EEE229 – Assignment 1

1 Introduction

This document covers the design of a Power Amplifier and Loudspeaker based upon the theory discussed in module EEE229. The Power Amplifier and Loudspeaker are intended to be combined as an active loudspeaker system. The analysis of both sections will be covered, alongside some brief conclusions about their performance.

2 Power Amplifier Analysis

2.1 Introduction

The Power Amplifier circuit before analysis can be seen in **Figure 2.1**. The aim of this task is to select biasing component values (R_1, R_2, R_c, R_{E1}, R_{E2}, R_{S1}, R_{S2}) for the circuit based upon a set of quiescent conditions and specifications for the circuit (**Section 2.2**). The calculation of C_E and C_1 is not required. This will also involve the calculation of the required supply rail voltages.

The overall design of this circuit consists of two key sections: A Voltage Amplifier (generated using T5) and a Push-Pull Current Amplifier (generated using Darlington Pairs T1 and T2, T3 and T4). Diodes $D_{1\text{-}5}$ set the bias points for the Darlington Pairs relative to each other. C_1 is used to AC couple the input signal to the Voltage Amplifier input.

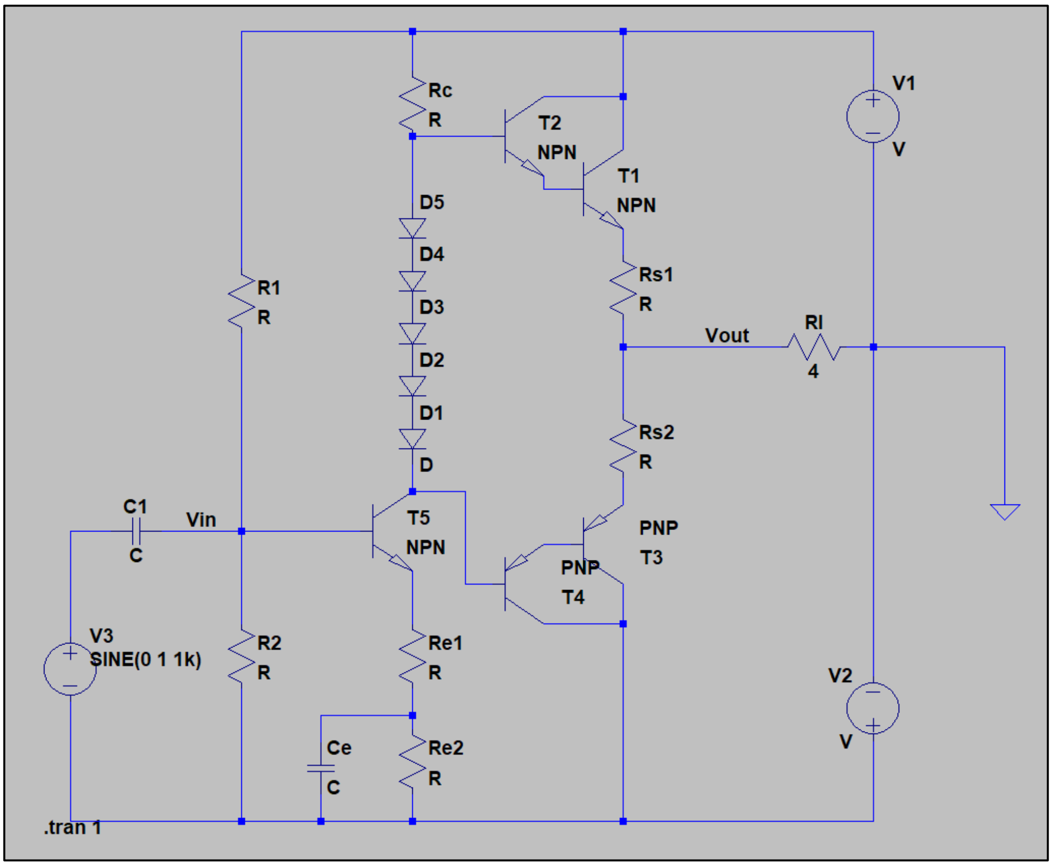

Figure 2.1: The Power Amplifier Circuit

2.2 Specification and Quiescent Conditions

The following specification and quiescent conditions are given:

Output Power: 100W (RMS)

Power Supply Rails: Symmetrical Rails with undefined Voltage

Darlington Transistors (T1 and T2, T3 and T4): h_{FE} = 1500, V_{BE} = 1.4V

Voltage Amplifier Transistor (T5): h_{FE} = 300, V_{BE} = 0.7V, Voltage Gain (above 20Hz) = 25

Load Resistor (R_L): 4Ω **Diode Forward Voltage:** 0.7V

I_{BIAS} (Current flowing through R_C): 25mA

V_E (Voltage across R_{E1} and R_{E2}): 2V

It is assumed that the AC Gain of the Amplifier is exclusively controlled by R_C and R_{E1}.

