3. Audio Amplifier

Part 1: Transistor Level Design

Chapter 3 Goals

- Become familiar with, analyze, and construct the following amplifiers:
  - Common-collector (CC) amp
  - CE-CC two stage amp
  - Class AB push-pull amp
  - CE-class AB two stage amp
  - Op-amp audio amplifier
  - Op-amp-class AB two stage amp
  - LM386 audio amp

An audio amplifier's job is to boost the signal level for driving a speaker. Gain is therefore important. Bandwidth is not generally an issue at such low frequencies. Signal distortion can be important for sound quality. Distortion increases as the signal level to the input of the amplifier exceeds the transistor's small signal limit, or as the output exceeds the available voltage range or current limits. Finally, the audio amplifier can draw the most power of any component in an AM radio. An excessive power requirement will limit battery life.

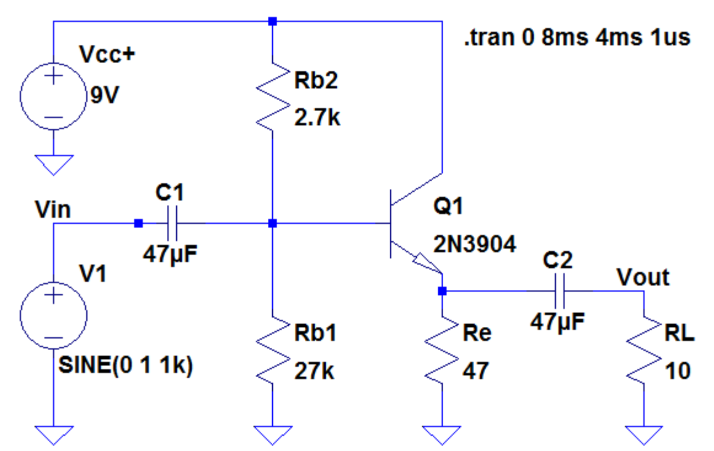

Figure 3.1: Common-collector (CC) amplifier

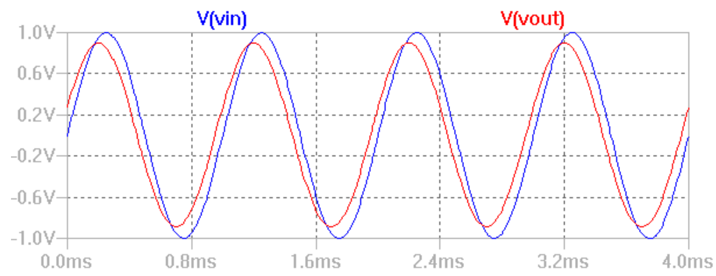

Figure 3.2: transient simulation of CC amp

3.1 Buffer Amplifier

In the previous chapter (see Table 2.1), you saw how the amplifier gain drops as the load resistance drops. A buffer amplifier is often placed between the amplifier and a low resistance load. The buffer amplifier has ideally a unity gain, but presents a high input impedance.

A buffer amplifier can be realized with a BJT through a common-collector configuration. This type of amplifier, shown in Figure 3.1, is also referred to as an *emitter-follower*, since the output on the emitter ideally follows the input signal on the base (that is, the gain is about 1). Notice the input has a 1 V amplitude; about a volt or two is the typical value we'd like to have at our speaker for a loud output.

3.2 LTspice: Two-Stage BJT Amplifier

1. Construct the CC amplifier of Figure 3.1 in LTspice. Run the DC Op Pnt to find the transistor Q-point:

   Q(_________ , _________)

2. Run a transient simulation with an 8ms stop time, 4ms delay time, and 1µs time step (see Figure 3.1 .tran statement). Plot the output and input voltages (this should look like Figure 3.2) and determine the gain of this CC amplifier.

   Gain (R_L = 10 Ω) = _________

3. Notice that the emitter resistor Re is only 47 Ω. If we want to reduce the current through the transistor, and therefore reduce the power requirement, we can increase Re.

- Change Re to 100 Ω and re-simulate. What happens?

