EEE223

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1 Power amplifier design

The amplifier circuit is given by Figure 1 and is our job to figure out the values that are not given to us in Table 1 so that the amplifier is correctly biased while stating any assumptions made.
To begin we will work out the value of the power supply as it's much easier to work out all of the other circuit parameters using this. We know from out given values that the average power is 100W given in Table 1 and we are given the resistance is 4Ω and using the equation:

$$P = \frac{(\frac{V_p}{\sqrt{2}})^2}{R} \tag{1}$$

Re-arranged to give:

$$V_p = \sqrt{2PR} \tag{2}$$

To give us a value of 28.3 for peak voltage over the load (R_L) which isn't good for our supply as there is a voltage drop over R_s and T_1 and by inspection $R_s = 0.35V$ due to the voltage drop of the diodes and transistors $D1 - D5$ and T_1, T_2 dropping $0.7V$ over both R_s resistors. And assuming a worst case scenario in full conduction the transistor will drop 1 volt (an average value) giving us 29.65V which with a bit of leeway for component tolerances and power supply tolerance we can say a 30V supply for V_{ss}.
Now we have our V_{ss} we can easily work out our values for R_1 and R_2 as it is a simple potential divider with a current leaking through the transistor. We know the voltage at the base of T_3 needs to be 10.7 volts higher than our negative supply and to simplify we can create an equivalent circuit with voltage 60 Volts shown in Figure 2(due to plus and minus 30V supply) and as we know there is 49.3V(60-10.7) over R1 and we choose the current (must be considerably larger than the transistor base current of $33\mu A$ so i chose $1000\mu A(1mA)$ otherwise the small change in current from the signal would change the voltage and possibly turn the transistor on and off giving us a very dodgy signal) and using $V = IR$ we get that $49.3k\Omega$ as the whole current passes through R_1 whereas R2 only passes the remainder of the current ($1000 - 33\mu A$ but we will ignore this tiny loss as it is minature in relation) shown by I_2 in Figure 2 with the current taken by T_3 followed by the equation:

$$\beta = \frac{I_c}{I_b} \tag{3}$$

where once again we can use $V = IR$ to get a value of $10.7K\Omega$ for R_2.

Like usual we can work out value of voltage over a resistor in this case we are working on R_c as we can get the voltage above as it's connected directly to $V_s s$ and with the drop of 0.35V over R_s and the V_{be} of 1.4V so the voltage over R_c is 30-0.35-1.4=28.3 and we need the bias current to pass through T_2 of 5mA and assuming T_2 is an equal version of T_1 the current in T_1 base comes back in through T_2 so 5mA is correct. As we have the current and voltage we can get the value of R_c resistance as $5.56k\Omega$

We can now work out the resistor values for both R_s as we know at maximum the voltage over the load will be 28.3V and a 4 ohm load makes a peak current of 7.1A which we can use as the worst case scenario current and for worst case the voltage over R_s is $V_{ss} - V_{ce} - 28.3$we need to go off the peak current so that there is enough voltage spare to drive the load R_L and using this we get $R_s = 0.1\Omega$

Circuit parameters	Values
Speaker average power	100W
T1,T2 current gain	700
T1,T2 base emitter voltage	1.4
T3 base emitter voltage	0.7V
T3 current gain	150
D1-D5 forward voltage	0.7V
RL	4R
T3 bias current	5mA
VRE	10
T3 voltage gain	25

Table 1: Values given for Figure 1 amplifier

From Figure 1 we can make a few assumptions to simplify the circuit down assuming we have a small signal model to calculate R_E1 such as this:
For small signals capacitors are ignored.
R_1, R_2 are so large that current can be ignored.
R_E2 is in parallel with a capacitor so assume capacitor takes all the current.
V_ss shorts to ground.
Diodes are perfectly biased so current can flow freely both directions including transistors.
Any current through T_1 or T_2 is ignored as it is counteracted by the other so the entire path can be ignored.

This gives us the our small signal equivalent circuit in Figure 3. Using this circuit we can see by inspection the equations:

$$V_{in} = I_e \cdot R_{e1} \tag{4}$$

$$V_{out} = I_c \cdot R_c \tag{5}$$

But saying that $I_c = I_E$ we get that:

$$G = \frac{V_{out}}{V_{in}} = \frac{R_c}{R_{e1}} \tag{6}$$

Using this for a given gain and a given R_c we can get that $R_{E1} = 226$ we also know that the total of our R_E resistors must equal $2k\Omega$ as T3 must have 5.033mA passing through with 10V over using $V = IR$ so $R_{E2} = 1800$ as an round value.
With all of the resistor values now found all we need are the capacitor values so we only need to think about AC signals.Both C and C_e must allow all audio signals pass through as we assumed for our small signal model that these capacitors were negligible impedance (in comparison to the resistors in the system) and with lowest audio hearable around 20Hz this is what we will use for our frequency as this is when the capacitors have their highest impedance. The term negligible is very non-specific which doesn't help us choose our value but for me i am saying 5% is negligible so a max impedance for C is given by $0.05R_1//R_2$ giving us a value of 450Ω at 20Hz and using the equation:

