TÉCNICO LISBOA

Circuit Theory and Electronics Fundamentals

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4th Laboratory Report

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1 Introduction

The goal of this laboratory assignment was to optimize a given audio amplifier, and doing both the theoretical and simulation analysis. The architecture of the given circuit can be seen in the following picture.

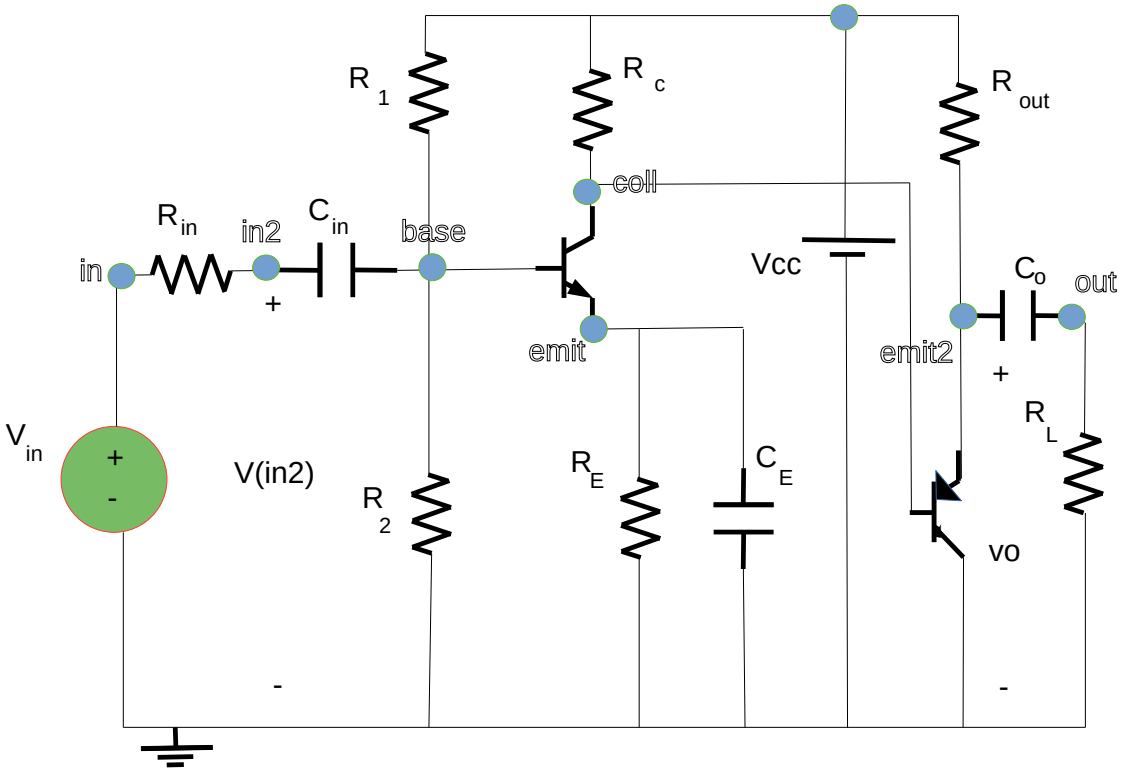


Figure 1: Audio amplifier - given circuit

The input of this circuit is connected to an independent voltage source, which generates an ac signal with an amplitude of $10mV$. The source has an impedance of 100Ω, and the amplifier is going to be connected to a speaker which has an impedance of 8Ω. As we can see in the previous picture, the circuit is supplied by an independent 12V DC source (vcc).

The circuit comprises a gain stage and an output stage, which will be seen in a more detailed way in section 2.

2 Theoretical Analysis

In this section, the circuit shown in figure 1 is analysed theoretically.

Like we said in section 1, both of the stages of the amplifier are going to be analysed in a more detailed way in this section.