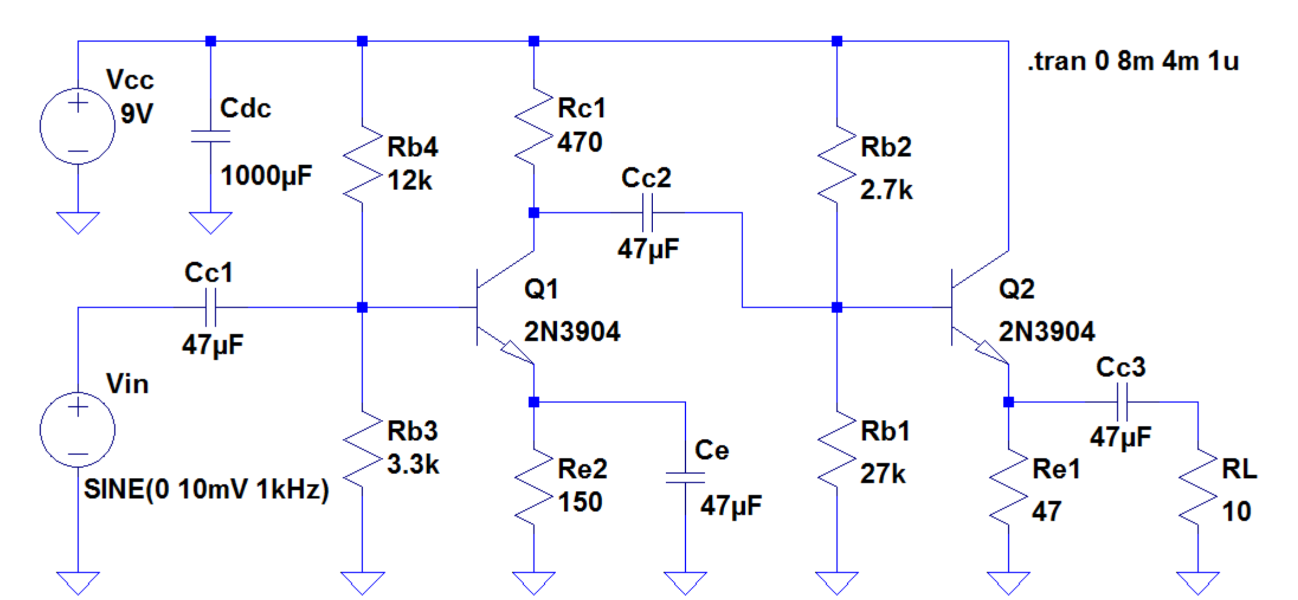

Figure 3.3: Two stage CE-CC amplifier

4. Now, in LTspice build the two-stage amplifier circuit shown in Figure 3.3 consisting of a CE amp followed by a CC amp. You can copy and paste your earlier CE amp design.

- Note the addition of a decoupling capacitor from power to ground. Use a large electrolytic capacitor (1000 µF), placed from power to ground (observe the capacitor polarity!) on your breadboard.

5. Set the amplitude of Vs to 0 V, and run the DC Op Pnt. Find the total power dissipated in this circuit. This is the *quiescent power dissipation*, P_Q, since there is no AC signal to amplify (*i.e.* the amplifier is "quiet").

- The best way to determine P_Q is to inspect the power delivered by the 9V supply. Be careful, as the current polarity may imply a negative P_Q!

- P_Q (default two-stage amp): ____________
- Note the voltage polarity across the capacitor Cc2. This is very important information for when you assemble the two-stage amplifier of the next section.

6. Set the amplitude of Vs to 10 mV (as shown in Figure 3.3). Perform a **transient simulation** as

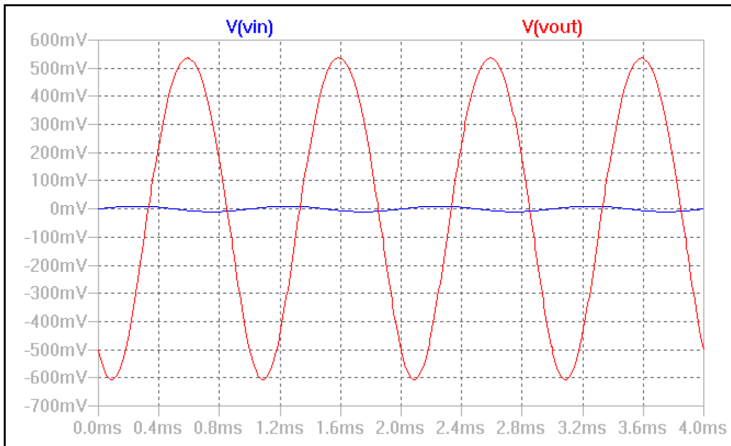

Figure 3.4: transient simulation of CECC amp

before (see Figure 3.4) and determine the gain of your amplifier.

Gain = __________

The limits to the available range for the output may result in a distorted audio signal. You may notice this in the output where the positive peak is at a higher amplitude than the negative peak.

7. In order to more clearly see distortion in our LTspice simulation, increase the input signal amplitude to 20 mV (from the default 10 mV) and re-simulate. **Comment** on what happens to the output.

3.3 Build and Test the Two-Stage Amplifier

A typical loudspeaker is a very simple device consisting of a paper or plastic cone affixed to a voice coil (an electromagnet) suspended in a magnetic field. An AC signal through the coil produces back-and-forth movement of the coil and diaphragm, thus producing sound waves of the same frequency as the AC signal. The cross section of a typical moving-coil speaker is shown in Figure 3.5.

Your speaker is a 1/2 Watt "8 ohm speaker". The 8 Ω refers to the speaker impedance, Z, a combination mostly of coil wire resistance and coil inductance. The speaker can handle a voltage amplitude of about 2.83 V. Relating this amplitude to power and impedance, we have

$$P = \frac{1}{2}\frac{v^2}{Z} = \frac{1}{2}\frac{(2.83V)^2}{8\Omega} = 0.5W$$

Typically, signals with an amplitude of a volt or so are needed to achieve a loud signal.

1. Prepare your speaker

- Some speakers may come with wires pre-attached, and this step can be skipped.
- ~ 3" lengths of wire; ~3/8" bared at each end
- Bend one end of wire (see Figure 3.6)
- Feed bent end of wire through speaker eyelet and apply long-nosed pliers to gently make a snug connection.
- Apply solder; soldering stations are available in the back of the room. The GTA will show you how to properly solder. Also, please peruse this very handy guide: http://mightyohm.com/files/soldercomic/FullSolderComic_EN.pdf
- Repeat for other wire.

