TÉCNICO LISBOA

Integrated Masters in Aerospace Engineering, Técnico, University of Lisbon

Circuit Theory and Electronics Fundamentals

Laboratory Report 4

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1 Introduction

For the fourth laboratory assignment on our Circuit Theory and Electronics Fundamentals course, we had to improve, design and analyse an Audio Amplifier Circuit, which was especially interesting due to the presence of the BJT (Bipolar Junction Transistors), a new component we recently learned and were looking forward to understand experimentally the way it influences a circuit.

The circuit itself, as explained in our lectures, consisted of two different stages, the Gain Stage (which is designed with the objective of amplifying the voltage, in order to have the most possible gain) and the Output Stage (whose main goal is lowering the impedance of the gain stage, allowing the load to take almost full advantage of the gain). The full circuit can be seen in the picture below.

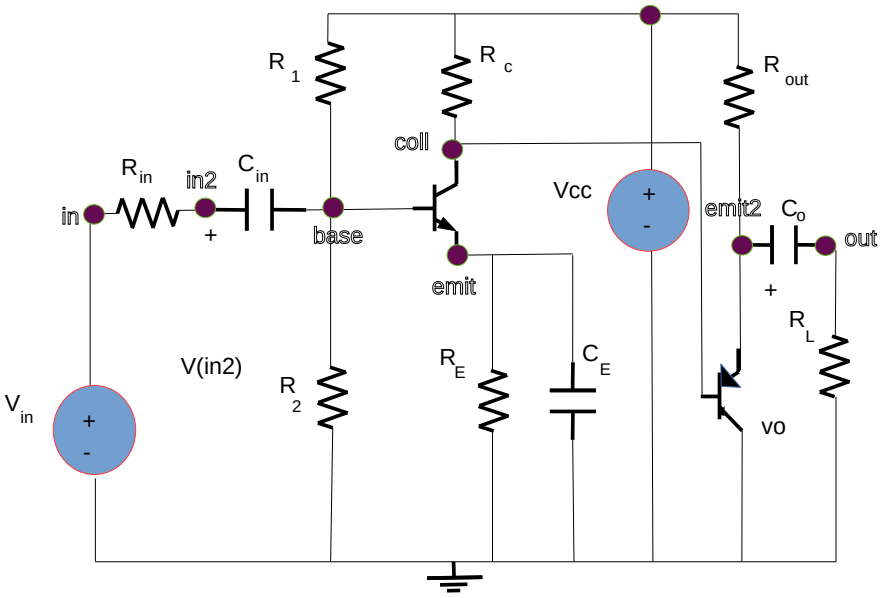

Figure 1: Circuit

In this report, we will perform a comparison between our theoretical analysis and the simulation results, trying to explain any major discrepancies.

2 Theoretical Analysis

2.1 Gain Stage Description

Firstly, we will make a brief description of how the gain stage works. As previously stated, its objective is to amplify the voltage input. In order to do so we utilize the following components: NPN BJT (negative-positive-negative bipolar junction transistor), Resistors, Capacitors and voltage sources.

The V_{cc} voltage source is added with the objective of ensuring the transistor is acting in the Forward Active Region. The condition for operating in such region is $V_{CE} > V_{BE}$.

Both the capacitors have important functions within the circuit. The C_{in} capacitor (coupling capacitor) acts as a DC block, ensuring that the transistor is in the desired operating region. The second capacitor, C_E, is a bypass capacitor. Taking a look at the formulae for the capacitor impedance: $\frac{1}{jwc}$, we can understand what this means. For low frequencies, the capacitor impedance is really high, which makes all the current flow through the RE resistor. On the other hand, for high frequencies, the capacitor impedance is really low, making it act almost as a short circuit. Therefore, almost all current flows through it.

It is also relevant to look at the impedance seen by the input voltage source, as it needs to be a lot greater than the resistance associated with the generator. The formulae is the following:

$$Z_{I1} = (R_1||R2)||r_{\pi 1} \tag{1}$$

Taking a look at the output impedance formulae (2), we can see that it is really high, in comparison to the load resistance of 8 Ohm. Therefore, by the voltage divider rule, it becomes obvious that we need to add another stage to lower the impedance seen by the load. (note that we are doing a high-frequency analysis, considering $R_E \simeq 0$)

$$Z_{O1} = r_o||R_C \tag{2}$$

2.2 Output Stage Description

As said before, the main goal of the output stage is to lower the output impedance.