Let's begin with the gain stage. The gain stage consists of a common emitter amplifier, with a NPN transistor, which allows us to obtain a high input impedance (Z_{i_1}), and a high gain A_V. However, this type of amplifier has a very high output impedance (Z_{o_1}), which causes a degeneration of the signal output. In order to solve this problem, the gain stage is connected to an output stage, which consists of a common collector amplifier, whith a PNP transistor. This stage has a gain a little bit lower than 1, but still very close to 1, and a very high input impedance (Z_{o_2}), which preserve the high gain of the previous stage. In addition, this circuit has a very low output impedance (Z_{o_2}), which means that almost all the gain is going to be delivered to the speaker.

2.1 First Point

Our theoretical analysis starts by computing the operating point, using the theoretical DC model studied. In order to do this, we harnessed the mesh method provided in the Octave script to which we added the new components.

The current directions used are shown in figure **??**, and their values are presented in table 1, as well as the values of V_{CE} and V_{BE}, and V_{EC} and V_{EB}, respectively for the NPN and the PNP transistors, in order to prove that they're working in the forward active region ($V_{CE} > V_{BEON}$ and $V_{EC} > V_{EBON}$).

VCE	6.700109e+00 V
VBEON	7.000000e-01 V
VEC	7.504614e+00 V
VEBON	7.000000e-01 V
IB1	5.815111e-06 A
IC1	1.039160e-03 A
IE1	1.044976e-03 A
IB2	-3.284384e-05 A
IC2	7.465405e-03 A
IE2	7.498249e-03 A

Table 1: V_{CE}, V_{BE}, V_{EC}, V_{EB}, and circulation current values

2.2 Second Point

The second point in this analysis consists in computing the gain and input and output impedances separately for each stage.

In order to do this kind of analysis we have to consider the incremental model of the circuit.

In order to compute the gain of each stage, we used the formulae which were taught in the theoretical classes (which were also given in advance in Octave's script). We can use this simplified formulae, because we are assuming medium/high frequencies. Based on this assumption, we can replace the capacitor with a short circuit.

In a similar way, we computed the input and output impedances, using the formulae given in the theoretical classes (which were also given in advance in Octave's script), which are based on the same assumption.

To make things a little bit more clear, the input/output impedances are determined by connecting, for example, a voltage source to the stage's input/output and replacing the output/input with a short circuit. By determining the current that flows across the added voltage source, we can determine the input/output impedance by just applying Ohm's law. This values are shown in tables 2 and 3, respectively for the input and the output stages. The overall output impedance and gain are shown in table 4.

AV1dB	3.158539e+01 dB
ZI1	2.419648e+03 Omega
ZO1	4.652785e+03 Omega

Table 2: Gain, input and output impedances - gain stage

AV2dB	-9.207782e-02 dB
ZI2	7.218471e+04 Omega
ZO2	3.313468e+00 Omega

Table 3: Gain, input and output impedances - output stage

AVdB	3.120876e+01 dB
ZO	2.270796e+01 Omega

Table 4: Overal gain and output impedance

As one might observe, the input impedance of the output stage (Z_{i_2}) is substantially greater than the output impedance of the gain stage (Z_{o_1}). Hence, because the voltage divider applied at the input of the output stage is given by

$$v_{i_2} = \frac{Z_{i_2}}{Z_{o_1} + Z_{i_2}} \cdot v_{o_1} \tag{1}$$

if $Z_{o_1} << Z_{i_2}$, we can say that $v_{i_2} \approx v_{o_1}$. It's worth to mention that the gain of the output stage is approximately 1, so overall there is no significant signal loss when the two stages are put together.

$$AV2dB = -9.207782e-02 \Rightarrow AV2 = 0.989455 \approx 1 \tag{2}$$

2.3 Third Point

The third point of this theoretical analysis is to compute the frequency responce $\frac{V_o(f)}{V_i(f)}$.

In order to do so, we can't neglect the effect of the capacitors, since only this component's impedance is frequency dependent.

Being that, we calculated the transfer function of the circuit. To do that we calculated the two poles, the lower and high cut off frequency based on the document provided by the professor. Knowing that we built our transfer function and plotted the following figure.

