Class B and Class AB Audio Amplifier Operating Open-Loop and Closed-Loop

Objective

The main objective of this lab is to familiarize students with output amplifiers and the related issues of distortion and efficiency. Students will have a chance to experiment with Class B and Class AB amplifiers and to experience the ability of negative feedback to reduce amplifier distortion.

Reading

Read reduction of crossover distortion through feedback Hambley pgg. 559-566 and class B amplifiers Hambley pgg. 689-692. Or read "Class B output stage" section in Sedra Smith including "Reducing crossover distortion" subsection.

Background

In many electronics applications amplifiers have large output voltage swings and are required to deliver significant power at their output. A typical example is an audio amplifier driving a loudspeaker. The input to the amplifier is typically a low-amplitude low-power signal such as the LINE output of a CD player or an IPOD. This signal is typically less than $1V_{pp}$ and has a Thevenin impedance in the kΩ range. A standard loudspeaker may have an 8Ω impedance and require a driving voltage having a magnitude of several volts. Therefore, the power delivered to the loudspeaker is several watts.

In conclusion both voltage amplification and power amplification are needed. Typically a multiple-stage amplifier is used. Figure 1 shows a voltage gain stage followed by a power gain stage, which acts as a buffer and provides power to the loudspeaker. Whereas the first stage delivers little output power and can be easily implemented using an OPAMP, the second stage delivers significant output power.

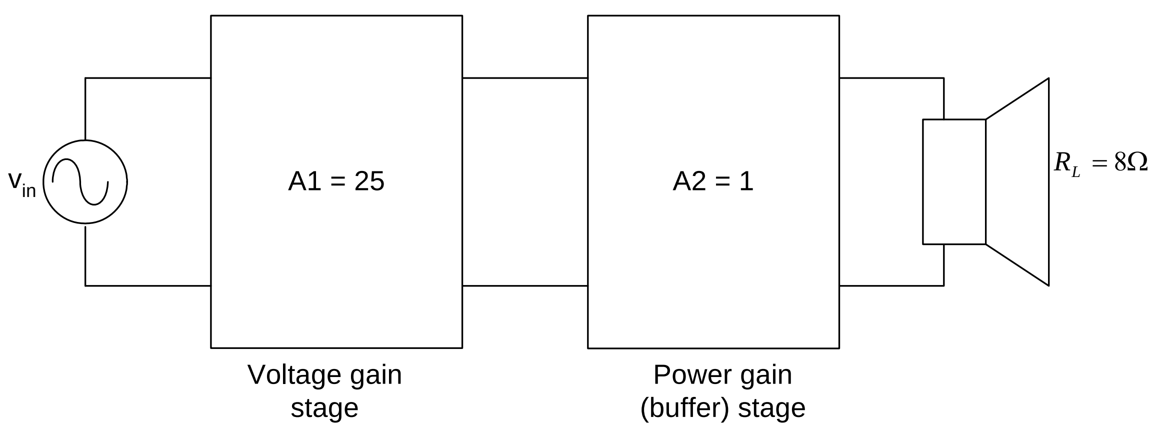


Figure 1: Two-stage audio amplifier

Output Amplifier Classes

A typical output (buffer) amplifier configuration is shown in Figure 2. This is a push-pull emitter-follower configuration utilizing an npn and a pnp transistor. This type of amplifiers can be operated in different modes depending on transistor biasing. In particular:

- Class A operation. Both transistors are in the active regions at all times. Therefore for a sine-wave input the conduction angle is 2π. This requires a bias current which is larger than the peak output current. This large bias current causes significant losses. It can be shown that the maximum possible efficiency is η=25%
- Class B operation. Only one transistor is in the active region at any given time and provides current to the load. Therefore for a sine-wave input the conduction angle is π. No bias current is required (V_{bias} = 0) and the maximum possible efficiency is η=78.5%. In reality given the non-zero base-emitter voltage the conduction angle will be somewhat less than π and the output voltage will exhibit crossover distortion.
- Class AB operation. This mode of operation is in-between the two modes described above. The goal is to reduce distortion without incurring the large losses of Class A operation. The transistors are biased with a small current. As a result, the conduction angle of each transistor is slightly larger than π and the crossover distortion is greatly reduced.

