LAB 4: AUDIO AMPLIFIER

Circuit Theory and Electronics Fundamentals

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May 23, 2021

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1 Introduction

The purpose of this laboratory assignment was to build an Audio Amplifier with an 8Ω speaker. It is important to understand that, in order to efficiently succeed on this task, one must find the most reasonable relationship between the money needed and the performance of the amplifier. This relationship is expressed as a figure of merit calculated with

$$M = \frac{VoltageGain \times Bandwith}{cost * LowCutOffFrequency} \tag{1}$$

The considered amplifier is presented in the following figure:

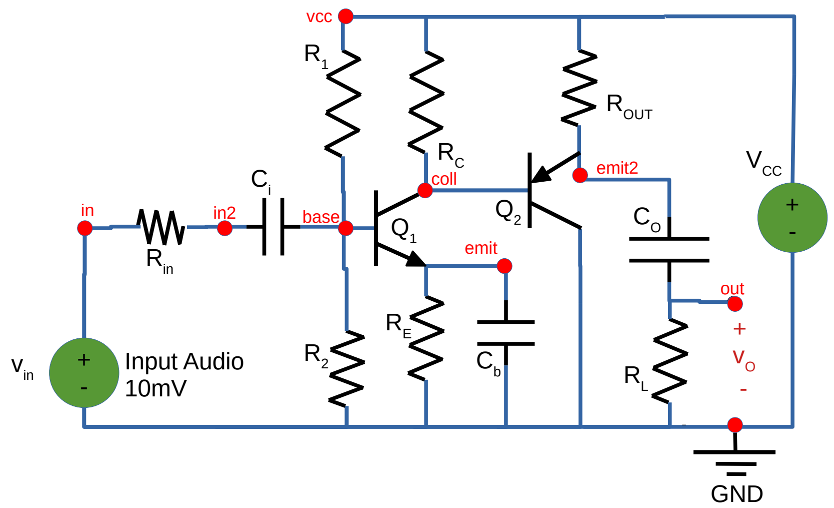

Figure 1: Schematic representation of the Audio Amplifier circuit.

The following table presents the values for the components considered in the circuit:

Component	**Value in Ω or μF**
R_{in}	100
R_1	120000
R_2	20000
R_C	800
R_E	100
R_{out}	200
C_i	11
C_O	175
C_b	400

Table 1: Components and its Values.

Note that R_L is the considered load. Hence, its value is just $R_L = 8\Omega$.

In Section 2, a theoretical analysis of the circuit is presented, using Circuit Theory and Electronics Fundamentals concepts. After that, in Section 3, the circuit is analysed via simulation, using the software Ngspice. The obtained results are then compared, explaining the reasons behind the differences and similarities found. Finally, one can find the conclusions of this study outlined in Section 5.

2 Theoretical Analysis

In this section, the previously shown circuit is theoretically analised.

The considered circuit is divided in a gain and an output stages. In the gain stage, the transistor Q_1 is operating in the forward active region, and the capacitor C_1 blocks the DC component of V_{in}, causing an open circuit at low frequencies. In sum, the bias circuit V_{CC}, R_1, R_2 will ensure the BEJ is ON.

The output stage is responsible for lowering the output impedance so that there is compatibility with the 8Ω speaker (load).

The circuit was analyzed by operating point. Therefore, it is possible to compute values such as the Input Impedance, Output Impedance and Gain, separately for both stages and for the total circuit.We can separate the stages and later connect their values **without significant loss** because, when comparing the impedance of both stages, one notices that the second stage (output stage) has a much greater impedance than the first one (gain). Hence, a considerably part of the voltage will be dropped in the output stage. Also, it is legit to think that the low impedance value is in harmony with the 8Ω value for the load impedance. It was also possible to reach some values to be used in the incremental model for the transistor (r_π ; r_O ; g_m). The following figure presents precisely the considered incremental model for the transistor:

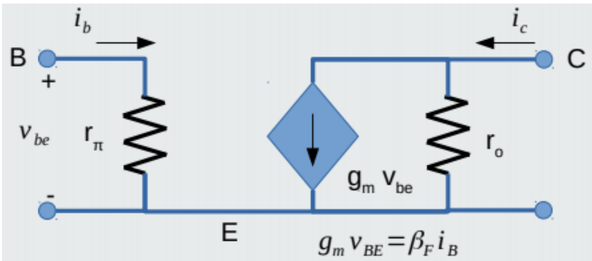

Figure 2: Incremental model for transistors.

The resulting values are all presented ahead, side by side with the ones obtained via simulation, for the purpose of comparison.

