator of ELVIS and set it to (1 kHz, 2.0 V, 0V) for (f_{fun},V_{pp},V_{offset}). You can choose signal route AO0 or AO1 - the signal will be applied to the corresponding channel on your myDAQ (4th and 5th pins from the left on the myDAQ). Connect the channel of your choosing to V_{in+}. The output signal is always generated in reference to the AO ground (AGND, 3rd pin), so connect this AO ground to V_{in-}.
You can measure the output characteristic of the LPF with the myDAQ as well with the oscilloscope option in ELVIS. Again, select an input channel AI0 or AI1 - the contact probes are only suitable to measure DC signals, do not use them for this measurement! Connect V_{out+} to the $+$ side of the channel of your choosing. The input channels measure the $+$ signal in reference to the $-$ signal, so connect the $-$ side to V_{out-}. Do not connect the $-$ side to AIAGND (6th pin), this will result in (DC) measurement offsets.
You can vary f_{fun} and check the behavior of V_{out} or you can use the Bode analyzer of ELVIS to generate a spectrum directly. Calculate the -3dB point and compare it with $f_{c,LPF}$. Does the LPF filter the signals as expected? Compare with the Bode diagram you constructed earlier.
Do not forget to take a picture or a screen shot of the measurements and of the graphs for your report.

A correctly implemented circuit will give a frequency response shown below when using the Bode analyser.



2.2 High-pass filter

As a next step, you will design and build a circuit that will filter out the frequencies below $f_{c,HPF}$. A high-pass filter (HPF) is shown in Figure 2.2.

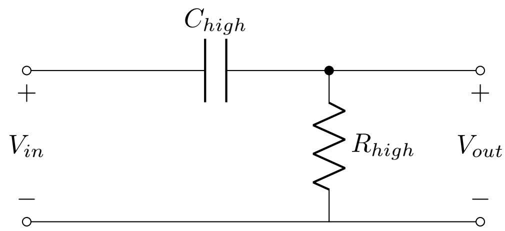


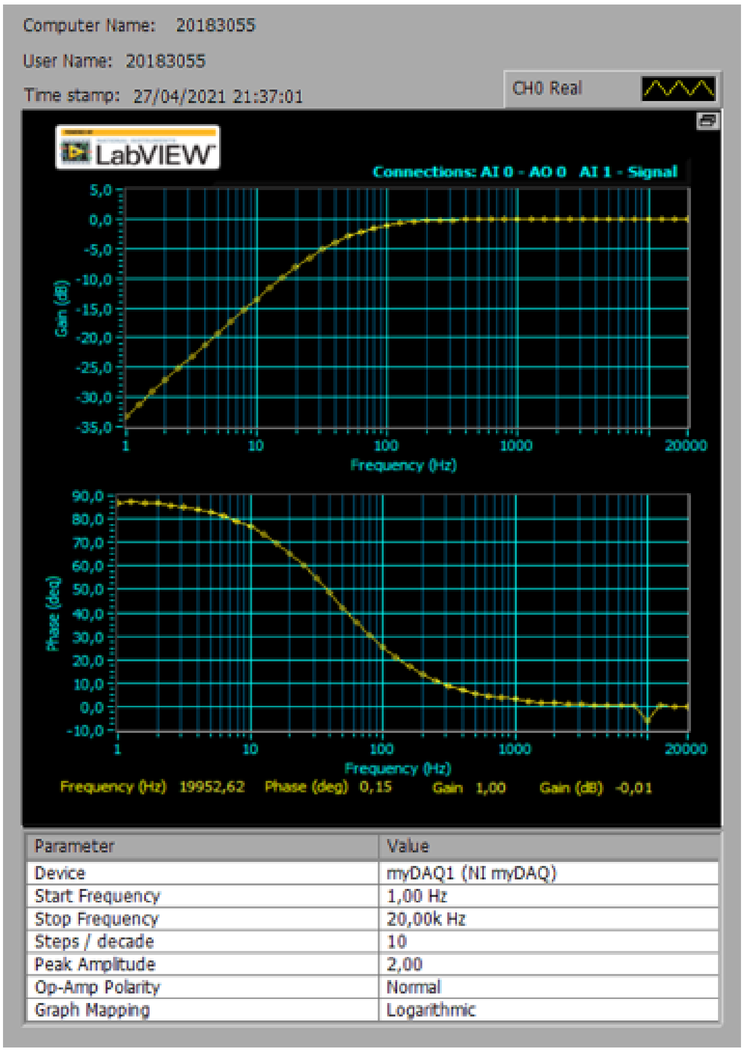
Figure 2.2: A high-pass filter which filters the input voltage V_{in} to output voltage V_{out} through resistor R_{high} and capacitor C_{high}.

