Integrated Masters in Aerospace Engineering, Técnico, University of Lisbon

Circuit Theory and Electronics Fundamentals

Laboratory Report 5

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Índice

1 Introduction

For the fifth laboratory assignment on our Circuit Theory and Electronics Fundamentals course, we had to dimension and implement a Band Pass Filter (BPF) using an OP-AMP (Operational Amplifier) with a central frequency of 1KHz and a gain at central frequency of 40dB. An OP-AMP is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output. We had available a certain number of components to build the circuit that is shown in the image below. In order to study the behaviour of the circuit, we use Ngspice to measure the output voltage gain in the pass-band, the central frequency, and finally the input and output impedance at the central frequency. Then, we use Octave to do the theoretical analyses (compute the frequency responses Vo(f)/Vi(f), the gain, and the input and output impedance at the central frequency. In this report, we will perform a comparison between our theoretical analysis and the simulation results, trying to explain any major discrepancies.

To measure the quality of the filter the following equation was used:

$$Merit = \frac{1}{cost * gaindeviation * centralfreqdeviation + 10^{-6}} \tag{1}$$

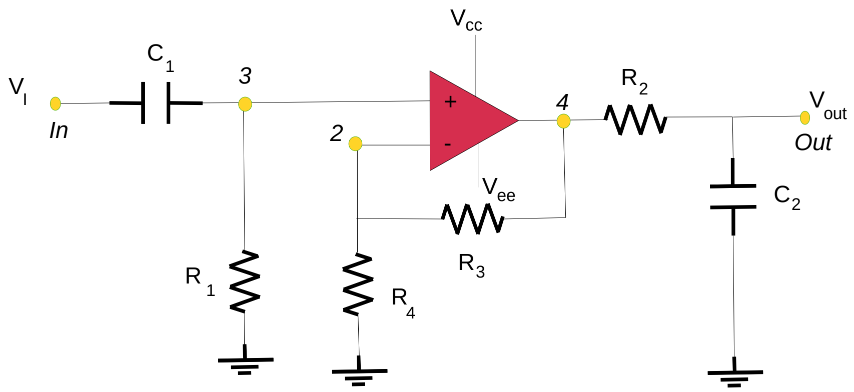

Figure 1: Circuit

A table with the values associated to each component is shown below. Note that the variables are in Volts, Ohms or Faradays.

R1	1.000000e+03
R2	1.000000e+03
R3	1.500000e+05
R4	1.000000e+03
C1	2.200000e-07
C2	1.100000e-07

Table 1: Circuit's components

2 Theoretical Analysis

2.1 Description and Mathematical Considerations

The Op-Amp (signal amplifier) used was considered ideal, which means that the internal impedance between v+ and v- is infinite and that there is no current flowing through it (v+ = v-). So, by connecting a capacitor (C_1) in series with the input voltage, we made a band pass filter, functioning as a high pass filter. Furthermore, in the final stage of the circuit, another capacitor (C_2) was connected in parallel with the output voltage, functioning as a low pass filter. Concluding, this circuit consists of a high pass filter, a signal amplifier and a low pass filter in series.

The circuit shown above was analyzed using Octave.

Initially we computed the input and the output impedance:

$$Z_{in} = R_1 + \frac{1}{j * w * C} \tag{2}$$

$$Z_{out} = \frac{R_2}{j * w_0 * C_2 * (R_2 + \frac{1}{jwC_2})} \tag{3}$$

Input Impedance	1.000000e+03 + -7.071068e+02j
Output Impedance	6.666667e+02 + -4.714045e+02j

Table 2: Impedances

Then we computed the gain:

$$Gain = A_V * A_H * A_L \tag{4}$$

$$A_V = 1 + \frac{R3}{R4} \tag{5}$$

$$A_L = \frac{1}{1 + R2 * C2 * s} \tag{6}$$

$$A_H = \frac{R1 * C1 * s}{1 + R1 * C1 * s} \tag{7}$$

Where A_V is the gain that results from the OP-AMP (signal amplifier), A_H and A_L are the gains that correspond to the high pass and low pass filters, respectively.