2.3 Circuit Analysis

We must analyse the circuit to calculate component values that will produce optimum quiescent conditions. The following assumptions are made:

1. The output voltage (V_{out}) is 0V under quiescent conditions; this provides the maximum available symmetrical output voltage swing.
2. There is a negligible voltage drop across R_{S1} and R_{S2}.
3. There is a negligible voltage drop across T1 and T3.

Given that the target output power is 100W we can calculate the required output current through the load R_L to achieve this power:

$$P_{out} = (I_{out})^2 \times R_L$$

$$\therefore I_{out} = \sqrt{\frac{P_{out}}{R_L}}$$

$$I_{out} = \sqrt{\frac{100}{4}}$$

$$I_{out} = 5\ A_{RMS}, \qquad \overline{I_{out}} = 5\sqrt{2}\ A\ (Approx\ 7.07\ A)$$

$$\therefore V_{out} = 20\ V_{RMS}, \qquad \overline{V_{out}} = 20\sqrt{2}\ V\ (Approx\ 28.3\ V)$$

Given our earlier assumptions we can set this maximum output voltage to the symmetrical supply voltage V_{CC}. Therefore V_{CC} = 28.3V. This maintains maximum efficiency in the amplifier as any additional voltage would be dropped across transistors T1 and T3, creating greater losses in the circuit (requiring greater heat sinks for cooling).

These assumptions also allow us to calculate the required quiescent current:

$$\overline{I_{out}} = 2I_Q$$

$$\therefore I_Q = \frac{5\sqrt{2}}{2}\ A\ (Approx\ 3.54\ A)$$

Given the voltage diode forward voltage V_D = 0.7, the voltage across diodes D_{1-5} can be calculated:

$$V_{D_{1-5}} = 5 \times 0.7$$

$$V_{D_{1-5}} = 3.5\ V$$

We can therefore say that the total voltage across R_{S1} and R_{S2} is 0.7V due to V_{BE} = 1.4V for the Darlington Pairs. This allows us to calculate the required value for R_{S1} and R_{S2}:

$$2R_S = \frac{V_{D_{1-5}} - 2 \times V_{BE}}{I_Q}$$

$$R_S = \frac{3.5 - 2.8}{7.07}$$

$$R_S = 0.099 \ldots$$

$$R_S \approx 0.1$$

As we know the quiescent current, we can also calculate the required base current for T2:

$$I_B = \frac{I_C}{h_{FE}}$$

$$I_B = \frac{3.54}{1500}$$

$$I_B = 2.36\ mA$$

As this required base current is less than 10% of I_{BIAS} (25mA) we can reasonably ignore it (the validity of the assumption will be discussed in the conclusion). Therefore, we can assume the following:

1. All the bias current flows through diodes D_{1-5}.
2. The Collector Current I_C and Emitter Current I_E of T5 are approximately equal.

These assumptions allow us to calculate the value of R_C and R_{E1} + R_{E2} using the following method:

$$R_C = \frac{V_{CC} - V_{B_{T2}}}{I_{BIAS}}$$

$$R_C = \frac{28.3 - 1.75}{25 \times 10^{-3}}$$

$$R_C = 1062\Omega$$

$$R_{E1} + R_{E2} = \frac{V_E}{I_{BIAS}}$$

$$R_{E1} + R_{E2} = \frac{2}{25 \times 10^{-3}}$$

$$R_{E1} + R_{E2} = 80\Omega$$

The individual values of R_{E1} and R_{E2} depend upon the requirements of gain at DC and AC of the circuit (discussed further in the conclusion), this is partly controlled by Capacitor C_E. R_{E1} and R_{E2} can be calculated using the following method:

$$R_{E1} = \frac{R_C}{Voltage\ Gain}$$

$$R_{E1} = \frac{1062}{25} = 42.5\Omega$$

$$\therefore R_{E2} = 37.5\Omega$$

The base current of T5 can be calculated using the method shown previously with $h_{FE} = 300$. This gives a base current of 83.3µA. In order to make this negligible we set the current through R_1 to be 10 times this value. Further analysis of the circuit shows that the required bias voltage for T5 is 2.7V above $-V_{CC}$. This is calculated by summing V_E and V_{BE} for T5. Given that we can calculate this voltage, we can calculate the required values for R_1 and R_2:

$$R_1 = \frac{V_{CC} - V_{BIAS}}{10 \times I_{Base}}$$

$$R_1 = 64.7k\ \Omega$$

$$R_2 = \frac{V_{BIAS} + V_{CC}}{10 \times I_{Base}}$$

$$R_2 = 3.24k\ \Omega$$

This calculation concludes the values needed to complete the circuit, thus we can now build a model in a program such as LTSpice and verify the circuits operation. The completed circuit diagram can be seen in **Figure 2.2**. The complete circuit values are:

R_1 = 3.24kΩ, **R_2 =** 64.7kΩ, **R_C =** 1062Ω, **R_{E1} =** 42.5Ω**, R_{E2}** = 37.5Ω, **R_{S1} or R_{S2} =** 0.1Ω

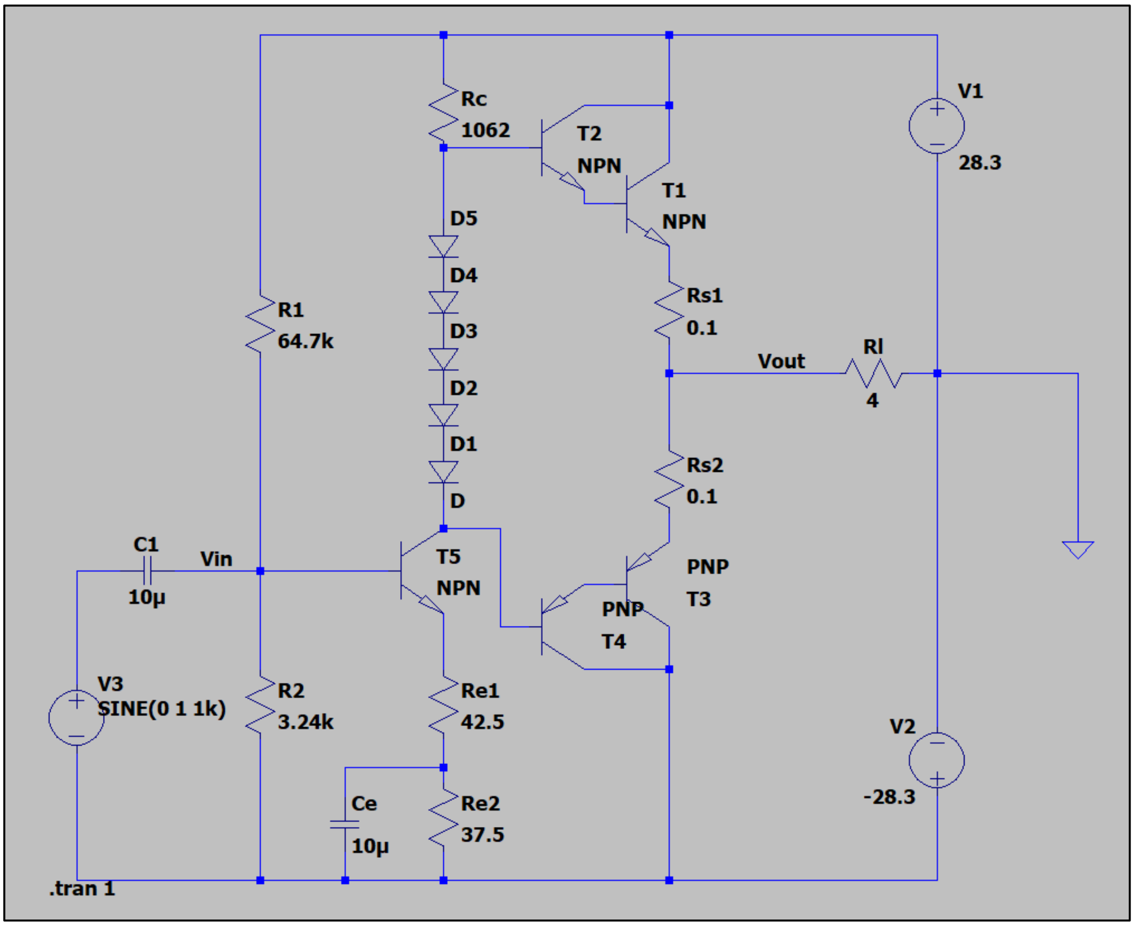

Figure 2.2: Power Amplifier Circuit with Ideal Values

2.4 Real World Values

Although the circuit analysis gives us exact values of required resistance these values of resistance cannot be purchased without considerable expense. Consequently, a circuit design with replacement values that can be purchased has also been constructed. This diagram can be seen in **Figure 2.3**.