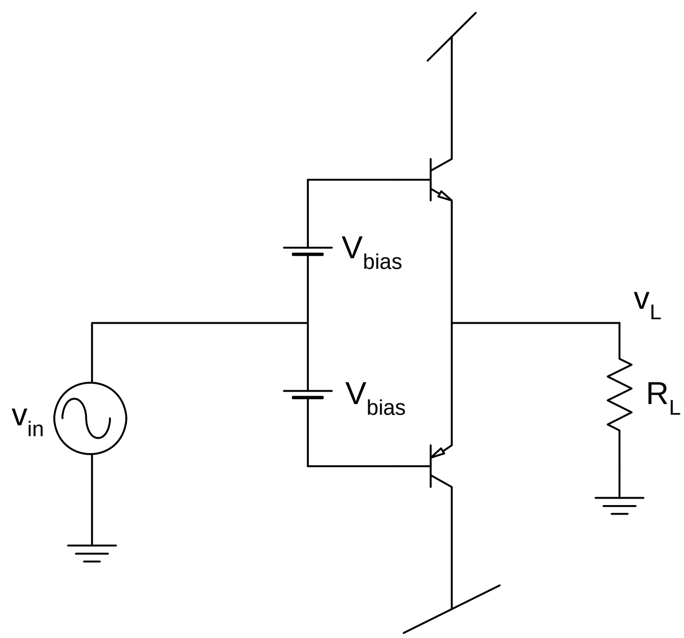


Figure 2: Push-pull amplifier

Two-Stage Amplifier Implementation

A circuit implementation of the two-stage amplifier of Figure 1 is shown in Figure 3. The input is amplified by an OPAMP in a non-inverting configuration. The gain of this first stage can be adjusted by using trimmer R2. The second stage is a Class B push-pull amplifier using transistors in a Darlington configuration. The Darlington configuration utilizes two transistors feeding each other. This has the effect of increasing the overall current gain at the expense of a larger (~1.2V) base-emitter voltage drop. Notice that both the input and the output are AC coupled through capacitors. When using a loudspeaker as a load, it is desirable to apply a purely AC signal, because a DC bias may cause the loudspeaker to fail. In the output a rather large capacitor is needed to obtain a cutoff frequency below 20Hz, which is the lower end of the audible frequency range. Two back-to-back electrolytic capacitors are used to avoid reverse-biasing of the polarized capacitors. Emitter resistors RE_N and RE_P are used to limit the output current and to stabilize the bias point against thermal drifts.

This configuration exhibits a significant crossover distortion. There are two approaches to reducing distortion:

1. Employ negative feedback to reduce distortion
2. Bias the amplifier to operate either in Class A or in Class AB.

Both these approaches are explored in this laboratory experience.

A closed-loop Class B configuration is shown in Figure 4. Output voltage V_b is fed back to the inverting input of the OPAMP. The high-gain negative feedback significantly reduces the crossover distortion of voltage V_b.

Figure 5 shows the case of the output amplifier biased in Class AB. The voltage drop across diodes D1 and D2 and across resistors RD1 and RD2 provides the required bias voltage. This configuration operates open-loop, but the crossover distortion is reduced by the Class AB operation.

In commercial audio amplifiers both biasing and negative feedback are used to achieve very low total harmonic distortion (THD). Output THD below 1% is standard for these amplifiers.