Using the previous equations we obtained the gained presented:

Central Frequency	1.006667e+02
Gain (dB)	4.005771e+01 dB
Gain Deviation	5.771376e-02 dB
Central Frequency Deviation	2.308672e+01 Hz

Table 3: Gain

To better understand the frequency response of gain, we plot the following graph 3. We can see that low and high frequencies have a a low gain and frequencies near to 1000 Hz have the maximum gain, as expected for a band pass filter. In the first stage the high pass filter blocks the low frequencies and in the final stage we have a low pass filter that blocks high frequencies. To ensure an high gain, we must focus obtaining an high AV , because near the central frequency both AH and AL will be approximately 1. We can see as well in graph 2 the plot for the theoretical phase of the output voltage which is similar to a normal bandpass filter.

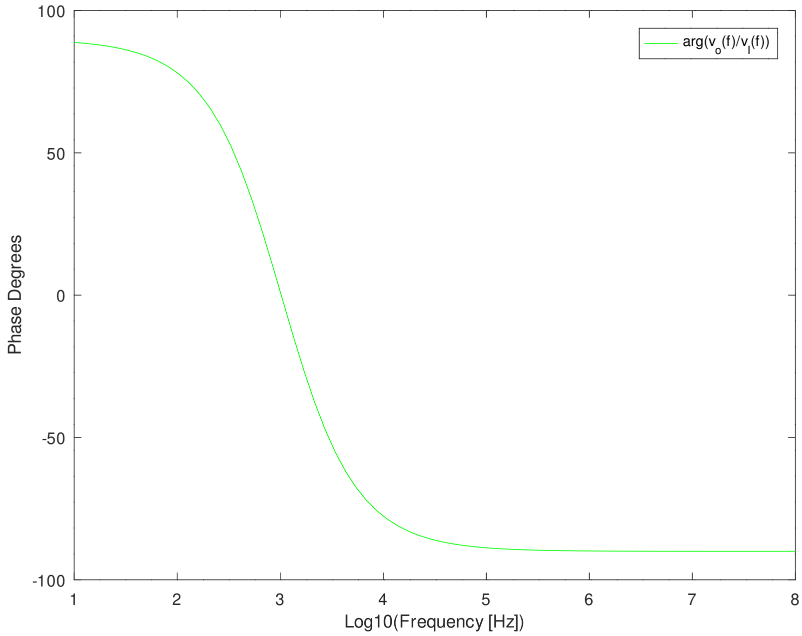

Figure 2: Octave phase response

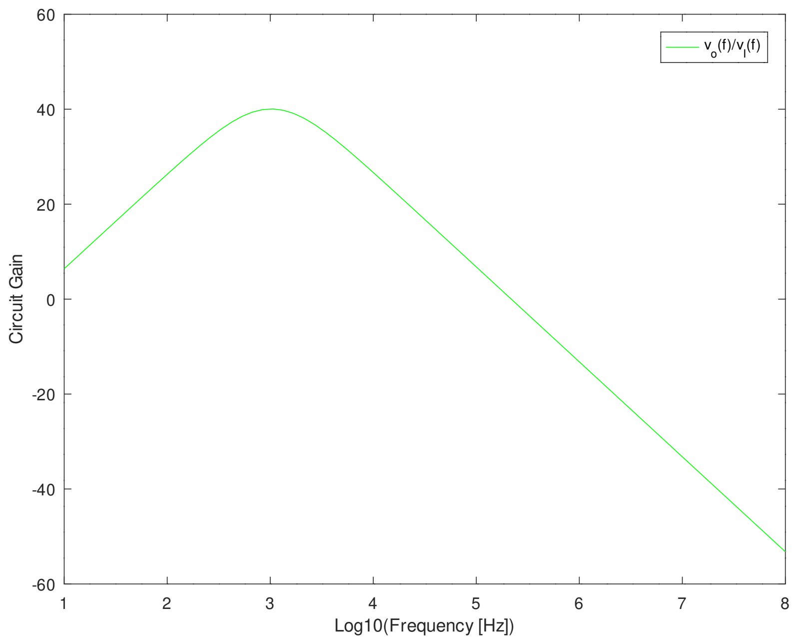

Figure 3: Octave gain response

We also computed the low cutoff frequency and the high cut off frequency, and with those two we compute the central frequency using the following equation:

$$\omega_L = \frac{1}{R1 * C1} \tag{8}$$

$$\omega_H = \frac{1}{R2 * C2} \tag{9}$$

$$\omega_0 = \sqrt{\omega_L * \omega_H} \tag{10}$$

Lower Cut Off Frequency	4.545455e+03 rad/s
Higher Cut Off Frequency	9.090909e+03 rad/s
Central Frequency	6.428243e+03 rad/s

Table 4: Frequencies

The figure of merit was also computed, following the expression presented in section 1.