2. Apply audio wave directly to speaker

- Insert speaker wires in a convenient location on your breadboard.
- Connect the generator and the scope to your speaker wires (see Figure 3.7)
- The load often influences the generator output. To test this, remove the speaker as a load by disconnecting one of its wires from the breadboard. Now use the scope and generator to create a 1 kHz sine wave. Your GTA will provide you with an input signal amplitude, vin, for your 1 kHz sine wave Record this amplitude here:

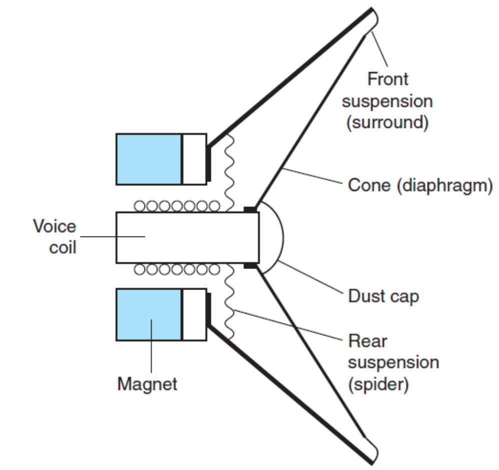

Figure 3.5: cross section of a moving coil loudspeaker.

Figure 3.6: wires and speaker prior to soldering. Note that some speakers are pre-wired.

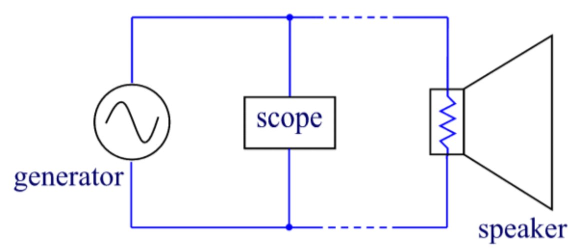

Figure 3.7: Driving the speaker directly from the generator

v_{in} = ____________

- Re-connect the speaker. What happens to the voltage amplitude?

$(v_{in})_{\text{with speaker}}$ = ____________

- Is the sound loud? Adjust the generator amplitude to increase the volume.

3. Build the CE amplifier shown in Figure 2.11 and insert it between the generator and the speaker as indicated in Figure 3.8.

- The CE amp portion of Figure 3.8 consists of all parts of Figure 2.11 between and including the pair of coupling capacitors C1 and C2. The "gen." is like the 1 kHz vin from Figure 2.11, only with your assigned value of v_{in}, and RL = 1 kΩ from Figure 2.11 is replaced with the 8Ω speaker.
- Conduct a sound check using the generator settings of step 2 (Your minimal amplitude at 1 kHz). Comment on how the output sounds.

4. Build the CC amplifier of Figure 3.1 and insert it between the generator and the speaker, replacing the CE amp in Figure 3.8.

- The CC amp consists of all parts of Figure 3.1 between and including the pair of coupling capacitors C1 and C1.
- Note that significant power is dissipated in the 47 Ω resistor. Use a 1/2 watt or 1 watt resistor, or use two 1/2 watt 100 Ω resistors in parallel.
- Conduct a sound check using the generator settings of step 2 (your v_{in} at 1 kHz). Comment on how the output sounds.

5. Build the two stage amplifier of Figure 3.3 and insert it between the generator and the speaker as indicated in Figure 3.9.

- RL = 10 Ω from Figure 3.1 is replaced with the 8Ω speaker.
- Conduct a sound check using the generator settings of step 2 (Your v_{in} at 1 kHz). Comment on how the output sounds.

- Use the oscilloscope to view the output signal at the speaker. Is this signal noisy? Comment.

- Replace the speaker with a 10 Ω resistor. Use the oscilloscope to examine the input and the output signal at this level. Record voltage amplitudes and gain in Table 3.1.

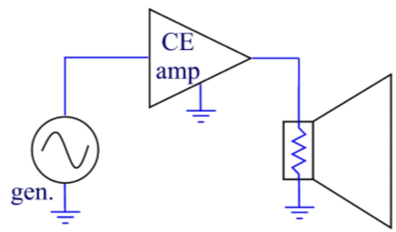

Figure 3.8: Inserting the CE Amp between the generator and speaker

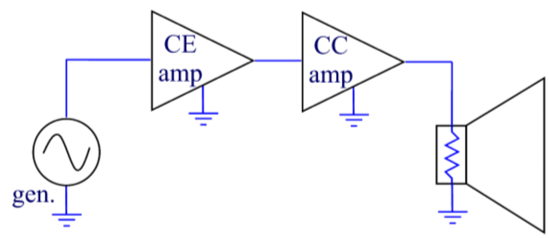

Figure 3.9: Inserting the CE and CC Amps between the generator and speaker

Table 3.1: voltage amplitudes and gain for the two stage amplifier terminated in a 10 Ω load

Output amplitude	
Input amplitude	
Gain(V/V)	

6. Determine the power dissipation of your two-stage amplifier

- The quiescent power dissipation is the power required when there is no signal to amplify, so disconnect the input signal.
- A simple way to determine P_Q is to feed the voltage supply through a 100 Ω resistor as shown in Figure 3.10. Adjust the supply such that V_{cc} = 9 V on the circuit side of the resistor. Then, you can find the total current fed to the amplifier circuit by measuring the voltage drop across the resistor and dividing by 100 Ω. The P_Q is then this current multiplied times V_{cc} (9 V).