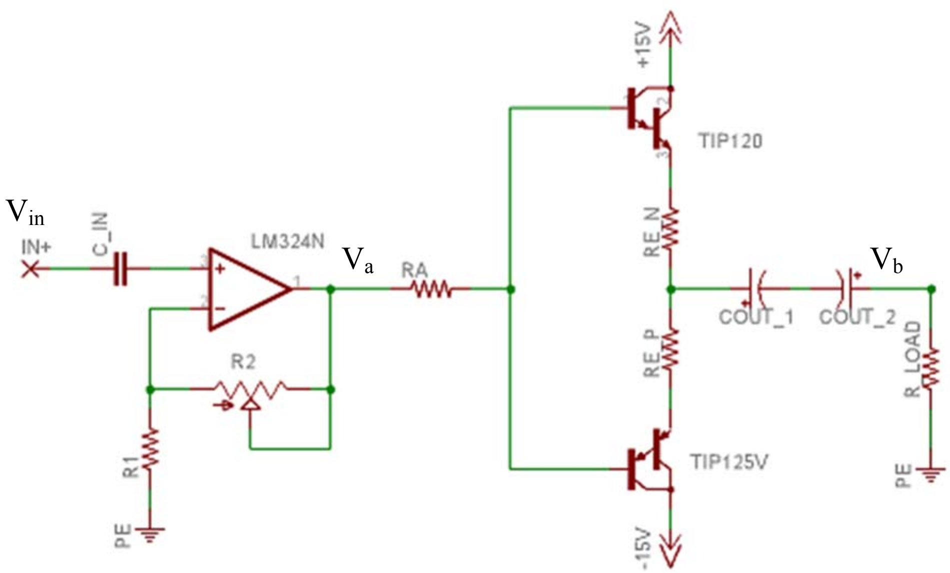


Figure 3: Class B audio amplifier operating open-loop

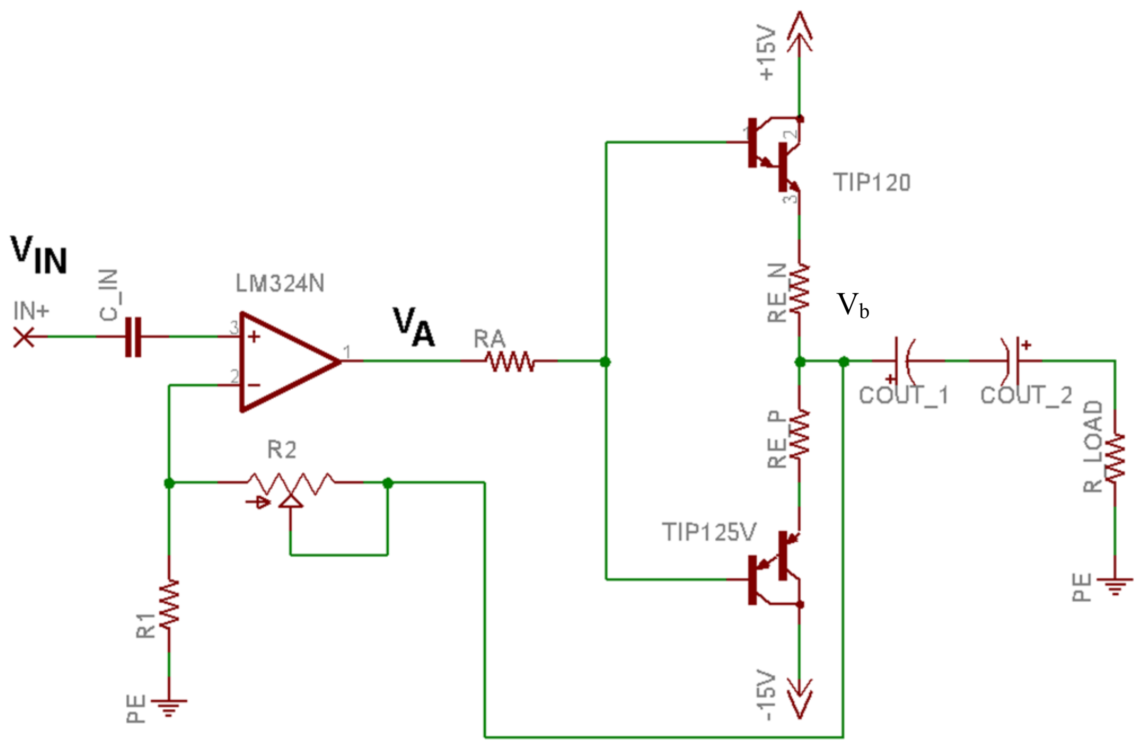


Figure 4 Class B audio amplifier operating closed-loop

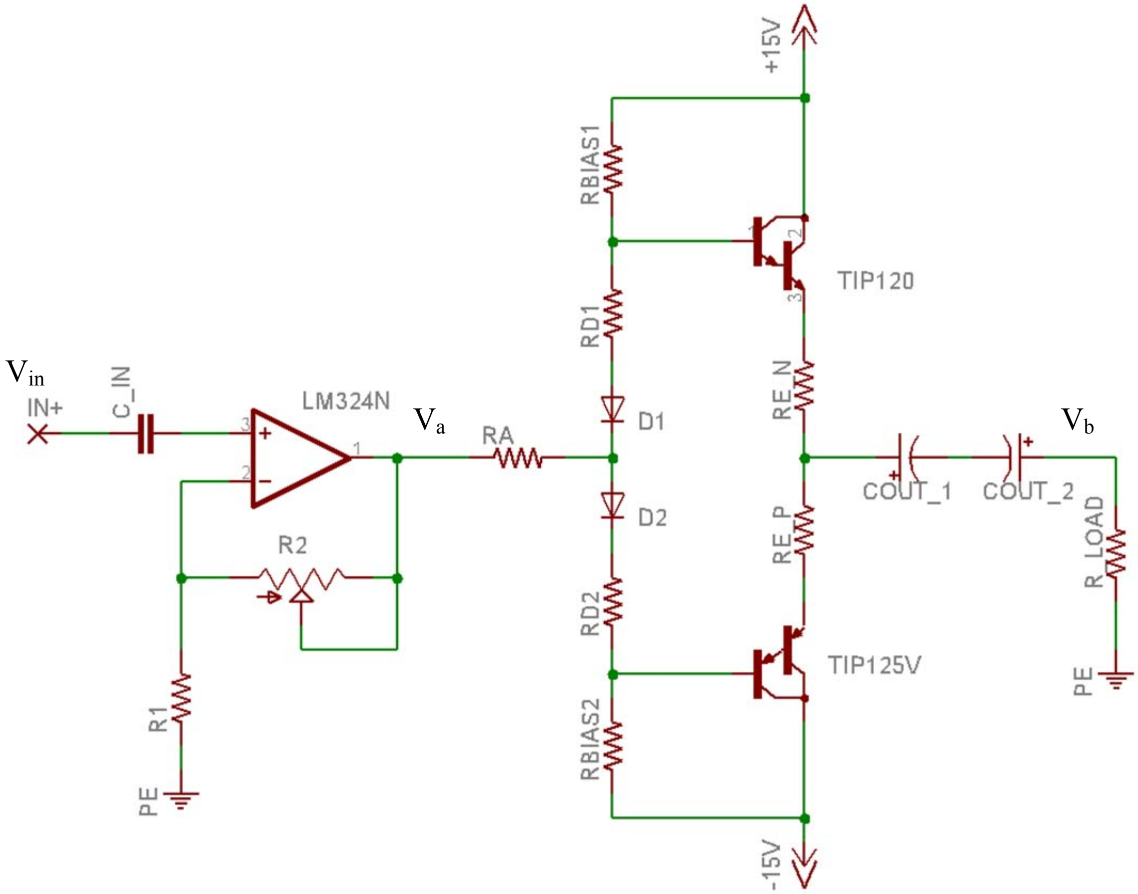


Figure 5 Class AB audio amplifier operating open-loop

Pre Lab

1. Perform text-based SPICE simulation of the three circuits shown in Fig 3-5. Use the following devices from the library eval.lib: a Q2N6059 transistor for the NPN Darlington, a Q2N6052 transistor for the PNP Darlington, and a D1N914 for the biasing diodes. Use a 200mV$_{pp}$ sinusoidal voltage source for V_{in}. Design the resistors R_1 and R_2 to yield 5V$_{pp}$ at the output of the OPAMP. For the class AB amplifier of Fig. 5 design the resistors R_{BIAS1}, R_{BIAS2}, R_{D1} and R_{D2} used in the bias network to yield I_{bias} = 10mA and V_{bias} = 1V assuming the voltage drop across the diodes is equal to 0.6V at 10mA.
2. Perform a .TRAN simulation of each circuit. Produce a plot of 2 cycles of input voltage V_{in}, OPAMP output voltage V_a, and voltage across load resistor R_{LOAD} V_b for each circuit. Produce another plot of $I_{e\text{-}npn}$ and $I_{e\text{-}pnp}$ for each circuit. Comment on the class of operation for each case.
3. Perform a .FOUR analysis of each circuit to find the Total Harmonic Distortion.

Lab Project

Class B output amplifier

1. Construct the circuit shown in Figure 3, which consists of a non-inverting voltage amplifier cascaded with a Class B push-pull emitter follower. A power resistor will be used as a load.
2. Apply a 200mV_{pp}, 1kHz sine wave to V_{in} using the function generator. Adjust the potentiometer R_2 until V_a = 5V_{pp}. Capture a single screenshot showing V_{in} and V_a , with amplitudes and frequency measured using the scope's built-in measurement functions. Is V_a visibly distorted?
3. Capture a single screenshot showing V_a and V_b. Is V_b visibly distorted? What voltage does V_a need to exceed before V_b becomes nonzero. Show a cursor measurement of this phenomenon in your report.
4. Use the oscilloscope's MATH function to perform a FFT on V_b. Adjust the horizontal scale to show only the first 10 harmonics. Capture a screenshot showing a cursor measurement of the magnitude of the fundamental component. Additionally, measure and tabularize the magnitude of the remaining 9 components (you may have to adjust the vertical scale to see some components). Calculate the THD.