For this stage, we utilized resistors, a capacitor, a PNP BJT and a voltage source. Similarly to what was described in the previous stage, the voltage source is used to ensure the transistor operates in the desired region (forward active region), satisfying the condition for PNP BJT: $V_{EC} > V_{EB}$. Furthermore, the capacitor C_O also acts as a coupling transistor, blocking the DC and ensuring the transistor stays in the forward active region.

Again, it is also relevant to look at the impedance seen by the input voltage source (3), as it needs to be much lower than Z_{O1}, so that there is no loss between both stages (voltage divider formulae, equation X).

$$Z_{I2} = \frac{(g_{m2} + g_{\pi 2} + g_{o2} + g_{E2})}{g_{\pi 2}(g_{\pi 2} + g_{o2} + g_{E2})} \tag{3}$$

$$V_{in2} = \frac{Z_{I2}}{Z_{I2} + Z_{O1}} V_{O2}. \tag{4}$$

Taking a look at the output impedance formulae (5), we that the output stage achieves its purpose of diminishing the impedance seen by the load.

$$Z_{O2} = \frac{1}{(g_{m2} + g_{\pi 2} + g_{o2} + g_{E2})} \tag{5}$$

2.3 Merit Figure and Values Determination

The main goal of this lab was to design the best possible audio amplification circuit. The quality of our work is evaluated with the calculation of a merit figure, which takes into account the following parameters: -the voltage gain between the voltage generator input, and the load output; -the lower cut-off frequency (and higher cut-off frequency), which corresponds to the minimum (and maximum) frequency value of the bandwidth, and represents the first (and last) frequency for which the signal is correctly amplified, which is desired to be as low (as high) as possible. Both these frequencies are calculated by determining when the output voltage is 3db less than the gain; -the bandwidth of our amplified signal, which is the range of frequencies for which our input signal is correctly amplified (it's calculated by subtracting the higher cut-off frequency by the lower cut-off frequency); -the cost of the circuit.

The formulae for the merit figure is the following:

With the objective to obtain the biggest possible merit figure, we ran an optimization using Simulink, a very useful toolbox of the Matlab program. With this, we obtained the following values for our resistors and capacity of the capacitors:

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
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 1: Optimization results and merit

After discovering all the needed values, we can also plot the gain, input and output impedances of both the circuits.

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

Table 2: Gain stage: gain in dB, input and output impedance

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

Table 3: Output stage: gain in dB, input and output impedance

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

Table 4: Total circuit gain and output impedance

And, finally, the frequency response $\frac{V_o(f)}{V_i(f)}$

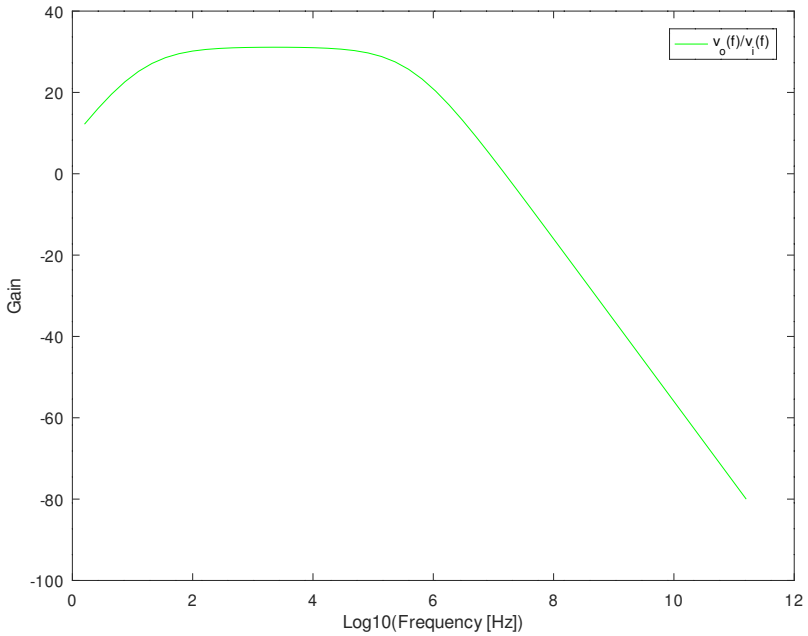

Figure 2: Octave Frequency response

3 Simulation Analysis

In this section of our 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. We are particularly interested in the merit figure value, as it measures how well our circuit completes the task of amplifying the audio.