P_Q = _______________

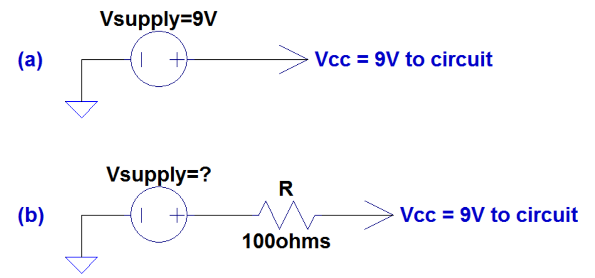

Figure 3.10: (a) original supply, (b) voltage fed through a 100 ohm resistor. Vsupply is adjusted to maintain Vcc = 9V. Current supplied by the generator is (Vsupply – Vcc)/100 Ω.

3.4 The class AB Push-Pull Amplifier

The CC amplifier of section 3.1 is called a *class A amplifier*. A Q-point is set, and regardless of whether there is a signal to amplify, power is dissipated in the amplifier.

A basic class B amplifier, in a push-pull configuration as shown in Figure 3.11, has the efficiency advantage that the npn BJT is only on during the positive half cycle, and the pnp BJT is only on during the negative half cycle. There is therefore little quiescent power dissipation in the transistor portion of the amplifier. A drawback to the class B amplifier, however, is that it takes roughly 0.7 V to turn on the forward biased pn junctions in the BJTs, so the output signal can show significant distortion (Figure 3.12).

A class AB amplifier solves the distortion problem, but doesn't have as high efficiency. As Figures 3.13 and 3.14 show, adding a pair of diodes in the base bias string ensures that there is just sufficient voltage to turn on the pair of transistor pn junctions, and the output signal is far less distorted.

These push-pull configurations are rather like a pair of emitter follower circuits; that is, the ideal voltage gain of this amplifier will be one. Thus, the circuit of Figure 3.13 would replace the CC amplifier in our 2-stage audio amp.

<u>3.4a LTspice Simulation</u>

1. Assemble and test the "default" circuit for the basic class B push-pull amplifier (Figure 3.11).

- Note that C1 and C2 are electrolytic capacitors, so be careful of their polarity.

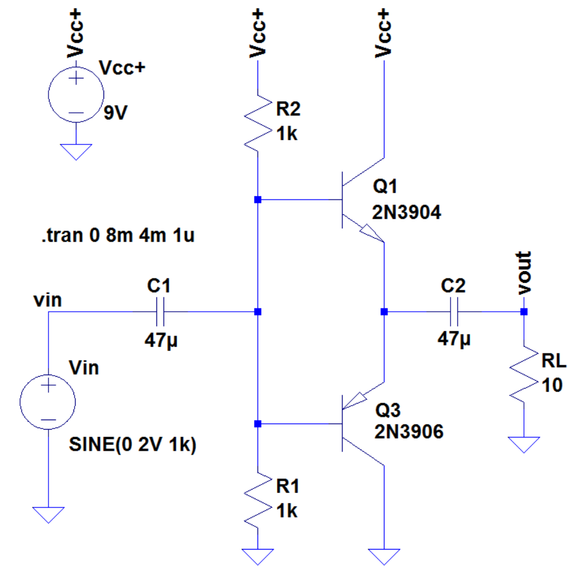

Fig 3.11: A basic class B push-pull amplifier

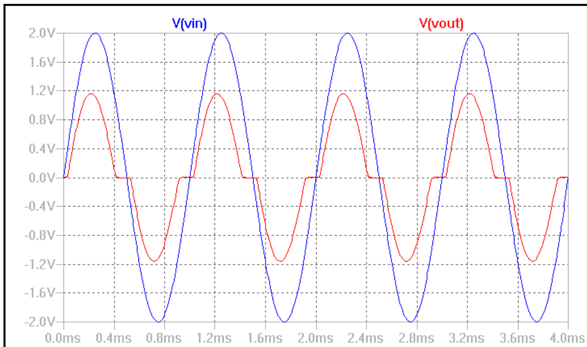

Fig 3.12: Transient simulation of the basic class B push-pull amplifier

2. Now set the amplitude of VSIN to 0 V, and run the DC simulation (DC OP PNT). What is the total quiescent power dissipated in this circuit?

P_Q = _______________

3. Now reset VSIN to a 2 V amplitude and observe the transient output at the source and across the load. This should appear as Figure 3.12.

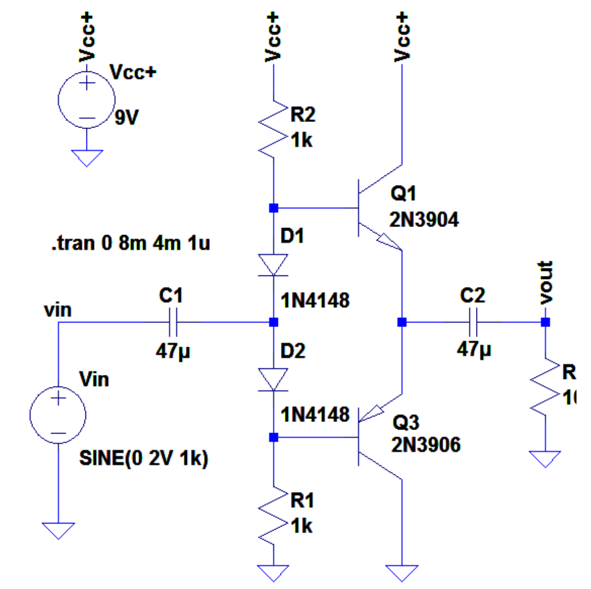

Fig 3.13: A class AB push-pull amplifier. The diodes ensure the pair of transistor pn junctions are "on".