Class B output amplifier with Feedback

5. Modify the circuit to include the voltage follower within the opamp feedback loop as shown in Figure 4.
6. Apply a 200mV_{pp}, 1kHz sine wave to V_{in} and adjust R_2 until V_{load} = 5V_{pp}. Capture a screenshot of V_a and V_b. Has the amount of distortion been visibly reduced? Comment on the possible reason for the improvement.
7. Repeat step 4 for this circuit.

Class AB output amplifier

8. Modify the circuit as shown in Figure 5. Remove the voltage follower from the opamp feedback loop. Add a diode based biasing circuit to the emitter follower. Use the biasing resistors you calculated in the pre-lab assignment and used in your simulations.
9. Apply a 200mV_{pp}, 1kHz sine wave to V_{in} and adjust R_2 until V_a = 5V_{pp}. Capture a screenshot of V_a and V_b. Has the crossover distortion observed in step 2 been reduced by the addition of a bias circuit?
10. Repeat step 4 for this circuit.
11. Connect a loudspeaker to the output and play some music. Acquire a screenshot of voltages V_{in} and V_b. Is the output voltage a faithful amplified replica of the input voltage?

Lab Report

You are to submit a lab report with the following information:

- Design of resistances used in the non-inverting amplifier stage.
- Design of biasing resistors for the Class AB voltage follower stage.

- Simulation results for each circuit, including voltage waveforms and THD results from the .FOUR analysis.
- All screenshots described in the Lab Project section above.
- Calculation of THD for each circuit from experimental data. Compare this to simulated THD.
- Comment on the effectiveness of each circuit in reproducing a pure sine wave at the output. Explain how the second and third circuits each improve the output waveform.

APPENDIX: Total Harmonic Distortion (THD)

Total harmonic distortion is a measure of the signal energy in the second and higher harmonics as compared to the energy in the fundamental.

$$THD = \sqrt{\frac{V_{orms}^2 - V_{1rms}^2}{V_{1rms}^2}} = \sqrt{\frac{\sum_{n\neq 1} V_{nrms}^2}{V_{1rms}^2}}$$

and

$$V_{orms}^2 = V_{1rms}^2 + V_{2rms}^2 + V_{3rms}^2 + \ldots\ldots = V_{1rms}^2 + \sum_{n\neq 1} V_{nrms}^2$$

where V_{1rms} is the rms amplitude of the fundamental component of the output voltage, V_o, and V_{nrms} is the rms amplitude of the n^{th} harmonic of the output voltage.