First of all, it's important to analyse and ensure the transistors are working in the desired region as, otherwise, none of our predictions would be validated. First of all, taking a look at the NPN transistor, which is present on the gain stage, the condition for operating on the forward active region is that $V_{CE} > V_{BE}$. In the simulation, we obtained the following results:

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

Table 5: NPN transistor in forward active region

On the other hand, for the PNP transistor, present on the ouput stage, the condition for operating in the forward active region is $V_{EC} > V_{EB}$. In the simulation, we obtained the following results:

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

Table 6: PNP transistor in forward active region

Now it's important to analyse certain components of the circuit to fully understand their functioning.

3.1 Coupling Capacitors

As previously explained, the coupling capacitors are responsible for blocking the DC signal, as we only want to amplify the AC signal. The DC block is especially important, because it could imply that the transistor isn't always in the forward active region. Taking a look at the capacitor impedance formula, $\frac{1}{jwc}$, if the frequency is equal to zero, the impedance will be infinite, and therefore it will act as an open circuit. We've seen on classes that higher capacitances, lead to lower cut-off frequencies, and larger bandwidths. We were able to witness this on the simulation.

3.2 Bypass Capacitors

The main functionality of the bypass capacitor is to allow almost all current to flow through, since it will have a really low impedance for medium-high frequency. This capacitor was needed in this circuit, since the presence of the R_E resistor, took a significant toll on the gain value. The R_E resistor could not be removed since it has the important function of diminishing the temperature effect in the DC voltage.

3.3 Resistor R_C

Lastly, it's important to address the way resistor R_C impacts the gain. As the gain and R_C are proportional, the higher the resistor value, the higher the gain and consequently, the merit.

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.

3.4 Impedances Analysis

Now, we will take a look at the output and input impedances, which are computed in the tables below:

Zin	-1445.61 + 303.661 j

Table 7: Input impedance in Ohm

Zo	25.852 + 1.292 j
Zo(int)	25.8843

Table 8: Output impedance in Ohm

As previously explained, when looking at the impedances, we expect the impedance seen by the input voltage generator to be really high, in order to minimize the voltage drop due to the internal resistance of the voltage generator (following the voltage divider formula). On the other hand, when looking at the output impedance, we expect it to be really low, so the load resistor takes almost full advantage of the voltage, when looking at the voltage divider formula. As you can see in the table above, the output impedance is still quite high when compared to the 8 Ohm load resistor. This is due to the optimal merit value obtained in our Matlab optimization.

3.5 Merit Figure

Finally, after explaining our thought process and the way components impacted our circuit, let's take a look at the merit figure, as well as all the important values that should be taken in consideration in its calculation.

VGain	34.1403
Bandwidth	1.22339E+06 Hz
LowerCutoffFreq	15.8089 Hz
HigherCutoffFreq	1.22341E+06 Hz
Cost	2198.94
merit	1201.48

Table 9: Simulation results

3.6 Comparison between Theoretical and Simulation Analysis

Even though we are pretty satisfied with our simulation results, it is important to note that are some discrepancies between the theoretical and the simulation analysis. This could be due to some errors associated with the theoretical model used, when compared to the "real" one in NGspice.