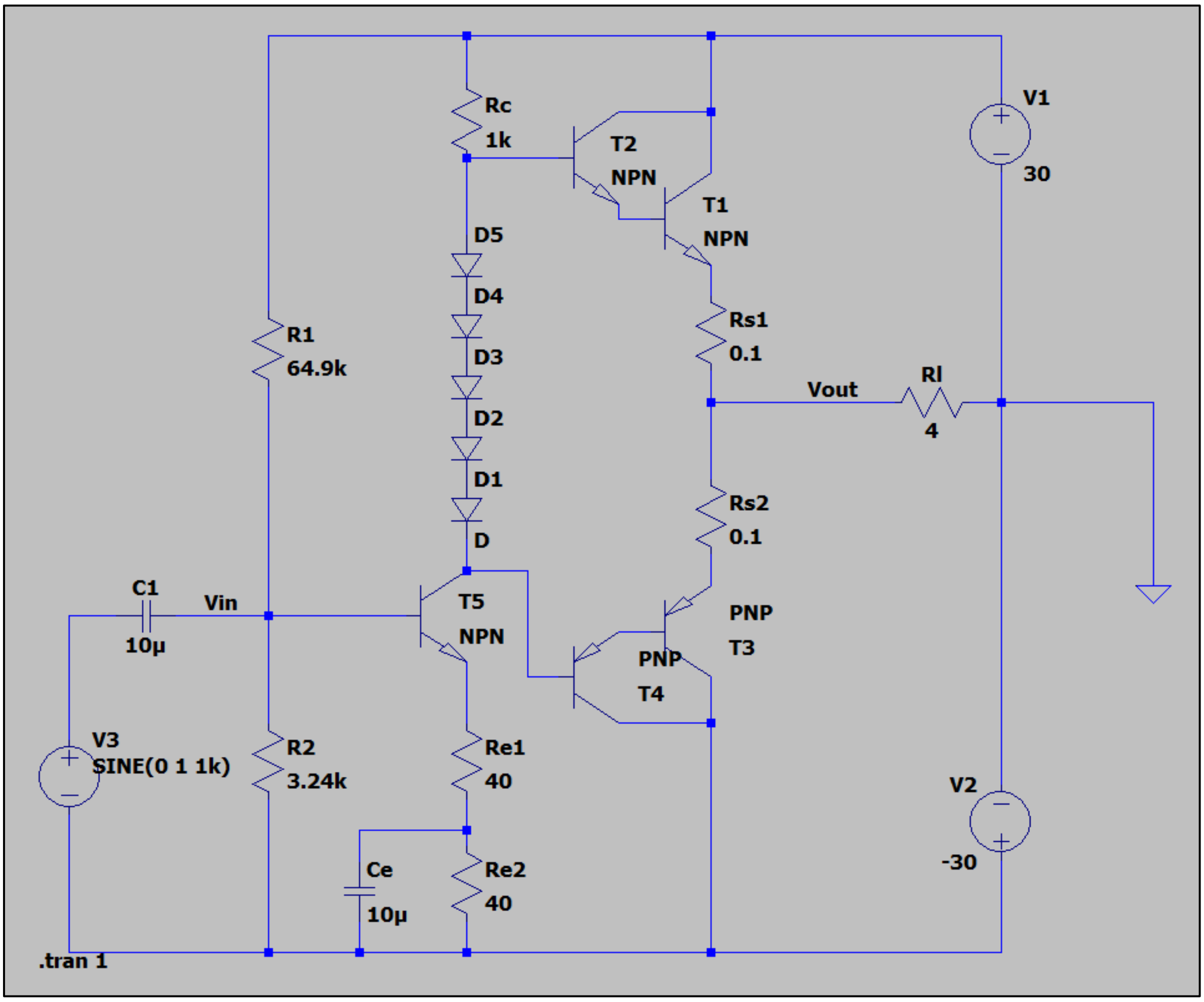

Figure 2.3: Power Amplifier Circuit with Real Values

The values of V_{CC} and $-V_{CC}$ have also been changed in order to accommodate for voltages drops across T1 and T3. Power supplies at 30V are also very common, whereas a 28.3V power supply is much harder to obtain.

2.5 LT Spice Analysis

Using the Circuit diagram, we can analyse the performance of the circuit and the selected values using LT Spice. The output waveform of the ideal circuit can be seen in **Figure 2.4**. This shows the circuit response to a 1V Amplitude 1kHz Sine Wave input.

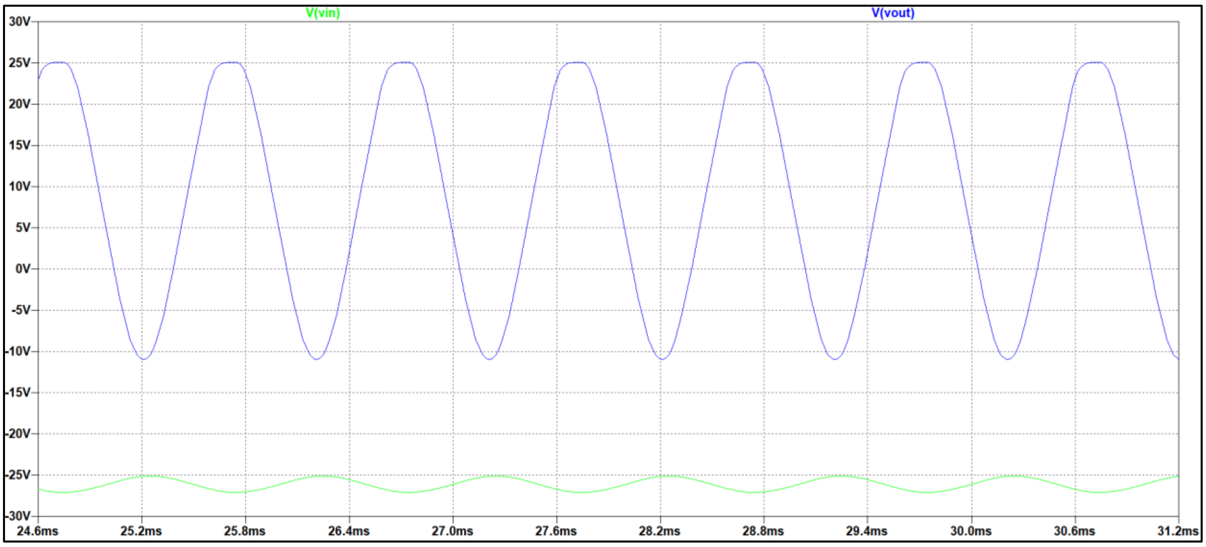

Figure 2.4: Ideal Circuit LT Spice Model Output Waveforms

2.6 Conclusion

The circuit analysis was successful in that it gave us biasing component values to use in our circuit. However, these values were calculated using a set of assumptions which may or may not be valid in the real world. Analysis of the output waveform in **Figure 2.4** shows that the circuit does not operate as predicted; thus, we can conclude that some or all the assumptions made were not correct.

Firstly, the circuit shows an extremely large DC offset of approximately 8V. This can be attributed to two factors. Firstly, we have assumed that the DC Gain (h_{FE}) of the Transistors is the same. This is never the case as the gain characteristics of transistors are difficult to control during manufacture due to the doping of the semiconductor material varying with impurities. Secondly, it was assumed that the base current of T2 and T4 was negligible, this is not true. Thus, our value for R_C is incorrect, as is our value for $R_{E1} + R_{E2}$.

These two factors have caused one T1 to be biased on more than T4, creating a positive DC offset. This DC offset would almost certainly destroy a loudspeaker it was connect to due to the constant power dissipation in the loudspeaker coil causing it to overheat and melt. Additionally, the DC offset generates a large amount of distortion in the positive peaks of the output waveform when a greater input amplitude than 1V is used. This is due to the output voltage clipping against the available supply voltage rails. A greater value of supply voltage than shown in the ideal circuit would have to be used due to the voltage drop across the transistors T1 and T3 and resistors R_{S1} and R_{S2}.