Finally, the frequency response of the circuit was studied, from where the gain $\frac{V_{out}(f)}{V_{in}(f)}$ was obtained, by means of the nodal method, applied with the transistor incremental model, resulting in the following system (with $G_x = \frac{1}{R_x}$ and $g_{\pi_x} = \frac{1}{r_{\pi x}}$):

$$\begin{cases} (V_{in2} - V_{in})G_{in} + (V_{in2} - V_{base})j\omega C_i = 0 \\ V_{base}G_2 + (V_{base} - V_{CC})G_1 + (V_{base} - V_{in2})j\omega C_1 + (V_{base} - V_{emit})g_{\pi_1} = 0 \\ V_{emit}G_E + V_{emit}j\omega C_b + (V_{emit} - V_{base})g_{\pi_1} + (V_{emit} - V_{coll})g_{O_1} - (V_{base} - V_{emit})g_{m_1} = 0 \\ (V_{coll} - V_{CC})G_C + (V_{coll} - V_{emit})g_{O_1} + (V_{base} - V_{emit})g_{m_1} + (V_{coll} - V_{emit2})g_{\pi_2} = 0 \\ (V_{emit2} - V_{CC})G_{out} + (V_{emit2} - V_{out})j\omega C_O + (V_{emit2} - V_{coll})g_{\pi_2} + V_{emit2}g_{O_2} - (V_{coll} - V_{emit2})g_{m_2} = 0 \\ V_{out}G_L + (V_{out} - V_{emit2})j\omega C_O = 0 \end{cases}$$

Again, the plot result is presented side by side with the simulation one, ahead.

3 Simulation Analysis

Actually, this was the part of the work that was firstly made, as the outputs are more reliable (reasons explained ahead) and we wanted to choose the best combination of resistance and capacitance values, in order to obtain the best merit we could for the configuration shown before. We would like to enhance the role of some of the components and the effects of the changing of their characteristic values.

The coupling capacitors' (C_i and C_o) capacitances are mainly responsible for decreasing the low cut-off frequency of the band, increasing its width. The bypass capacitor C_b contradicts the lowering effect of R_E in the gain of the circuit. Lastly, the resistor R_C, connected to the collector of the gain stage, made it possible to, once again, increase the final gain value. As said, these values were chosen as a way to improve the relation of cost-quality of the circuit, represented by the merit formula.

Lastly, one can check on Table 2 that both transistors are operating in the forward active region, as $V_{CE} > V_{BE}$ (for NPN transistor 1) and $V_{EC} > V_{EB}$ (for PNP transistor 2).

4 Result comparison

4.1 Operating point

Tables 2 show the operating point computed values, obtained with Ngspice and Octave, respectively.

Comparing both analysis results, one notices a few differences, resulting of the different approach the two methods use to simulate the components of the circuit. Ngspice used a very refined transistor model, with a great number of parameters, which enables a detailed analysis that produces results that pretty much describe the behaviour of a real transistor. On the other side, the inputs made on Octave use nothing but a clever way to divide the analysis process in several relatively easy steps that can be put together in the end, providing reasonable values and plots for the circuit parameters. Much of what is made there disregards the highly non-linearity that is characteristic of the transistors, thus the visible differences. Besides that, regarding Octave's analysis, frequency approximations are taken into account.

One of the differences is the sign of the emitter's currents, due to the consideration of two distinct directions.

The values calculated for the incremental analysis parameters, obtained with Octave, are shown in Table 3.

4.2 Frequency analysis

Figures 3 and 4 represent, respectively, the magnitude of the gain in dB $dB(v(out))$ as a function of f. Figure 5 represents the phase of the gain in degrees $ph(v(out))$ as a function of f. Note that it was chosen a logarithmic scale for the frequency axis (the space between each two consecutive vertical white lines represents a decade) and that both plots were made for a frequency range of $10\ Hz$ to $100\ MHz$, with a representation of 10 points per decade.

Quantity name	Value [V or A]
base	1.223292e+00
coll	7.829332e+00
emit	5.322652e-01
emit2	8.553871e+00
in	0.000000e+00
in2	0.000000e+00
out	0.000000e+00
vbe1	6.910263e-01
vcc	1.200000e+01
vce1	7.297067e+00
veb2	7.245389e-01
vec2	8.553871e+00
@q1[ib]	2.864133e-05
@q1[ie]	-5.32265e-03
@q1[ic]	5.294010e-03
@q2[ib]	8.067530e-05
@q2[ie]	-1.72306e-02
@q2[ic]	1.714997e-02

Quantity name	Value [V or A]
base	1.219089e+00
coll	7.870393e+00
emit	5.190895e-01
emit2	8.570393e+00
VBE1	7.000000e-01
VCE1	7.351304e+00
VEB2	7.000000e-01
VEC2	8.570393e+00
q1[ib]	2.888645e-05
q1[ie]	5.190895e-03
q1[ic]	5.162008e-03
q2[ib]	7.511184e-05
q2[ie]	1.714803e-02
q2[ic]	1.707292e-02

Table 2: Operating point analysis - a variable preceded by @ is of type *current* and expressed in Ampere; other variables are of type *voltage* and expressed in Volt. $q1$ and $q2$ refer to the transistors, b, e, and c to their base, emitter and collector terminals (respectively) and the rest is defined as before. On the left, the values obtained via simulation in Ngspice. On the right, the ones obtained from Octave.

Quantity name	Value [Ω or S]
gm1	2.064803e-01
rpi1	8.654577e+02
ro1	1.350250e+04
gm2	6.829168e-01
gpi2	3.004474e-03
go2	5e-04

Table 3: Parameters obtained for the incremental analysis using Octave.