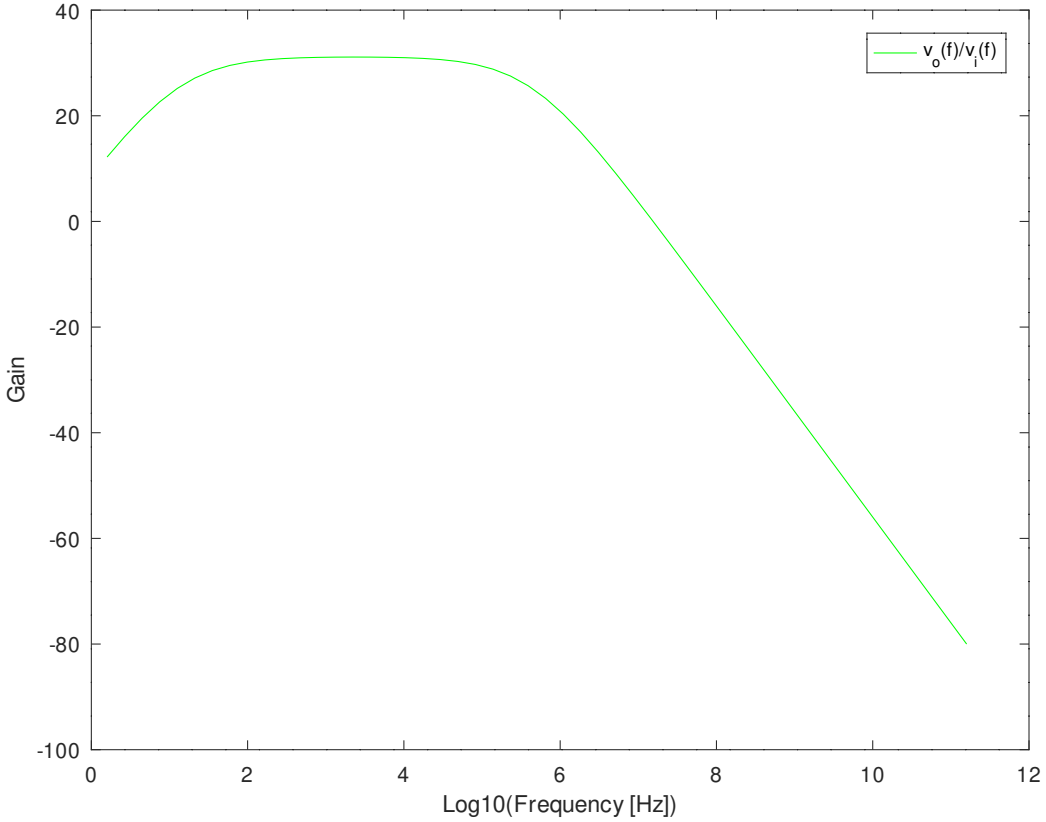


Figure 2: Frequency response of the amplifier ($\frac{V_o(f)}{V_i(f)}$)

Finally, the theoretical merit is shown below, as well as the high and low cutoff frequencies, the cost and the bandwidth.

Merit	4.921738e+02
HighCutOff frequency	4.377991e+05 Hz
LowCutOff frequency	1.262427e+01 Hz
Cost	2.198943e+03 MU's
Bandwidth	4.377865e+05 Hz
Max Gain	3.111556e+01 V

Table 5: Theoretical variables of merit

3 Simulation

In this section, a briet description of the circuit modeled through NGspice is going to be presented and the values obtained on it are going to be compared with the ones obtained on octave. The purpose of the simulation was to maximise the merit obtained and, as such, to obtain the values of the gain, bandwidth and the lower and higher cut off frequencies as well as the input and output impedances.

In order to do that, the circuit in study was modelled in the program. For that, transistors of the given models (NPN transistor for the gain stage and PNP transistor for the output stage) were used on the two common amplifiers and the rest of the components specifications changed to be on par with the values optimised through the Matlab software (Simulink) and as seen in the octave sript.