Central Frequency Deviation	2.308672e+01 Hz
Gain Deviation	5.771376e-02 dB
Cost	1.428600e+04 MU
Merit	3.024424e-06

Table 5: Cost and merit

3 Simulation Analysis

In this section of the report, we are going to simulate the modeled circuit using Ngspice. Our main objective with this simulation is confirming the validity of our theoretical approach and try to explain any major discrepancies. Therefore, we will be paying close attention to the values of the gain, central frequency and input/output impedances, trying to obtain the best results possible for our application. Finally, we will compute the merit figure, looking forward to having the best possible value.

Firstly, it is important to analyse the frequency domain and determine the output voltage gain. For this, we utilized the .meas function. The main goal of our work was designing a passband filter, that would cut both low and very high frequencies, obtaining the following results, which are shown in the table below (6.

Central Frequency (Hz)	1000
Gain (dB)	39.977
Central frequency deviation	0
Gain deviation	0.263873

Table 6: Ngspice results

3.1 Impedances

Now, it's important to take a look at the input and output impedances, as they play a key role in our circuit.

Firstly, looking at our input impedance (table 7), we wanted to have a very high resistance, as it would imply that the voltage in node 2 is as similiar to the input voltage as possible. This would be very beneficial for the gain, because having a high quocient of $\frac{R_2}{R_3}$, improves significantly the gain value.

On the other hand, for the output impedance (table 8), we need to make it as low as possible in order to have the highest possible output voltage. It is clear why if we take a look at the voltage divider formula.

Zin	998.999 + -7.2972 j

Table 7: Input impedance from Ngspice

Zo	0.20916 + -14.4657 j

Table 8: Output impedance from Ngspice

Finally, we plotted the merit figure and cost in order to confirm how effective our circuit design was.

Cost	14057.9
Merit	0.000269578

Table 9: Cost and Merit

4 Theoretical Results and Simulation Comparison

For this section, we are going to perform a general comparison between theoretical results obtained through Octave and simulation results obtained with Ngspice.

Both impedances are similar in theoretical and simulation analysis, because the OP-AMP is not perfect and ngspice uses a more complex models to analyse it.

Input Impedance	1.000000e+03 + -7.071068e+02j
Output Impedance	6.666667e+02 + -4.714045e+02j

Table 10: Impedances

Zin	998.999 + -7.2972 j

Table 11: Input impedance from Ngspice

Zo	0.20916 + -14.4657 j

Table 12: Output impedance from Ngspice

Then looking to the gain response, we can see that both of them are similar, but, again, since Ngspice uses more complex models to obtain the gain, we find some differences between them, as we can see in the central frequency and the maximum gain value.

Central Frequency	1.006667e+02
Gain (dB)	4.005771e+01 dB
Gain Deviation	5.771376e-02 dB
Central Frequency Deviation	2.308672e+01 Hz

Table 13: Gain

Central Frequency (Hz)	1000
Gain (dB)	39.977
Central frequency deviation	0
Gain deviation	0.263873

Table 14: Ngspice results

Comparing the phase plots of both analysis, in octave we find two roots and two poles because of the presence of two capacitors, but in Ngspice we have two roots and four poles. This is due to the OP-AMP models used. In octave we considered it an ideal one, but in fact the OP-AMP has capacitors that produce two more poles and, again, Ngspice uses more complex models.