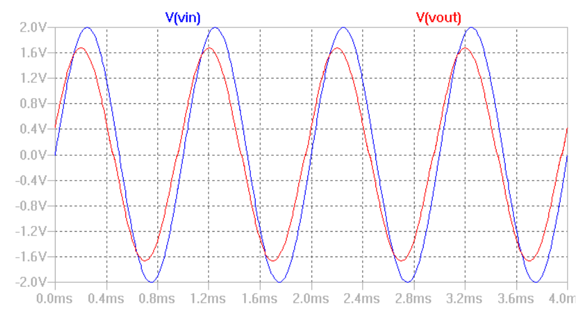

Fig 3.14: Transient simulation of the class AB push-pull amplifier.

4. With the 2 V amplitude input signal on, the circuit's power dissipation varies with time. This time-varying "instantaneous power" can be observed in the simulation window.

- Hold down the "alt" key while you click on the supply voltage Vcc+.
- Notice that the result indicates negative power. Since dissipated power is positive, negative power indicates the DC source is a source of power.

5. The average dissipated power can also be found from the plot.

- Hold down the "ctrl" button and click on the name of the measurement in the simulation window. A new window opens that displays the average power.
- Record this power, where we will neglect the small amount of power being delivered by the 2 V amplitude input signal.

P_{avg} = _______________

6. Modify the circuit of Figure 3.11 by adding a pair of 1N4148 diodes to get the circuit schematic of Figure 3.13.

7. Now set the amplitude of VSIN to 0 V, and run the DC simulation. Observe the voltages around the transistors and the currents. Calculate the total power dissipated in the circuit, P_Q.

P_Q = _________________

How does this compare with the value found for the class B push-pull amplifier (step 2)?

8. Now reset VSIN to a 2 V amplitude and observe the transient output at the source and across the load. This should appear as Figure 3.14.

9. Repeat steps 4 and 5 to find the average power dissipated in the circuit:

P_Q = _________________

How does this compare with the value found for the class B push-pull amplifier (step 5)?

3.4b Build and Test Circuit

1. Breadboard the class B push-pull amplifier with the 2N3904/2N3906 transistors as shown in Figure 3.11.

- Run the supply voltage through a 100 Ω resistor as shown in Figure 3.10; you will adjust the supply voltage to maintain 9V on the circuit side of this resistor, and can then easily determine supplied power for the source.
- Use a 10 Ω resistor as the load rather than the speaker.
- Check the bias voltage with no input signal applied and determine the circuit's quiescent dissipated power P_Q.

P_Q = _____________

2. Set the input level to 2 V amplitude. Comment on the output signal waveform.

3. Now breadboard the class AB push-pull amplifier by adding the diodes as shown in Figure 3.13. Check the bias voltages with no input signal applied and determine the circuit's quiescent dissipated power P_Q.

P_Q = _______________

How does this compare with the value found for the class B push-pull amplifier (step 1)?

4. Set the input level to 2 V amplitude. Comment on the output signal waveform and how it compares to the signal of step 2.

5. Now replace the 10 Ω load resistor with the speaker. Play around with the input signal frequency and amplitude to see if you think this amplifier might be sufficient for your radio.

6. Replace the 2[nd] stage CC amp of Figure 3.3 with your class AB push-pull amp. Insert it between the generator and the speaker as was indicated in Figure 3.9. Reduce your input power level.

7. Determine the gain for this new two-stage amplifier and fill out Table 3.2. **If you see significant clipping, reduce your input power level.**

Table 3.2: voltage amplitudes and gain for the CE/push-pull amplifier terminated in a 10 Ω load

Output amplitude	
Input amplitude	
Gain(V/V)	

8. Conduct a sound check using the generator settings of step 2 (The CE stage input is a 1 kHz sine wave with amplitude 20 mV). Comment on how the output sounds.

Part 2: Chip Level Design

3.5 LM386 Amplifier

The LM386 is an integrated circuit amplifier designed for use in low voltage consumer applications such as audio amplifiers. It features very low quiescent power dissipation, and the voltage gain is adjustable from 20 to 200.

1. The pin-out for the LM386 is shown in Figure 3.15. More information on the LM386 can be found on line.

2. Construct an audio amplifier with a gain of 20 using the LM386 (see Figure 3.16). You will not have all of the exact components indicated in this figure, but get as close as your parts will allow. Also, the input audio signal, v_{in}, would ideally come in on the indicated 10 kΩ potentiometer for volume control. In your audio amplifier, feed the audio signal directly to pin 3.
3. Insert your LM386 amplifier between the generator and the speaker (as indicated in Figure 3.8 where the CE amp is replaced with the LM 386 amp).

- Conduct a sound check using the generator settings of step 2 (20 mVpp at 1 kHz). Comment on how the output sounds. Increase it to 100 mVpp and comment on sound.
- You might wish to change the connecting parts between pins 1 and 8 to vary the gain (see Figure 3.17).