$$X = \frac{j}{2\pi fC} \tag{7}$$

To give us a capacitor value of $18mF$. Now we need to repeat this for C_E in comparison to R_E2 giving a value of 90Ω which corresponds to $88mF$.
with this we now have every value of component and now all we need are the maximum ratings for these components each of which are done using $P = VI$ and $P = I^2R$ and isn't worth explaining any further except that each item has been over estimated to count for either mixing ac and dc conditions or to allow leeway for component, power supply and mathematical tolerances while assuming a max signal current. All values are given in Table 2.

1.1 Power dissipation analysis

For this amplifier given the thermal resistance of the transistor packages and connections it is impossible to get a heat sink that would work for these values (temperature and power) and so

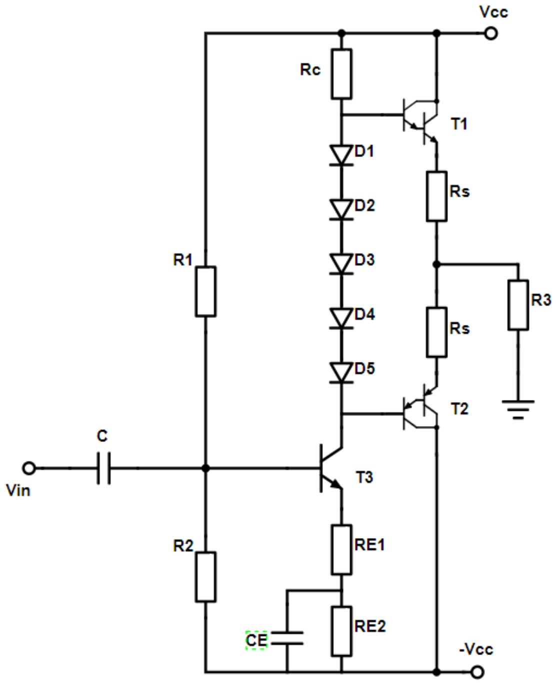

Figure 1: Class A/B amplifier circuit.

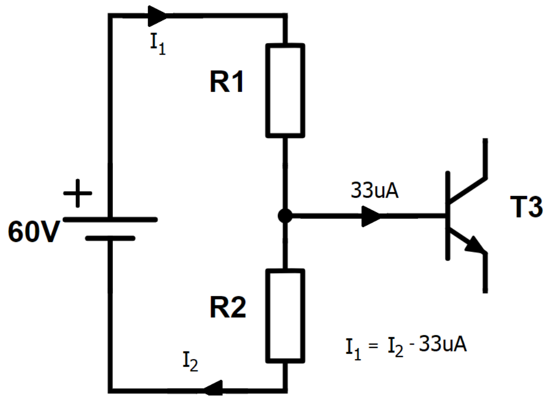

Figure 2: Equivalent circuit for calculating R1 and R2

we must use multiple transistors in parallel to dissipate the power, due to this we can use many transistors and make the contact resistance negligible and we only need to think about the heat sink dissipation. For power dissipation the temperature of a device is given by the voltage in an equivalent circuit where current through the device is the power dissipation and the thermal resistance of the heat-sink is given by a resistor. For this circuit the only components that dissipate enough energy to require a heat-sink are the two transistors and the speaker but the speaker isn't part of our system to be designed and so we only need to look at our two power amplifier transistors T_1 and T_2. At max our transistors are dissipating is 110 Watts, this means our equivalent circuit will have a current source of 110 Amps(Watts), we must now find an appropriate heatsink, the one i have found has a thermal resistance of 0.5Ω (Temperature per Watt) ignoring the contact thermal resistance with a current and resistance we can then say (Using Ohms law) that the voltage over our heatsink (Temperature) is 55V (55^oC)which is an acceptable temperature and requires a T03 package which is common for power transistors. The circuit of which is shown in Figure 4.