Assignment 2

Given that $C_{high} = 1.0\mu F$, calculate R_{high} such that frequencies below 40 Hz are attenuated. Draw a Bode plot. You can do this by calculating the gain (in dB) at frequencies $f = [1, 30, 40, 100, 1000, 2000]$ Hz from the transfer function of the filter and connecting these points.

Now validate your design by building it on your Breadboard Breakout. You can again use the settings (1 kHz, 2.0 V, 0V) for (f_{fun},V_{pp},V_{offset}) for the signal generator and repeat the steps performed at Assignment 1.
Calculate the -3dB point from a Bode plot or by sweeping f_{fun} manually and compare it with your calculated $f_{c,HPF}$. Does the HPF filter the signals as expected? Compare your measurements with the Bode plot you constructed earlier.
Do not forget to take a picture or a screen shot of the measurements and of the graphs for your report.

A correctly implemented circuit will give a frequency response shown below when using the Bode analyser.



2.3 Non-inverting amplifier

You can amplify signals with an operational amplifier (OpAmp). An OpAmp is a voltage-controlled voltage source like you learned about in week 2, see Figure 2.3. In an ideal OpAmp, input resistance $R_a = \infty$, internal resistance $R_b = 0$ and gain constant A is very large.

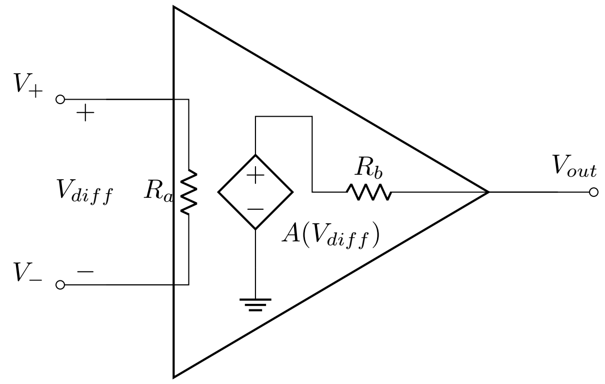


Figure 2.3: An OpAmp can be seen as a voltage-controlled voltage source.

The actual gain of an OpAmp circuit $G = V_{out}/V_{diff}$ is determined by its surrounding resistive network. For the configuration shown in Figure 2.4, the output voltage is

$$V_{out} = \frac{AV_+}{1 + A(R_1/(R_1 + R_2))}. \tag{2.1}$$

You do not need to remember the equations for non-inverting gain in this course.

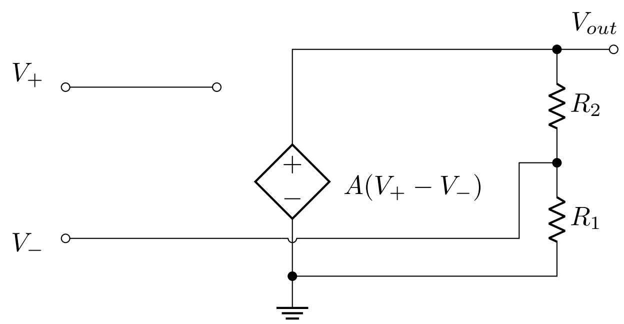


Figure 2.4: A voltage-controlled voltage source with resistive network.

Figure 2.5 shows the non-inverting amplifier from Figure 2.4 with the more commonly-used symbols for OpAmps. We will use the same symbols from now on.