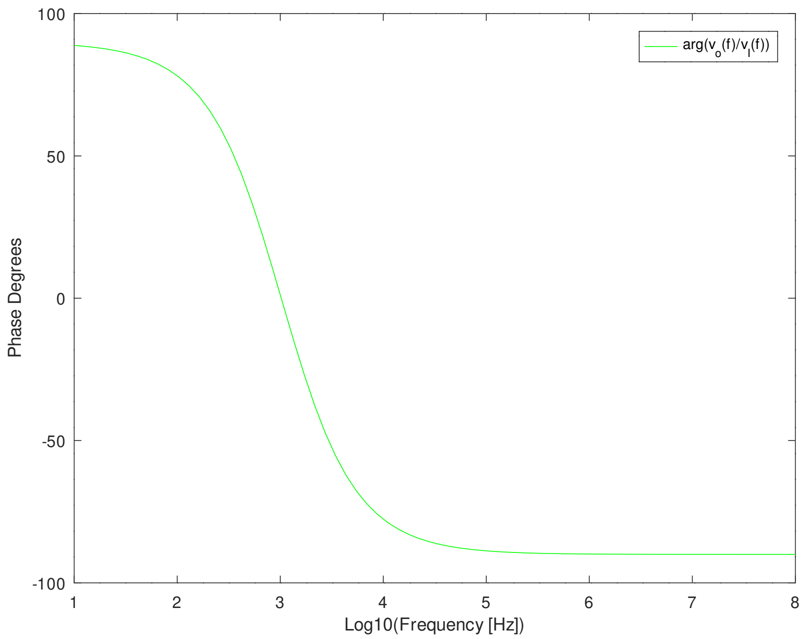

Figure 4: Octave phase response

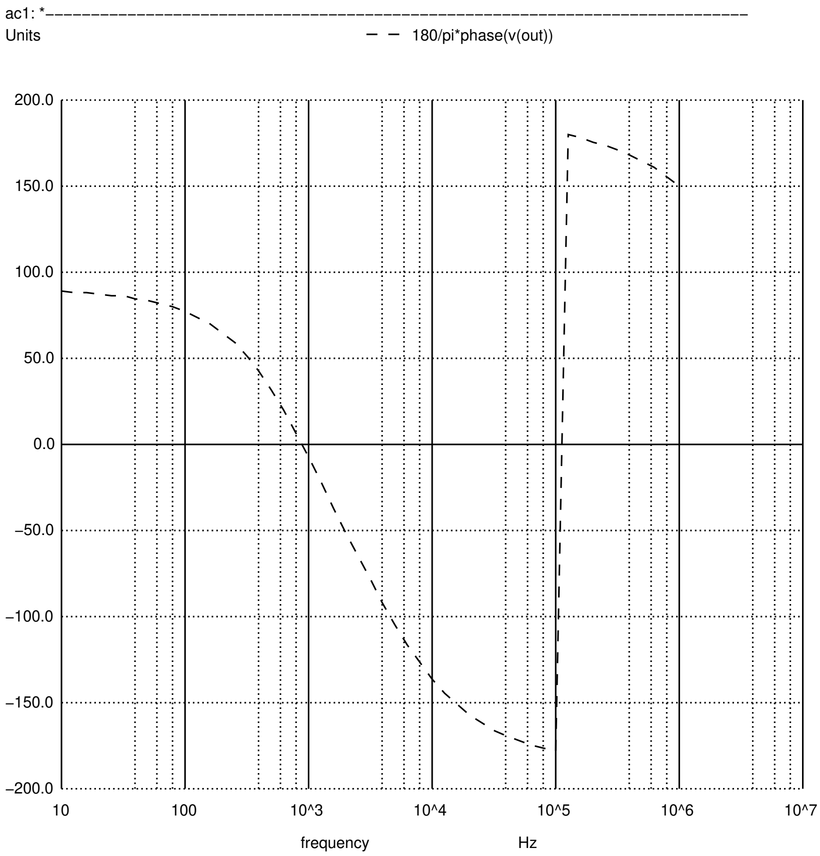

Figure 5: Ngspice phase response

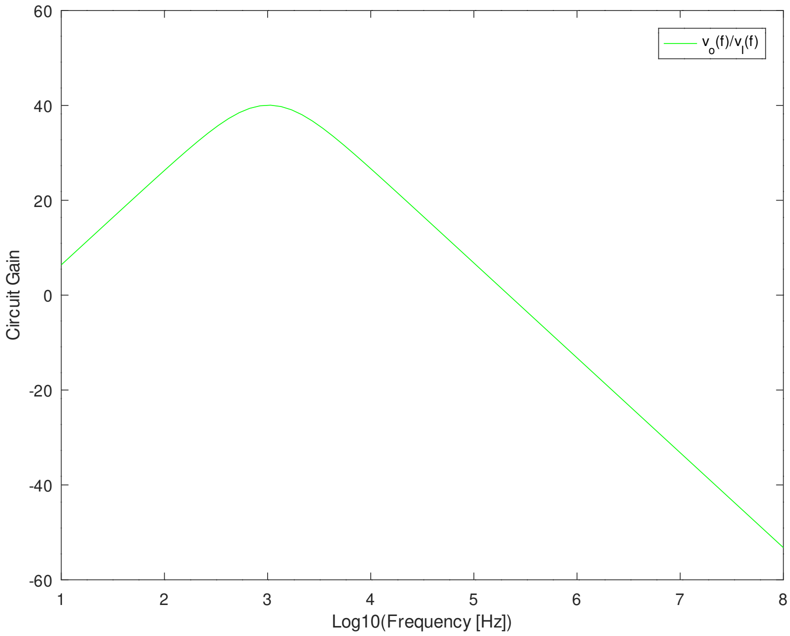

Figure 6: Octave gain response

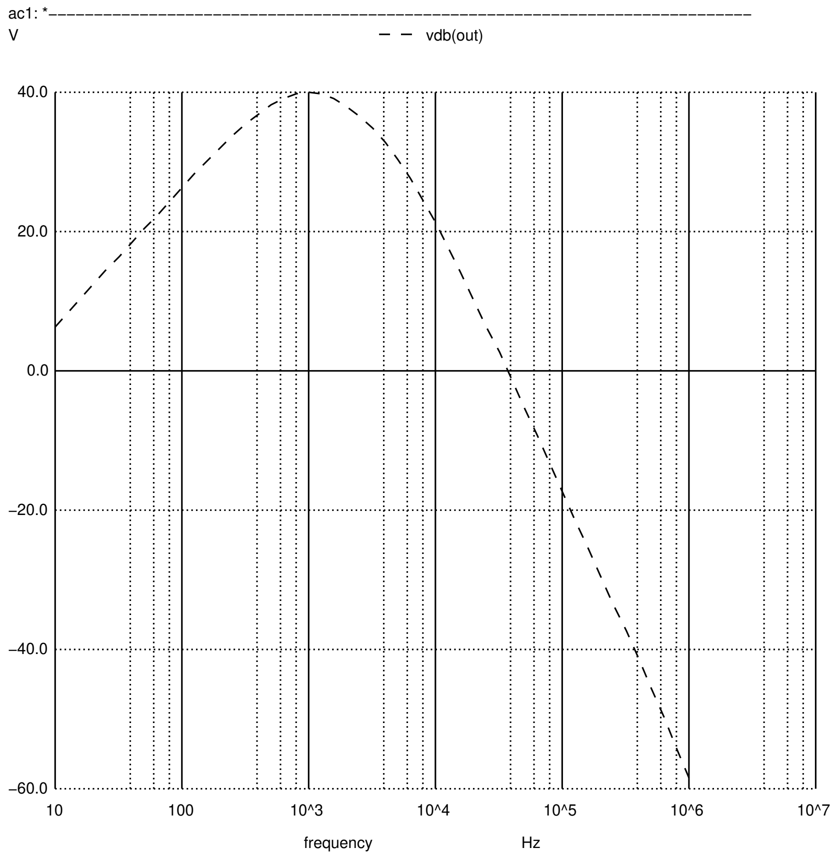

Figure 7: Ngspice gain response

5 Conclusion

In this laboratory assignment we were able to deepen our knowledge regarding OP-AMPs and its applicability in various devices, in our case, to design a passband filter. Our objetive was to maximise the voltage gain within a certain frequency range, spending as little as possible on the components used. Overall, we were satisfied with the obtained results. Nonetheless, it is important to mention that there was some mismatch between what we expected theoretically, and what was obtained in the simulation. These variations are mainly due to the non-linearity of the components, such as the OP-AMP. There were several parameters that were overlooked in the theoretical analysis, and are most likely the cause of the discrepancies.