An additional area of note is Capacitor C_E which partially controls the AC gain of the Voltage Amplifier. Setting R_{E2} with a greater value than R_{E1} causes an increase in Voltage Amplifier gain at High Frequencies due to the capacitors acting like a short circuit. Equally, the inverse is also true.

3 Loudspeaker Analysis

3.1 Introduction

This section covers the analysis of a loudspeaker based upon the theory covered in Professor Dave Stone's section of module EEE229. The characteristics of the loudspeaker will be used to generate an equivalent electrical circuit and a diagram of the loudspeaker will also be produced.

The loudspeaker oscillates due to the interaction between the magnetic field generated by the voice coil and the magnetic field generated by the permanent magnets surrounding the coil. The voice coil floats between the permanent magnets and thus moves when a current is passed through it.

3.2 Loudspeaker Specification

Loudspeaker Parameter	Value
Coil Diameter	5cm
Flux density in airgap	1.2T
Spring constant	3.55×10^6
Damping coefficient	88.83
Mass of moving system and air	106g
Number of turns in coil	100
Wire diameter	1.8mm
Wire material	Copper
Coil Inductance	10uH

Table 3.1: Loudspeaker Specification

3.3 Loudspeaker Cross Sectional Diagram

The following section shows a cross sectional diagram of the loudspeaker (**Figure 3.1**). This is what you would see if you cut the loudspeaker directly in half. Key sections have been labelled in order to better illustrate the loudspeakers operation.

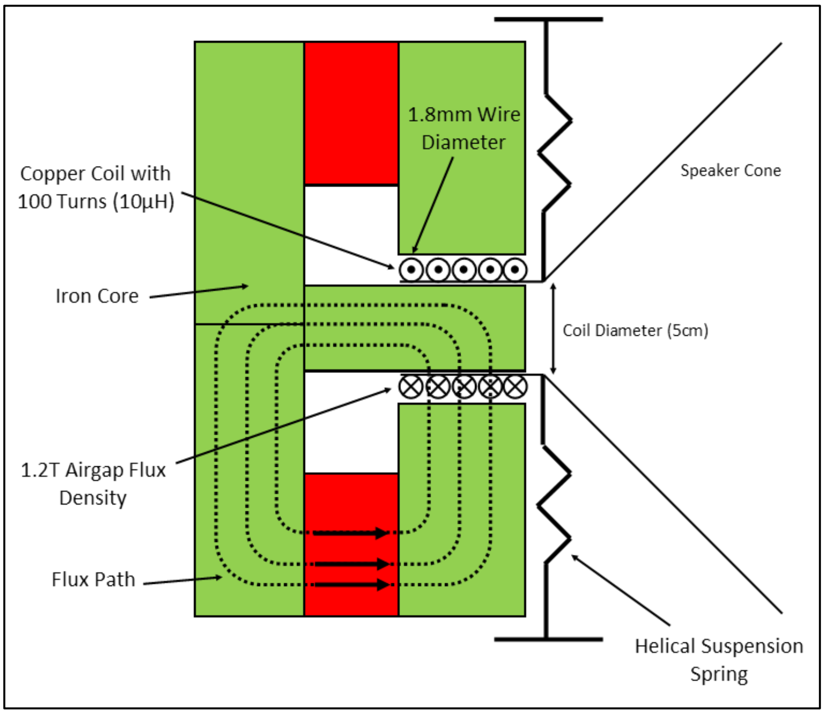

Figure 3.1: Loudspeaker Cross Sectional Diagram

3.4 Electrical Equivalent Circuit Analysis

This section details the analysis of the loudspeaker to generate the equivalent electrical circuit which can then be used in further analysis. Before we can analyse the loudspeaker to generate the equivalent circuit, we make the following assumptions:

1. The Flux Density in the airgap as perceived by the voice coil remains constant. This means that the coil does pass into the fringe field or entirely exit the magnetic field of the permanent magnets.
2. The force exhibited on the voice coil is linearly proportional to the current flowing through the voice coil.
3. The force produced by the coil whilst acting as a spring is linearly proportional to the amount the coil is compressed.
4. The coil has a constant impedance across all frequency ranges, it is purely resistive.
5. The displacement of the coil is proportional to the force applied to the coil.