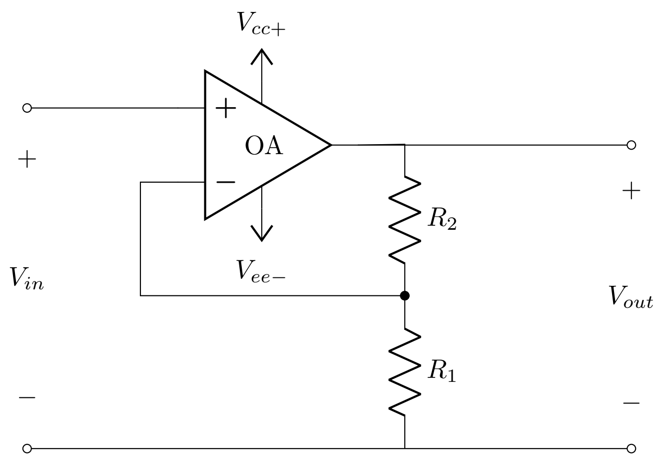


Figure 2.5: A non-inverting amplifier circuit which amplifies the input voltage V_{in} to output voltage V_{out} through resistors R_1 and R_2.

Assignment 3

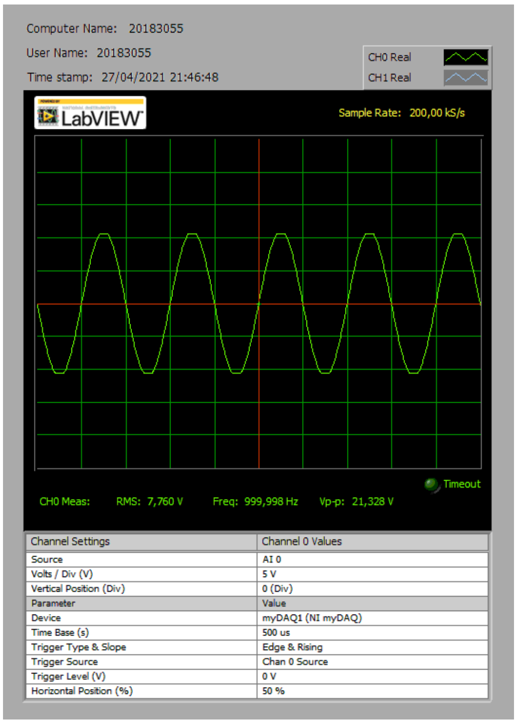
Inspect formula (2.1) and Figure 2.4. You know that the gain constant A of the OpAmp is very high, say $A \to \infty$. Prove that the gain of the configuration in the Figure $G = V_+/V_{in}$ is equal to $1 + R_2/R_1$.

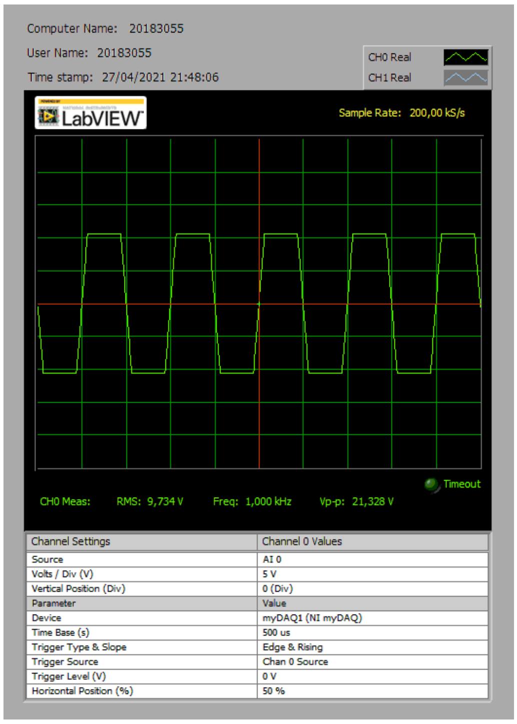
See Figure 2.5. Given that $R_1 = 1k\Omega$, calculate R_2 such that the amplification factor of the circuit is 11.