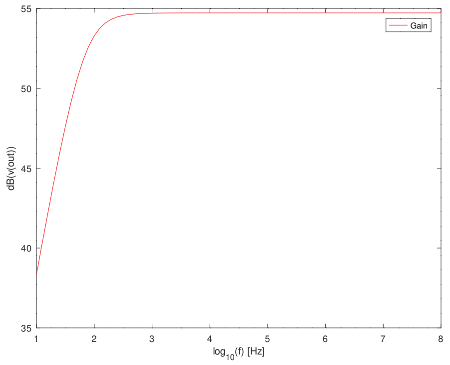

Figure 3: Magnitude in dB $dB(v(out))$ of the gain as a function of f, obtained with Octave.

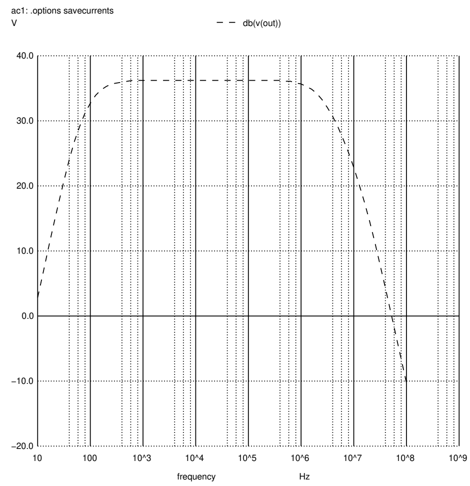

Figure 4: Magnitude in dB $dB(v(out))$ of the gain as a function of f, obtained with Ngspice.

Once again, due to Octave's linear approximation of a non-linear circuit, there are some disparities. Besides that, the upper cut-off frequency is estimated to be infinite.

4.3 Merit and other circuit related values

Tables 4 show some circuit related values, obtained with Ngspice and Octave, respectively.

Quantity name	Value [V, Hz, MU or other]
zin	9.597303e+02
zout	6.261399e+00
gain	6.516901e+01
gaindb	3.628082e+01
cutofflow	1.121870e+02
cutoffhigh	2.472820e+06
bandwidth	2.472708e+06
cost	7.274000e+02
merit	1.974686e+03

Quantity name	Value [V, MU or other]
ZI1	8.238649e+02
ZO1	7.552526e+02
ZI2	2.718958e+04
ZO2	1.446382e+00
ZI	8.238649e+02
ZO	4.645195e+00
gain1	1.390652e+02
gain2	9.877587e-01
gaintotal	1.355388e+02
gaintotaldb	4.264127e+01

Table 4: Merit and other circuit related values. On the left, the values obtained via simulation in Ngspice. On the right, the ones obtained from Octave.

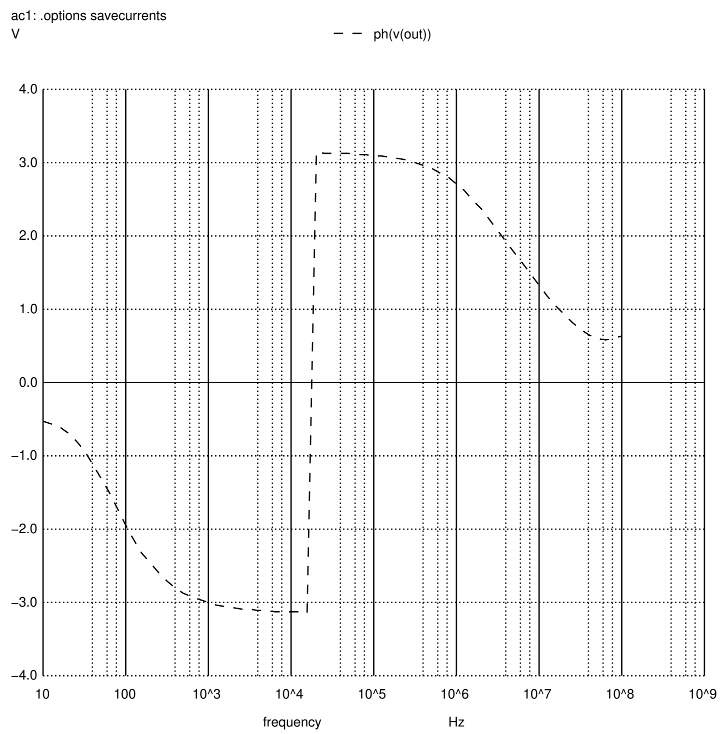

Figure 5: Phase in degrees $ph(v(out))$ of the gain as a function of f, obtained with Ngspice.

Once again, due to Octave's linear approximation of a non-linear circuit, there are some disparities.

5 Conclusion

Overall, the obtained merit was 1974.686 and the cost was $727.4MU$. However, there are several noticeable differencies in the obtained values, which is not that satisfactory, but it is the result of the employement of an imprecise theoretical analysis method.

In conclusion, we found this a very important circuit to develop and analyse, since it's practical applications are very useful. Besides that, it was also quite interesting to learn the way transistors work, as they are one of the most important components nowadays, being widely used in eletronics.