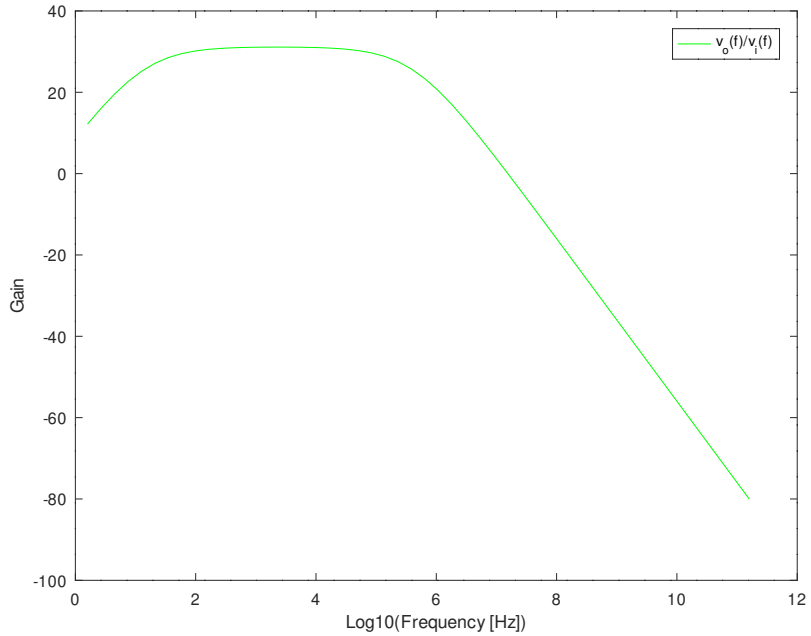

Figure 3: Theoretical Output Voltage

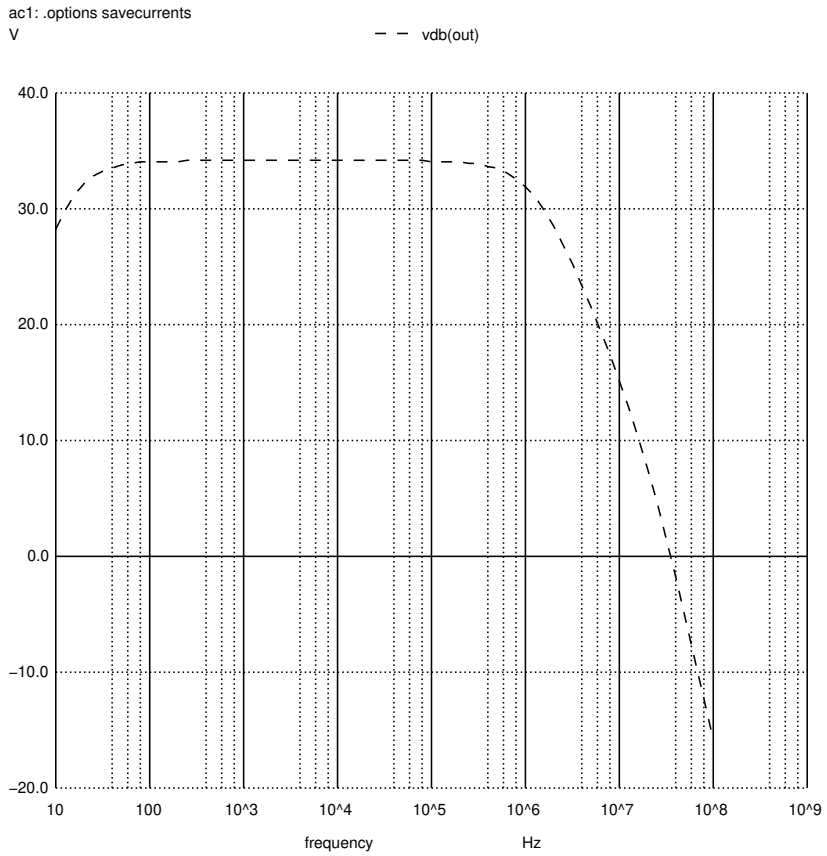

Figure 4: Simulation Output Voltage

Looking at both graphics, we can testify that the prediction of our theoretical model is accurate, in comparison to the simulation.

4 Conclusion

In this laboratory assignment we were able to deepen our knowledge regarding BJT's and its applicability in various devices, in our case, an Audio Amplifier. As a conclusion we can state that the results of Ngspice and Octave differ. This was expected as we used non-linear components, the transistors, in the circuit and they were replaced in the incremental analysis by two resistances and a dependent current source (linear components). To conclude, we believe that the main goal of the task proposed was achieved as we reached a high gain and large enough bandwidth to cover the human earing capacity. Overall this solution was a very successful one.