4. Measure the voltage gain and the quiescent power dissipation of your LM386 amplifier.

P_Q=__________

A_V=__________

Note: some students may elect to build their AM radio on a solder board. Never solder to the pin of a DIP (dual in-line package) device, since the heat could destroy the part. Instead, acquire an appropriate DIP Socket. Solder the legs of the socket to the board, and then insert the DIP into the socket.

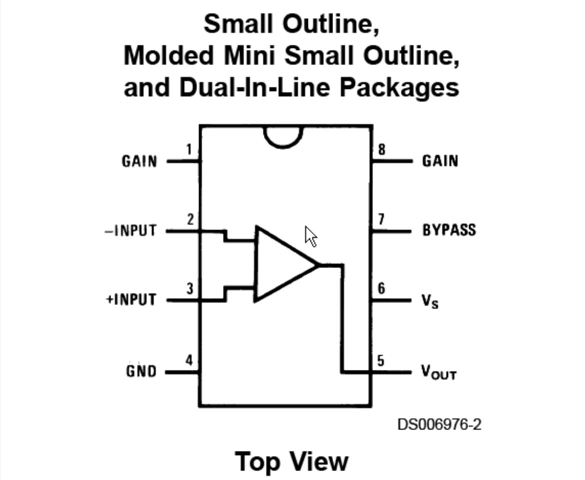

Figure 3.15: pin-out view of the LM386 (from the datasheet)

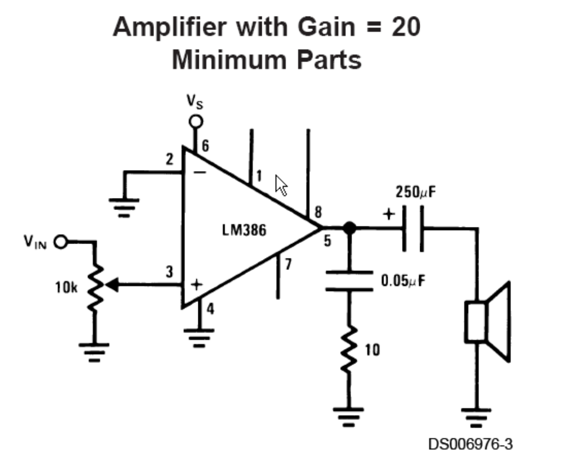

Figure 3.16: audio amplifier schematic with a gain of 20 (from the datasheet)

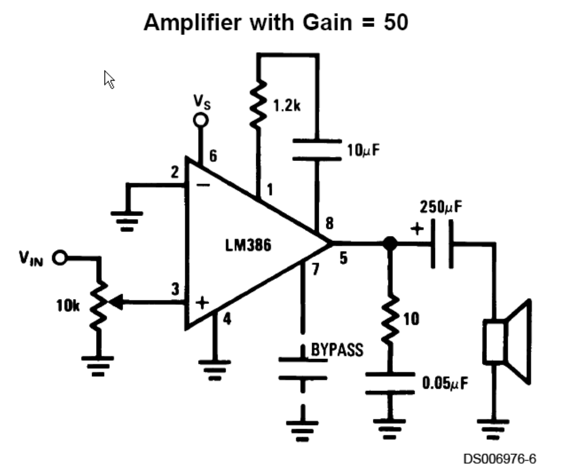

Figure 3.17: audio amplifier schematic with a gain of 50. A short across the 1.2kΩ resistor would result in a gain of 200. (from the datasheet)

3.6 Op Amp Audio Amplifier

Operational amplifiers, or op-amps, have become so commonly used that they are often thought of as just another device, like a resistor, inductor, or diode. The op-amp is an integrated circuit that amplifies the difference in voltage at a pair of input terminals. The op-amp's extremely high gain, high input resistance, and low output resistance allow it to most often be treated as an ideal device with some very useful properties that allow simple design of general purpose amplifiers, buffer amplifiers, summing and difference amplifiers, integrators, differentiators, and filters.

There are hundreds of varieties of op-amp to choose from, including those designed for low-noise, high power, or high frequency operation.

What follows is a very simplified treatment of op-amps sufficient for the design and realization of a first stage audio amplifier.

Figure 3.18 shows a simplified version of an op-amp. The difference in the two input voltages, v^+ and v^-, is amplified by gain A resulting in an output voltage v_o given by

$$v_o = A\left(v^+ - v^-\right) \quad (1)$$

For an ideal op-amp, the gain A is infinite and the resistance looking into the + and – terminals is also infinite. These considerations lead to the following **ideal op-amp conditions**:

$$\boxed{\begin{array}{l} v^+ = v^- \\ i^+ = i^- = 0 \end{array}} \quad (2)$$

Feedback governs op-amp circuit behavior. Consider the "inverting amplifier" configuration of Figure 3.19. Since $i^+ = i^- = 0$, we have $i_1 = i_2$, or

$$\frac{v_{in} - v^-}{R_1} = \frac{v^- - v_o}{R_2} \quad (3)$$

Now, since we also know $v^+ = v^-$, and in this circuit $v^+ = 0$ because we have shorted the + terminal, then we have

$$\frac{v_{in}}{R_1} = \frac{-v_o}{R_2} \quad (4)$$

Upon rearranging,

$$v_o = -\frac{R_2}{R_1} v_{in} \quad (5)$$

So, the amplifier gain depends on the ratio of R_2 and R_1. This is an inverting amplifier because of the negative in equation.