Now validate your design by building it on your Breadboard Breakout. You will use a LM741 OpAmp. Check the data sheet of the OpAmp for the pin configuration and supply voltage before building your design.
Using a symmetrical power supply is important. What do you think will happen if you use an asymmetrical power supply (e.g. $V_{ee-} = 0, V_{cc+} = 15V$, see Figure 2.5)?

Build the circuit in Figure 2.5 with the resistors of your choosing. Connect the signal generator of your myDAQ to V_{in} and the oscilloscope to V_{out} the same way as you did during the other assignments. You can again use the settings (1 kHz, 2.0 V, 0V) for (f_{fun},V_{pp},V_{offset})
Calculate the amplification factor. Does the amplification circuit amplify the signals as expected?
What happens if you set V_{pp} to 5.0 V? Describe what you see and explain.
Do not forget to take a picture or a screen shot of the measurements and of the graphs for your report.

A correctly implemented circuit will give the wave forms shown below.





2.4 Band-pass amplifier

The circuits you built so far, the LPF, HPF and the non-inverting amplifier can be combined into a band-pass amplifier, see Figure 2.7. Note that the non-inverting amplifier has an input and output resistance R_i and R_o, but we assume for now that these can be neglected ($R_i = \infty\Omega$,$R_o = 0\Omega$).

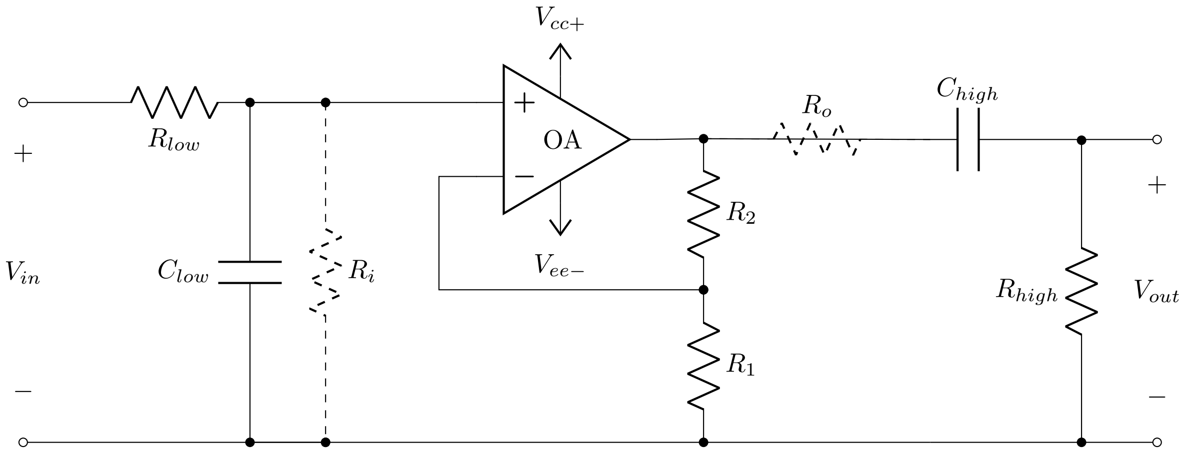
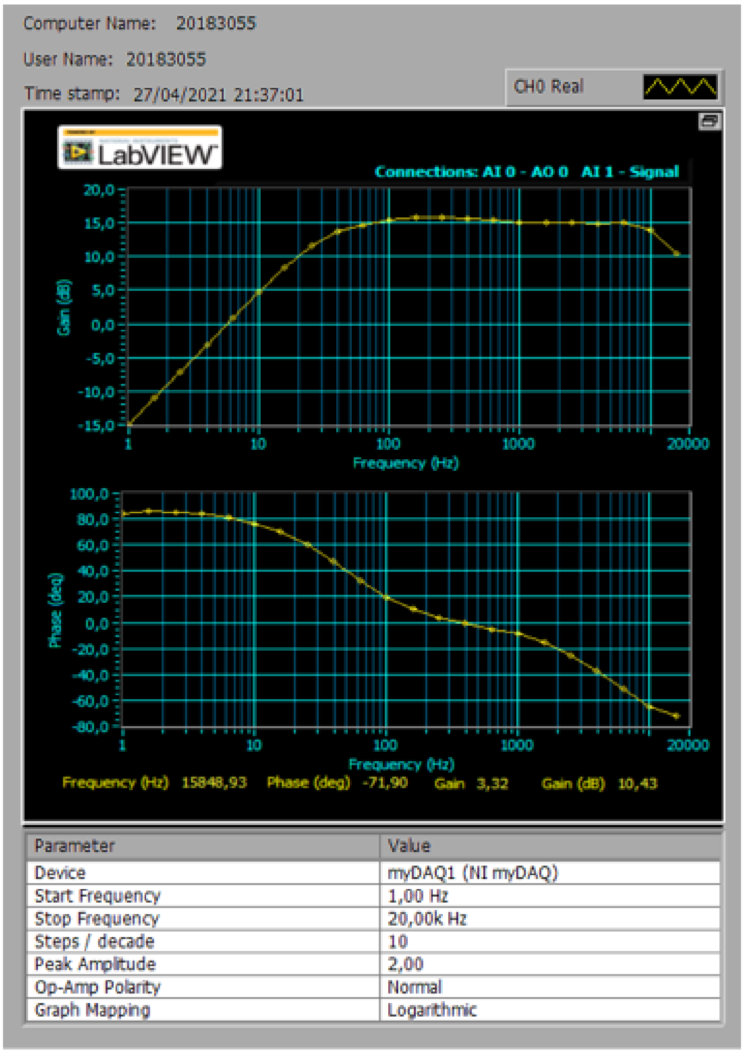