Using these assumptions, we can calculate the resistor, capacitor and inductor values that represent the mechanical loss, mass of moving air and spring (formed by the voice coil) in the loudspeaker respectively. Initially we calculate the force constant of the system:

$$K_e = BN\pi D$$

$$K_e = 1.2 \times 100 \times \pi \times 0.05$$

$$K_e = 6\pi\ (18.85\ to\ 2dp)\ NA^{-1}$$

This force constant allows us to calculate the capacitance model of the moving mass of air within the speaker cone as follows:

$$C = \frac{M}{(K_e)^2} = \frac{0.106}{(6\pi)^2}$$

$$C = 298\mu F$$

The force constant also allows us to calculate the equivalent inductance of the spring the voice coil forms along with the spring constant of the system:

$$L_s = \frac{(K_e)^2}{\sigma_s} = \frac{(6\pi)^2}{3.55 \times 10^6}$$

$$L_s = 100.1\mu H\ (Approximately\ 100\mu H)$$

Finally, using the force constant and the damping coefficient given in **Section 3.2** the equivalent resistance value to represent mechanical losses in the speaker can be calculated:

$$R_M = \frac{(K_e)^2}{K_d} = \frac{(6\pi)^2}{88.83}$$

$$R_M = 4\Omega$$

Additionally, we can calculate the series resistance of the voice coil in the loudspeaker:

$$R = \frac{\rho l}{A} = \frac{1.68 \times 10^{-8} \times \pi \times 0.05 \times 100}{\pi \times \left(\frac{0.0018}{2}\right)^2}$$

$$R = 0.1\Omega$$

These calculations allow us to generate the equivalent circuit as shown in **Figure 3.2**. This electrical equivalent circuit allows us to calculate the theoretical resonant frequency of the loudspeaker and predict its performance when paired with the model of the Power Amplifier.

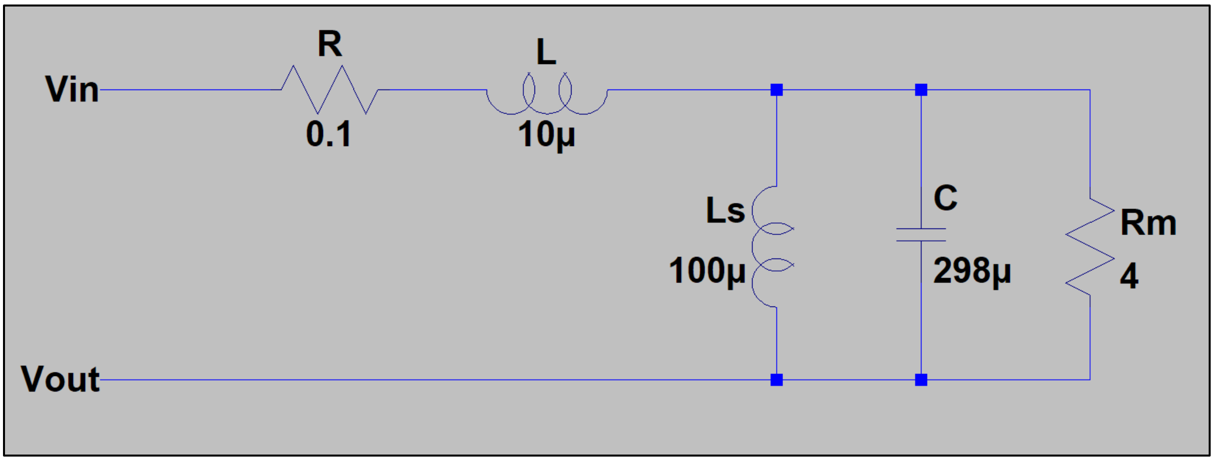

Figure 3.2: Loudspeaker Electrical Equivalent Circuit

3.5 Conclusion

We have now successfully generated a cross sectional diagram of the loudspeaker as well as an equivalent electrical circuit which can be used in modelling to determine the loudspeakers performance across a range of frequencies. This will allow us to better determine whether the design of our loudspeaker is applicable for the frequency range we aim to operate it over and whether the Power Amplifier circuit we have paired with it will drive it correctly and efficiently.