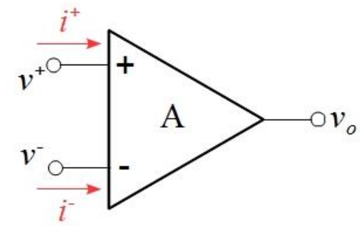

Figure 3.18: ideal Op Amp

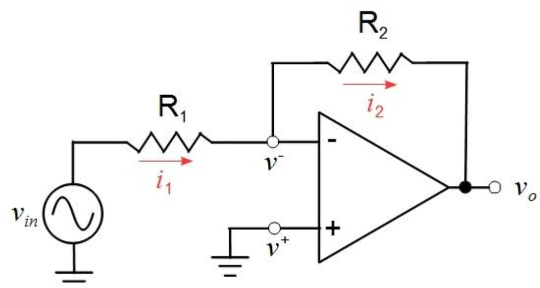

Figure 3.19: simple inverting amp

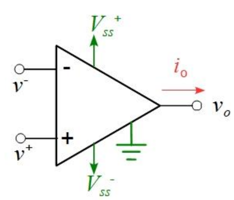

Figure 3.20: simple inverting amp

There are a number of non-idealities to deal with in an actual op-amp circuit. We will consider only a few.

First consider that the op-amp must be powered and grounded, as shown in Figure 3.20. It is most common to use a pair of voltage supplies, V_{ss}^+ and V_{ss}^-, though single supply design is also done. The supply voltage *rails* confine the output voltage:

$$V_{SS}^- < v_o < V_{SS}^+$$

Next, the output current i_o is limited to no more than 25 mA for most non-power op-amps. We saw earlier that much more current is needed to drive a speaker to provide appreciable volume, so the op-amp audio amp is usually the first stage of a 2 stage design.

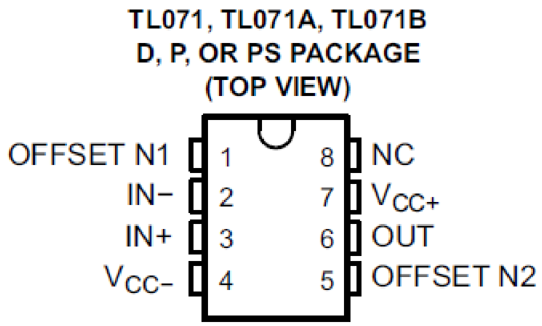

Figure 3.21: pin-out of the TL071 op-amp (from the datasheet)

In the LTspice and amplifier construction that follows, we will be using a very useful general purpose op-amp: the TL071. The pin-out for this op-amp is shown in Figure 3.21.

<u>3.6a LTspice simulation</u>

1. The TL071 is best modeled in LTspice by the UniversalOpamp2. Find and place this component on your schematic.

2. Change some of the UniversalOpamp2's parameters to better model the TL071.

1. Right click on the UniversalOpamp2 icon. The 'Component Attribute Editor' is displayed as in Figure 3.22. For our purposes we only need to change a few of the numbers
2. Based on the data sheets for the TL071, we change Avol (this is the low frequency open circuit gain) to 0.2meg, and the GBW (this is the gain-bandwidth product) and the slew rate to 13meg.
3. On SpiceLine we change the current limit ilimit to 20m. These changes are shown in Figure 3.23.

4. Now breadboard the simple inverting op-amp circuit schematic shown in Figure 3.24.

5. Use eqn. (5) to find the theoretical voltage gain for this circuit.

$$A_v = \frac{v_o}{v_i} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

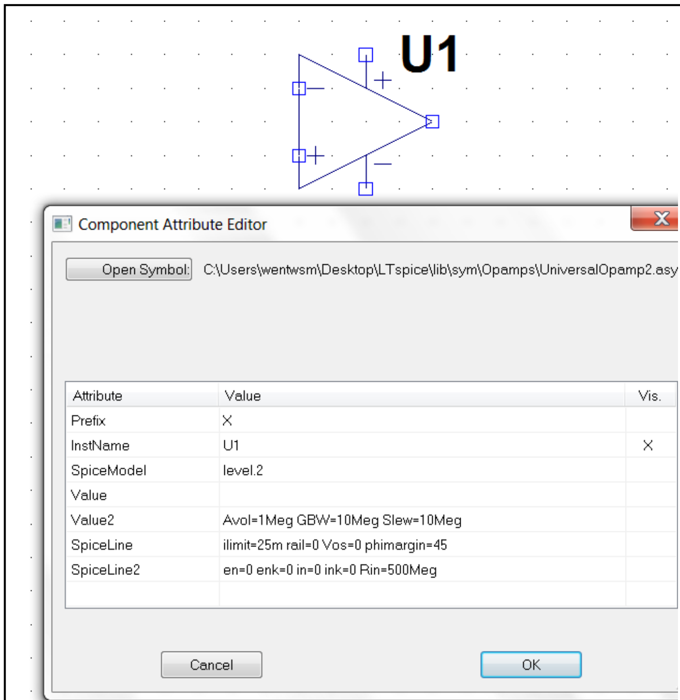

Figure 3.22: UniversalOpamp2 and its component attribute window.