Figure 2.7: A band-pass amplifier consisting of a low-pass stage, an amplifier and a high-pass stage.

Assignment 4

Build and measure the circuit shown in Figure 2.7 with the resistors you calculated during the other assignments. You can again use the settings (1 kHz, 2.0 V, 0V) for (f_{fun},V_{pp},V_{offset}). Create a Bode diagram of the behavior of the band-pass amplifier for different frequencies. Do not forget to take a picture or a screen shot of the measurements and of the graphs for your report.

A correctly implemented circuit will give the Bode plots shown below.



2.5 Band-pass amplifier for headphone

If your band-pass amplifier works well, you can start adapting the circuit such that you can connect a set of headphones to it and listen to filtered music samples delivered by your smart phone or laptop.

Assignment 5

Your headphones use energy, so they act as a resistor. Explain what would happen if you would connect a resistor to the pins of V_{out}, as is done in Figure 2.8. Do you expect the high-pass stage of the circuit to act the same or different from the situation without load resistor?

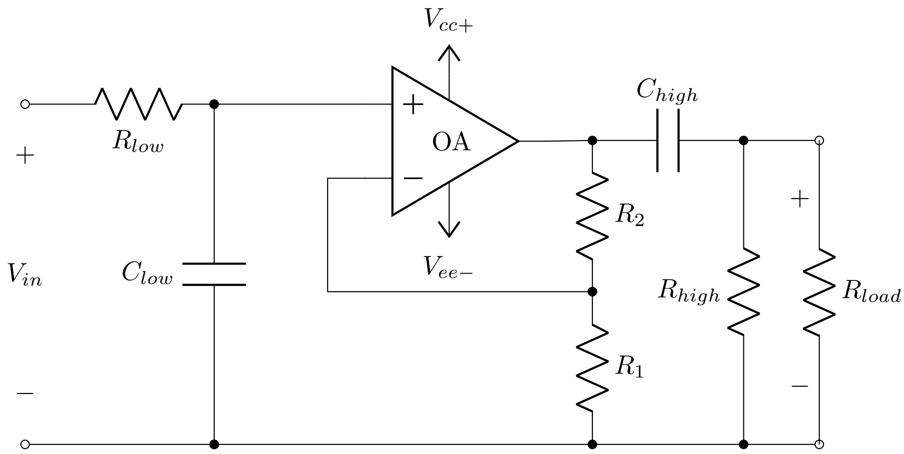


Figure 2.8: A band-pass amplifier with load resistor R_{load}.