With the circuit described, the next step was to analyse the simulations with the introduced values. The first step was to verify if the transistors were functioning in the foward active region, F.A.R mode. To do that the potential difference between the collector and the emitter and the base, for the NPN transistor, were calculated and, for the PNP transistor, the potential difference between the emitter and the collector and the base were calculated. In order to guarantee the previous condition it is necessary to guarantee the following conditions: $V_{CE} > V_{BE}$ and $V_{EC} > V_{EB}$. The results obtained are now presented:

Vce	4.92668 V
Vbe	0.654762 V
Correct F.A.R	

Table 6: Confirmation of NPN in FAR mode

Vec	5.77796 V
Veb	0.70695 V
Correct F.A.R	

Table 7: Confirmation of NPN in FAR mode

The next step was to simulate the operating point, since the values of this simulation are important to determine the incremental parameters. The values are shown in the next table.

base	7.990883e-01
coll	5.071008e+00
emit	1.443260e-01
emit2	5.777958e+00
in	0.000000e+00
in2	0.000000e+00
out	0.000000e+00
vbe	6.547623e-01
vcc	1.200000e+01
vce	4.926682e+00
veb	7.069504e-01
vec	5.777958e+00

Table 8: Confirmation of NPN in FAR mode

The rest of the values in study (gain, lower and higher cutoff frequencies and bandwidth), are presented in the following table. These were obtained using the fuction $meas$ as seen in

the NGspice script, taking into account that the gain is the maximum of the voltage output, the cutoff frequencies are the frequencies for which the output voltage is 3db less than the gain (as per definition) and the bandwidth is the difference between those frequencies.

VGain	34.1403
Bandwidth	1.22339E+06 Hz
LowerCutoffFreq	15.8089 Hz
HigherCutoffFreq	1.22341E+06 Hz

Table 9: Gain, cutoff frequencies and bandwidth values

Next, it is important to understand the purpose of certain elements of the circuit: the coupling capacitors; bypass capacitor and the resistor R_C.

3.1 Effect of the Coupling Capacitors

The coupling capacitors associated to the respective transistors have the primary function of blocking the DC signal. In fact, taking into account the impedance of a capacitor, when $\omega = 0$, $Z_C = \inf$ and the circuit is opened. This is necessary because of the main purpose of an amplifier: amplify the input AC signal. As seen on the classes, through the expression of the lower cutoff frequency, the higher the capacitances, the larger the bandwidth is going to be. As for the higher cutoff frequency little effects are going to be felt with the change of capacitance as shown in the formulae presented by the professor. However, only this tension would imply that the transitor wasn't always in the FAR. As such, an aditional DC independent voltage source is used in order to force it to be always in the required FAR. This DC component is eventually eliminated when the current reaches the other capacitor. All of this helps maintaing the operating point of the transistor, allowing it to operate at lower frequencies.

3.2 Effect of the Bypass Capacitors

As seen in the lectures, the resistor R_E has the function of lessening the effect of the temperaturre in the DC voltage. However by adding a resistor, the gain will lower. In order to negate this, a capacitor is added in parallel to the resistance. With this, the DC current will be affected by the resistor whilst the AC current passes through the capacitor because of its medium - high frequency (and as such the impedance of the capacitor is small - short circuit).

3.3 Effect of the Resistor R_C

Finally, the effect of R_C on the circuit gain is important to be studied. As the gain is proportional to the value of R_C, the higher R_C is, the higher the gain will be and thus the merit.

All of the effects mentioned above can be seen through the graphics below, where it is possible to see the bandwidth, the gain and the lower and higher cutoff frequencies.