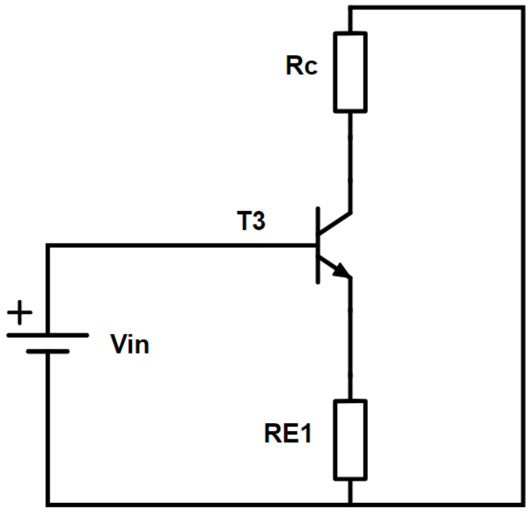

Figure 3: Equivalent small signal circuit

Name	Value	Max Power	Max Voltage	Max current
R_1	$49.3k\Omega$	50mW	50V	1mA
R_2	$10.7k\Omega$	11mW	11V	1mA
R_C	$5.56k\Omega$	150mW	30V	5mA
R_{E1}	226Ω	0.75mW	1.5V	5mA
R_{E2}	1800Ω	50mW	10V	5mA
$D_1 - D_5$	N/A	0.35mW	0.7V	5mA
$R_s(Each)$	0.1Ω	6.3W	0.8V	8A
R_3	4Ω	225W	30V	7.5A
C	$18mF$	1.5mW	15V	1mA
C_E	$88mF$	1mW	10V	1mA
T_3	N/A	0.2W	20V	10mA
T_1/T_2	N/A	110W(As $P_p \neq V_p I_p$)	30V	8A

Table 2: Table of calculated values

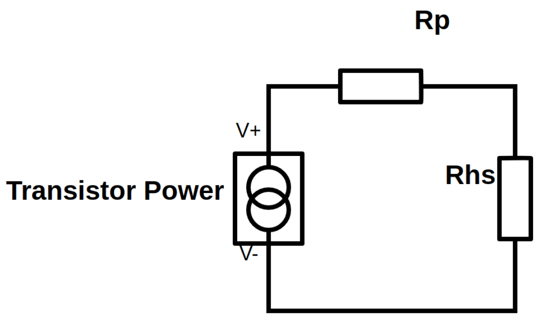

Figure 4: Transistor T_1/T_2 heat flow circuit.

2 Loudspeaker analysis

2.1 Equations

$$K_e = BN\pi D \tag{8}$$

Where: K_e is the electromagnetic constant of the system; B is the Field strength at the coil location; D is the Diameter of the coil; $N=$ Number of turns on the coil. Assuming the field density is constant throughout the coil.

$$R_c = \frac{\rho L}{A} \tag{9}$$

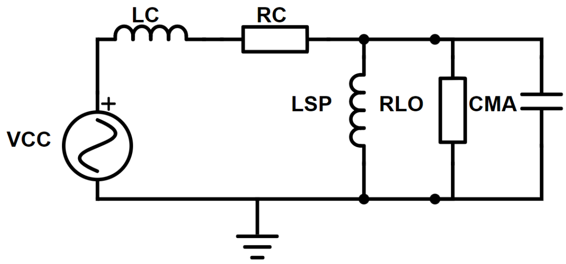

Figure 5: Equivalent circuit of the speaker resonance.

Where: R_c is the resistance(yes resistance not impedance) of the coil; ρ is the resistivity of copper; L is the length of wire; A is the cross sectional area of the wire. This equation assumes a constant current density throughout the wire and the wire is pure copper.

$$C_{ma} = \frac{M}{k_e^2} \tag{10}$$

Where: C_{me} is the equivalent capacitance of the air mass oscillated (including the cone mass); M is the mass of air and cone combined; This assumes that the cone mass also gets more difficult to move as frequency goes up the same way the air does.

$$L_{sp} = \frac{K_e^2}{\sigma_s} \tag{11}$$

Where: L_{sp} is the equivalent inductance of the helical springs movement; σ_s is the spring constant of the helical spring. This assumes the spring is pure and has no parasitic components whereas it could/should be represented by its own LC network as it would not react linearly at high frequencies(just like an inductor), and the spring is constantly in its linear elastic region.

$$R_{lo} = \frac{K_e^2}{K_d} \tag{12}$$

Where: R_{lo} is the equivalent parallel resistance for wasted energy in the system; K_d is the damping co-efficient.

2.2 Theory

Using these equations we can get a table of our circuit parameters which can be seen in Table 3. These values are used in conjunction with the circuit in Figure 4 to give us or simulation circuit seen in Figure 7. With this simulation we can see the gain of our speaker over the audio range 20Hz to 20kHz which is they typical hearing range. We would aim to have a gain of 0 across all values as this would mean no notes would be louder or quieter than others unless told to but of course with reactive components this is impossible so we must try to get as close as possible. As seen in Figure 6 the gain of the circuit averages around 0 at the mid frequencies but tapers off at the low and high frequencies and so would be used as a mid range speaker not for high or low frequencies. This graph was formed by the voltage over the parallel components as this directly correlates to the current through R_{lo} which is the power lost by the speaker system through operation (not coil heat dissipation) as reactive components don't use energy they just store it. Overall we can see that this speaker would be useful for mid range signals and ok for low frequency signals but awful for high frequencies.