To avoid that the headphones influence the filters, you can use a buffer circuit. A buffer circuit electrically disconnects the input and output stages, and makes sure these cannot influence one another. A simple example of a buffer circuit is an amplifier circuit with amplification factor one. In addition to the buffer stage, you need an extra resistor and capacitor R_{prot} and C_{prot} limit the currents running through the headphones. This is necessary to protect the headphones from accidental damage in case you made a design mistake. See Figure 2.9 for the circuit.

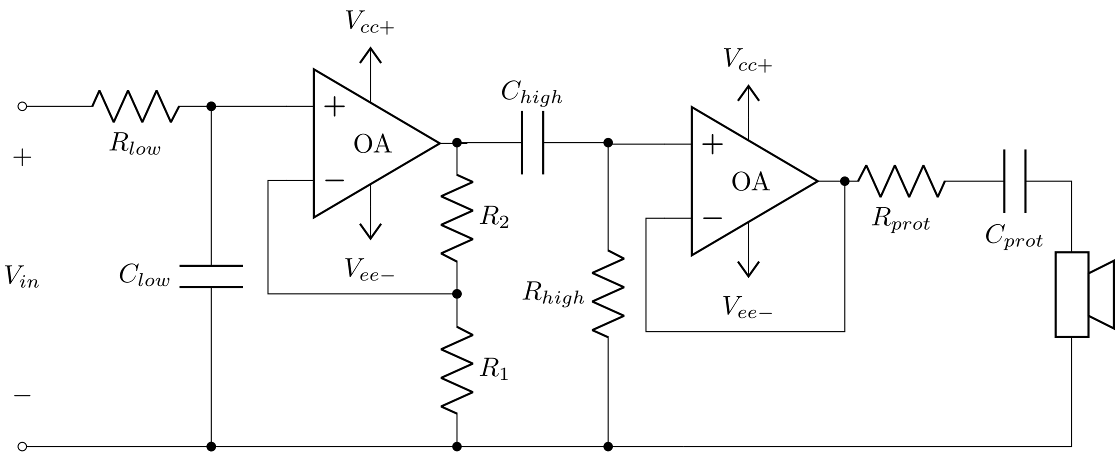


Figure 2.9: A band-pass amplifier with an output buffer and protection components R_{prot} and C_{prot} and the headphones.

Assignment 6

Study chapter 8.1 and derive from the amplification factor that the gain of the buffer is equal to 1.

Expand your circuit with the output buffer and protection components. You can use a second LM741 chip for the buffer OpAmp. Use $R_{prot} = 150\Omega$ and $C_{prot} = 1\mu F$. Before you connect the headphones, first test the complete amplifier with the function generator and oscilloscope.

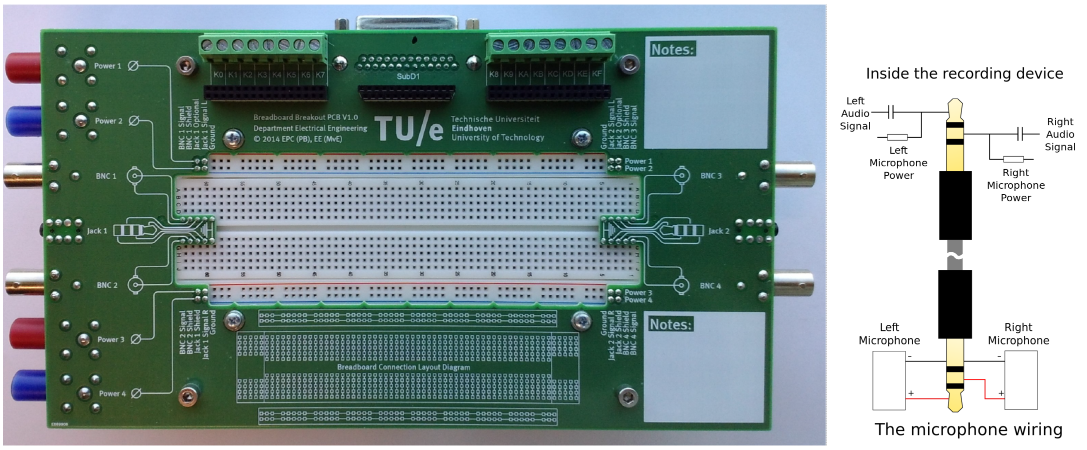
Use the jack sockets on the Breadboard Breakout (see Figure 2.10a) to connect the headphones to the output of your system and your smart phone to the input. You will need to connect the left and right pins of the jack sockets to each other to set the sound to mono, see Figure 2.10b. The ground of the jack plug should be connected to ground of the band-pass amplifier circuit. Modulate amplitude and frequency of the input signal to test the amplifier. You should be able to hear the sine waves with the headphones. Confirm that this works before progressing further.