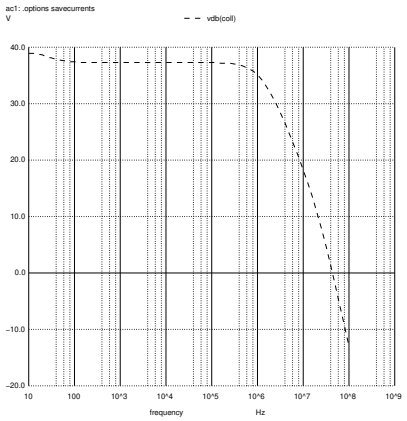
Next, the input and output impedances were calculated as seen on the tables below,

Zin	-1445.61 + 303.661 j

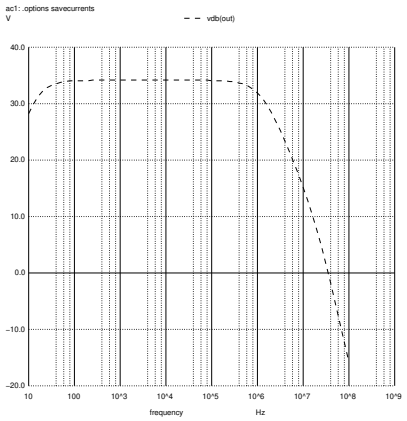
Table 10: Input impedance (Ω)

Zo	25.852 + 1.292 j
Zo(int)	25.8843

Table 11: Output impedance (Ω)



(a) Input Voltage



(b) Output voltage

As we can see, the input impedance is higher than the outup impedance. This plays well to maximise the gain as the voltage in node in2 needs to be as close to Vin as possible, reducing the losses. To do that, as we can see in the voltage divider formulae, it's necessary to increase the resistance value. The opposite logic is used to the output impedance. Again, considering the voltage divider formulae, the output impedance must be as small as possible to guarantee the maximum output voltage and gain. Even though the output impedance should be lower than the 8Ω to maximise the output voltage, because of the different parameters in the merit formula, our otimization made the value higher than the optimal value if it was the only one.

Finally the cost and merit of the circuit described and seen in the images before is calculated in ngspice. The results are shown on the table as it follows.

Cost	2198.94
merit	1201.48

Table 12: Cost and Merit of the circuit

4 Comparison

Now a comparison between the theoretical analysis and the experimental analysis results of the gain is done. In the previous sections, for the theoretical analysis an operating point analysis was performed and the values obtained. The table 8 shows the values obtained and compares them.

As we can see there are some errors associated with the theoretical model when compared to the experimental results, especially for the values of the voltage in the nodes. Nosso ********** TEKAs

In the Ngspice table, the only parameters in comparison are $@q1[ib]$, $@q1[ic]$, $@q1[ie]$, $base$, $coll$ and $emit$.

As one may observe, some discrepancies in the voltage values are noticeable. Nevertheless, the values of the currents flowing are are within reasonable intervals of similarity. Therefore, the gain computed in Octave should not be severely affected by this. It is important to highlight that the theoretical gain expression is dependent on the value of the current I_C because of the incremental parameter g_m.

Aditionally, the gain, bandwidth and cut off frequency results were also computed. As predicted, the voltage gain in the theoretical approach is greater than in the Ngspice computation. Moreover, since we do not have the theoretical high cut frequency, we can only compare the results for the low cut frequency, which are very similar as far as the order of magnitude is concerned. For this reason, as the bandwidth is the subtraction between high and low cut frequencies, it should not be compared.

5 Conclusion

In this laboratory assignment, the goal of the assignment was to create a circuit with the fuction of an audio amplifier, maximising the gain and bandwidth of it whilst minimizing its cost. To do that theoretical and experimental analysis were conducted and the results studied.

Even though the model used in the octave script is a pretty good approximation of a real amplifier, as the results between ngspice and octave differ significantly we can conclude that the model used isn't perfect. This may be explained because of the approximations used in the transistors model (each transistor is made of two resistances and a dependent current source), taking into account that these are non linear components.

In conclusion, with this laboratory assignment we were able to understand more deeply the functioning of BJT's and its applicability on different devices, such as sound amplifiers. Remembering the goal of having a high goal and a large enough bandwidth to cover the human earing capacity, we can say we are pretty satisfied with our results as we were able to achieve these goals and also improve on the merit obtained.