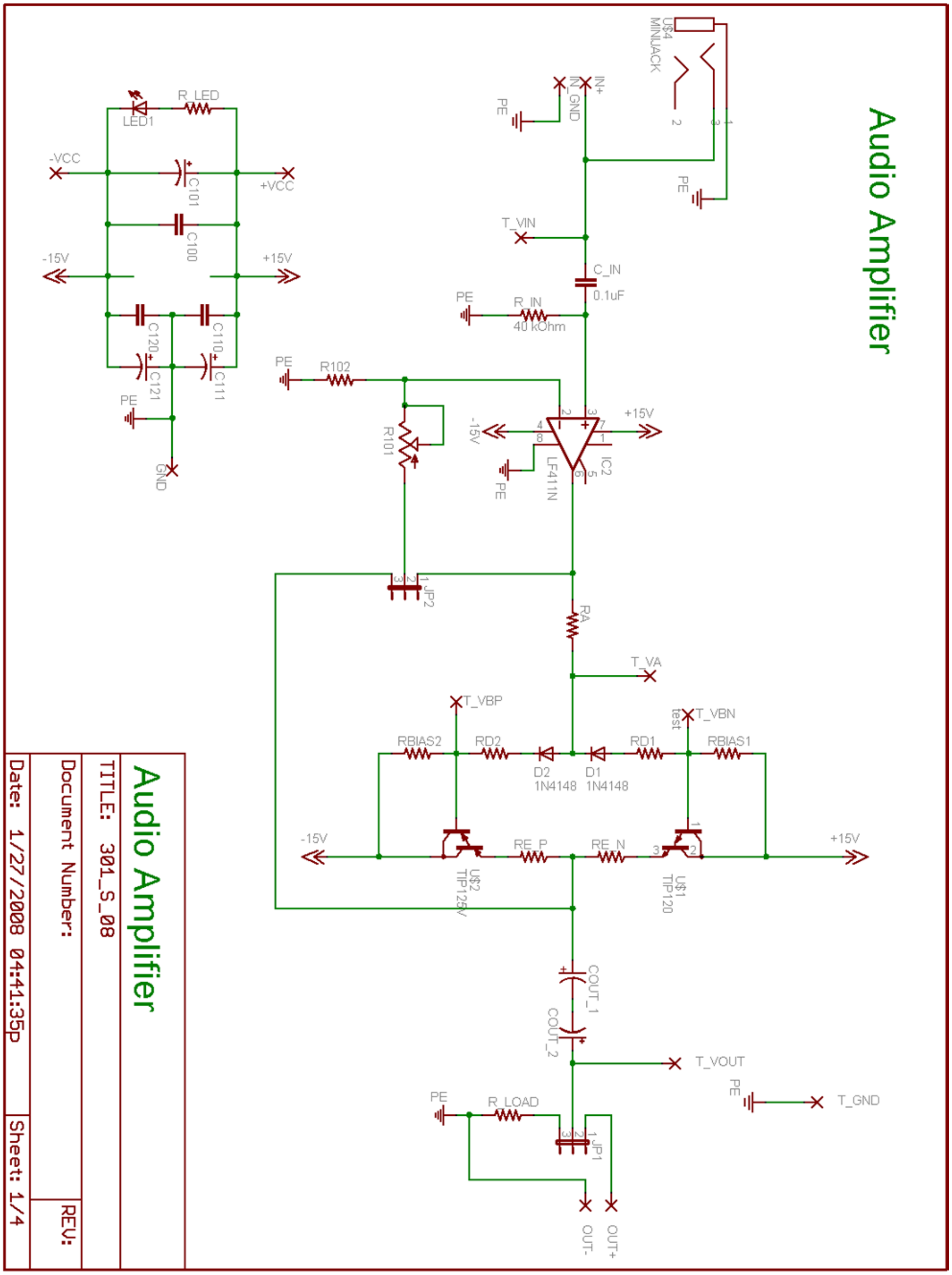
Remember your trigonometric Fourier series is:

$$v_o(t) = a_o + \sum_{n=1}^{\infty} a_n \cos(n\omega_o t) + b_n \sin(n\omega_o t)$$

$$V_{orms} \equiv \sqrt{\frac{1}{T}\int_T v_o^2(t)dt}$$

$$\omega_o = \frac{2\pi}{T}$$

$$V_{1rms}^2 = \frac{a_1^2 + b_1^2}{2}$$


Audio Amplifier
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Bill of Materials

C100	0.1 uF plastic	C-EU050-030X075	C050-030X075	rcl
C101	10 uF electrolytic	CPOL-USE2.5-6	E2,5-6	rcl
C110	0.1 uF plastic	C-EU050-030X075	C050-030X075	rcl
C111	10 uF electrolytic	CPOL-USE2.5-6	E2,5-6	rcl
C120	0.1 uF plastic	C-EU050-030X075	C050-030X075	rcl
C121	10 uF electrolytic	CPOL-USE2.5-6	E2,5-6	rcl
COUT_1	470 uF electrolytic	CPOL-USE5-10.5	E5-10,5	rcl
COUT_2	470 uF electrolytic	CPOL-USE5-10.5	E5-10,5	rcl
C_IN	0.1uF	C-EU050-030X075	C050-030X075	rcl
D1	1N4148	1N4148	DO35-10	diode
D2	1N4148	1N4148	DO35-10	diode
IC2	LM741P	LF411N	DIL08	linear
JP1		JP2E	JP2	jumper
LED1		LED5MM	LED5MM	led
R101	OPAMP pot resistor TBD	TRIM_US-B25P	B25P	pot
R102	OPAMP resistor TBD	R-US_0204/7	0204/7	rcl
RA	510 Ohm	R-US_0204/7	0204/7	rcl
RBIAS1	TBD	R-US_0204/7	0204/7	rcl
RBIAS2	TBD	R-US_0204/7	0204/7	rcl
RD1	TBD	R-US_0204/7	0204/7	rcl
RD2	TBD	R-US_0204/7	0204/7	rcl
RE_N	2R7	R-US_0204/7	0204/7	rcl
RE_P	2R7	R-US_0204/7	0204/7	rcl
R_IN	40 kOhm	R-US_0204/7	0204/7	rcl
R_LED	1k2	R-US_0204/7	0204/7	rcl
R_LOAD	10 R 1W	R-US_0411/12	0411/12	rcl