Loudspeaker parameters	Value	
Coil Diameter(D)	0.05	m
Flux density in airgap(B)	1.2	T
Spring constant(Sigma)	3.55E-6	Nm^{-1}
Damping co-efficient(Kd)	88.83	
Mass of moving system and air(M)	0.106	kg
Number of turns in coil(N)	100	
Wire diameter	1.8E-3	m
Wire material	Copper	
Coil inductance(Lc)	1.0E-6	H
Resistivity of copper(Rho)	1.72E-8	Ωm
Coil length (L)	15.7	m
Cross sectional area of wire(A)	2.54E-6	m^2
Rc	0.106	Ω
Ke	18.84	Tm
Cma	2.99-4	F
Lsp	9.99E-5	H
Rlo	3.99	ω

Table 3: Table of given and calculated values

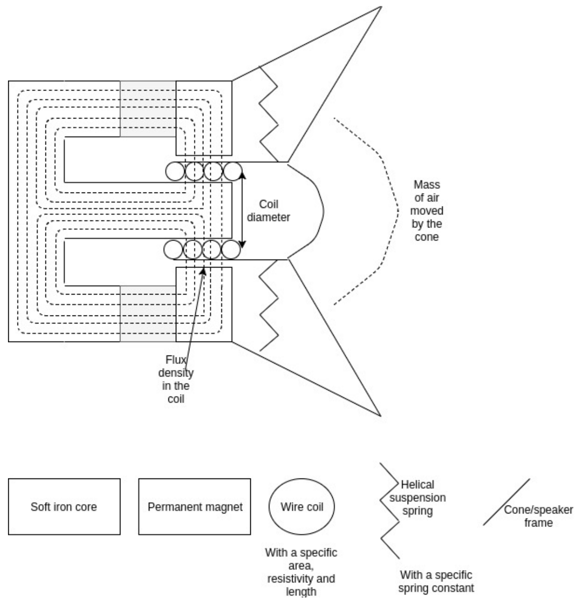

Figure 6: Cross-sectional diagram of a voice coil actuator

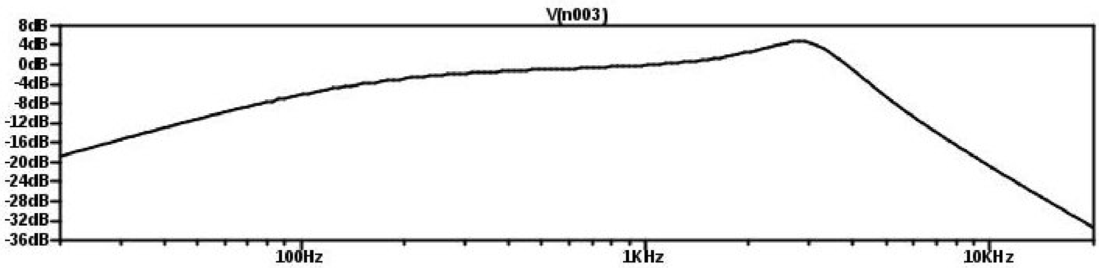

Figure 7: LTSpice equivalent circuit

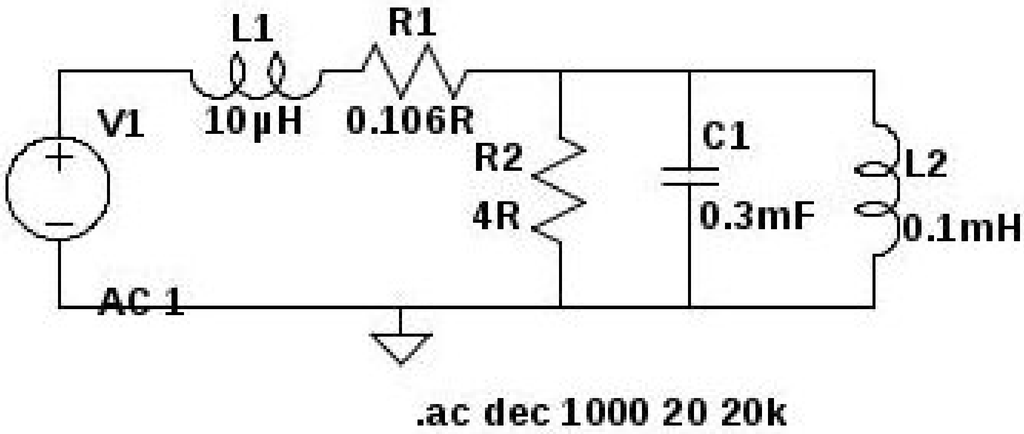

Figure 8: LTSpice equivalent circuit voltage over R_{lo}