Now connect your smartphone or laptop to the input of the band-pass amplifier. Again connect the left and right channel leads with each other such that the sound is set to mono. The ground of the input jack plug should be connected to ground of the band-pass amplifier circuit. Use the oscilloscope to observe the output level of your smart phone. Adjust the volume of your smart phone to limit the output signal such that $V_{pp} = 2.0V$.

Are the headphones producing any sound? Investigate how the filter cutoff frequencies $f_{c,low}$ and $f_{c,high}$ affect the quality of the sound. You can use the additional resistors and capacitors to do this.

Think of an elegant way to adjust the volume with the use of a potentiometer. Implement the solution and test it.

Again, do not forget to take a picture or a screen shot of the measurements and of the graphs for your report.



(a) (b)

Figure 2.10: The settings used in the final steps of the assignment.(a) The PCB used in this lab. (b) The inner connections of the jack plug. Connecting the left and right audio signal pins will set the sound to mono, resulting in a single audio signal rather than two (left and right). This can be done by connecting the corresponding PCB traces, see (a). Image obtained from [1].

2.6 Filter noisy sound file

Assignment 7

The final part of this assignment is a real engineering task: you are given the sound file *sample_distorted.mp4*, which is a recording of a droplet falling in water which is heavily distorted with several types of low-frequency and high-frequency noise (licence-free samples used [2, 3]). Tune your band-pass amplifier such that you remove as much of the noise as possible. *Hint: The lower cutoff frequency lies at about 450 Hz and the upper cut-off frequency between 1 and 8 kHz.*

There are at least three distinct methods of tuning your band-pass amplifier. Firstly, you build the circuit with a lower cut-off frequency of 450 Hz and tune the higher cut-off by repeatedly changing the resistor and capacitor values until the filtered sound is to your liking.

Secondly, you can determine the cutoff frequencies by determining the frequency range of the original file *sample_clean.mp3*. You can do so for instance by using Matlab's psd or spectrogram functions. Then, you can build the filters with the cut-off frequencies you found.

Lastly, you can build the circuit using the lower cut-off of 450 Hz and a higher cut-off of somewhere in the kHz range using a decent value for the capacitor and the potmeter you received. You can then tune the circuit with the potmeter until you reached a filter setting to your liking. Take the potmeter out and measure it to find its value and the higher cut-off frequency.

You can use the components that were provided to you in any setting or combination possible, but of course you need to be able to defend your choices if asked. Good luck!

Finished? Go to Canvas −> Quiz −> Home Lab 2021, and answer some questions / submit some data!

Bibliography

[1] DnetSvg at English Wikipedia - Transferred from en.wikipedia to Commons by Liftarn using CommonsHelper., Public Domain, https://commons.wikimedia.org/w/index.php?curid=11911452

[2] Mike Koenig, Sound Bible, sample 50164895, https://soundbible.com/380-Spooky-Water-Drops.html

[3] Mike Koenig, Sound Bible, sample 1944459053, https://soundbible.com/1125-High-Pitch-Dog-Whistle.html