Attribute	Value
Prefix	X
InstName	U1
SpiceModel	level.2
Value	
Value2	Avol=0.2Meg GBW=13Meg Slew=13Meg
SpiceLine	ilimit=20m rail=0 Vos=0 phimargin=45
SpiceLine2	en=0 enk=0 in=0 ink=0 Rin=500Meg

Figure 3.23: pin-out of the TL071 op-amp (from the datasheet)

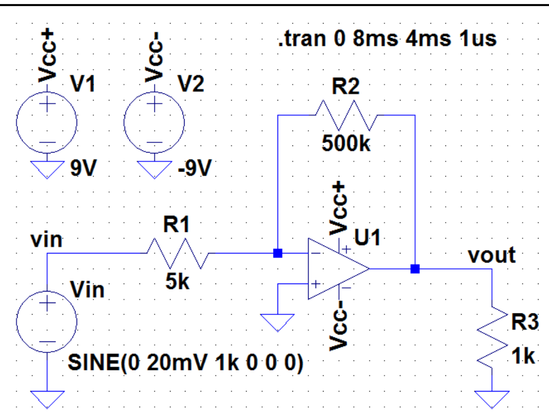

Figure 3.24: Simple inverting op-amp circuit driving a 10 ohm load.

6. Run a transient analysis as shown to duplicate Figure 3.25. What is the measured gain?

   A_v = ________________

   How does this compare with the theoretical gain calculated in step 4?

7. Change R3 in Figure 3.24 to 10 ohms and re-run the transient analysis. Describe what happens and why.

8. Change R3 back to 1 kΩ. Now replace Vcc- with ground and re-run the transient analysis. Describe what happens and why.

9. Add the class AB push-pull circuit to your op-amp circuit as shown in Figure 3.26. Run the transient analysis.

   A_v = ___________

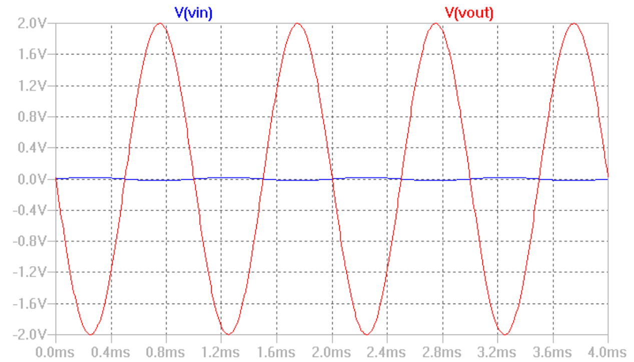

Figure 3.25: transient analysis of the op-amp circuit

Table 3.3: Gain and quiescent P_Q various amplifiers.

	Gain (V/V)	P_Q(watts)
CE/CC amp		
CE/class AB amp		
Op-amp/class AB amp		
LM386 amp		

<u>3.6b Build and test circuits</u>

1. Build the op-amp circuit of Figure 3.24 with R3 = 1 kΩ. Test it with a 1 kHz amplitude input signal of amplitude 20 mV (or the minimum amplitude you can generate if you cannot achieve 20 mV).

2. Now add the class AB stage to your op-amp circuit as shown in Figure 3.26. Test it with a 1 kHz amplitude input signal of amplitude 20 mV. Determine the gain of this two-stage amplifier:

   A_v = ___________

3. Replace the 10 ohm load resistance with your speaker. Play around with the input signal frequency and amplitude to see if you think this amplifier might be sufficient for your radio.

4. Fill out Table 3.3 to compare amplifiers

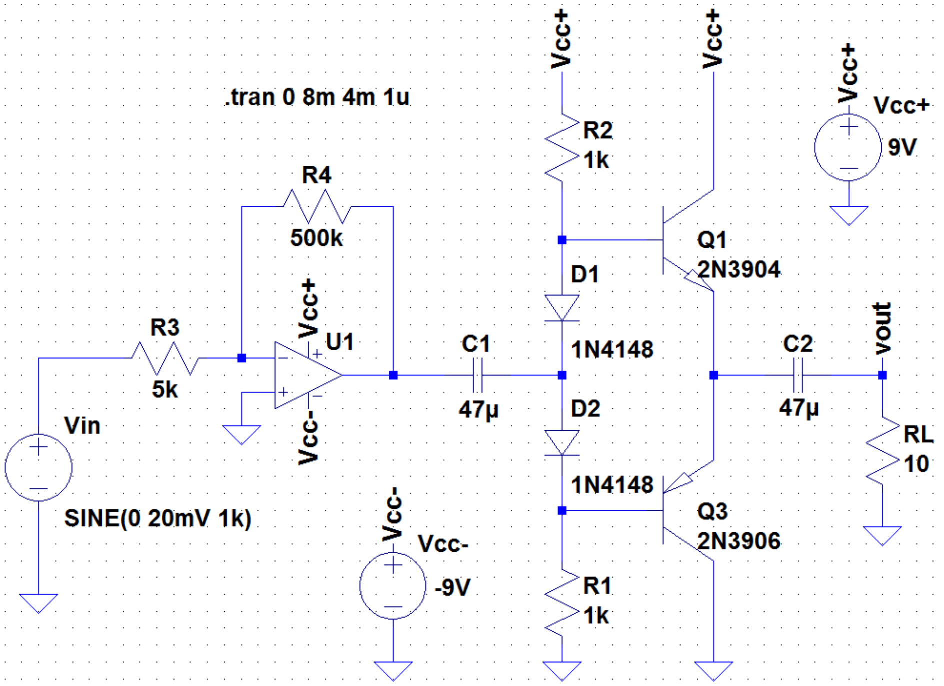

Figure 3.26: op-amp audio amplifier with a class AB second stage