13

Audio Circuits

There are two audio circuits in the NorCal 40A, the Automatic Gain Control, or AGC, and the Audio Amplifier. The AGC is an attenuator with JFETs that act as variable resistors. The Audio Amplifier is the LM386N-1, made by National Semiconductor. This integrated circuit appears in many different audio systems, and it costs about a dollar. The "–1" indicates a supply voltage range from 4 to 12 V. A "–4" version is available that allows a supply voltage up to 18 V. For the LM386N-1, the maximum output power is about one watt. In standby, it draws about 4 mA, which is a reasonable level for running off batteries.

13.1 Audio Amplifier

Figure 13.1 shows the schematic for the LM386N-1. It is more complicated than the previous circuits that we have looked at, and because it is an integrated circuit, most points are not accessible for measurements. There are three stages of amplification. The input is a differential amplifier, but it is made with pnp transistors rather than npn transistors. This turns things upside down. Each input has a pair of stacked pnp transistors. The stack gives the effect of a single transistor with a current gain of β^2. The differential amplifier is followed by a common-emitter stage. The output is a Class-B emitter follower that is similar to the one we discussed in Section 10.6. The only difference is that the pnp transistor has been replaced by a combination of a pnp transistor and an npn transistor that acts like a single pnp transistor, but with the large current gain that is characteristic of an npn transistor. The feedback resistance R_f and the emitter resistance R_e determine the gain of the amplifier.

The collector loads for the differential amplifier comprise a pair of transistors wired together as shown in Figure 13.2a. This circuit is called a *current mirror.* Notice that the bases are connected together and the emitters are connected together. Thus the base–emitter voltage for each transistor is the same. In Section 9.4 we found that the collector current I_c and the base–emitter voltage V_b in an active transistor are related by the equation

$$I_c = I_{cs} \exp(V_b/V_t). \tag{13.1}$$

If V_b is the same for both transistors, then the collector current is also the same, provided that the saturation current I_{cs} is identical for each. By putting the two

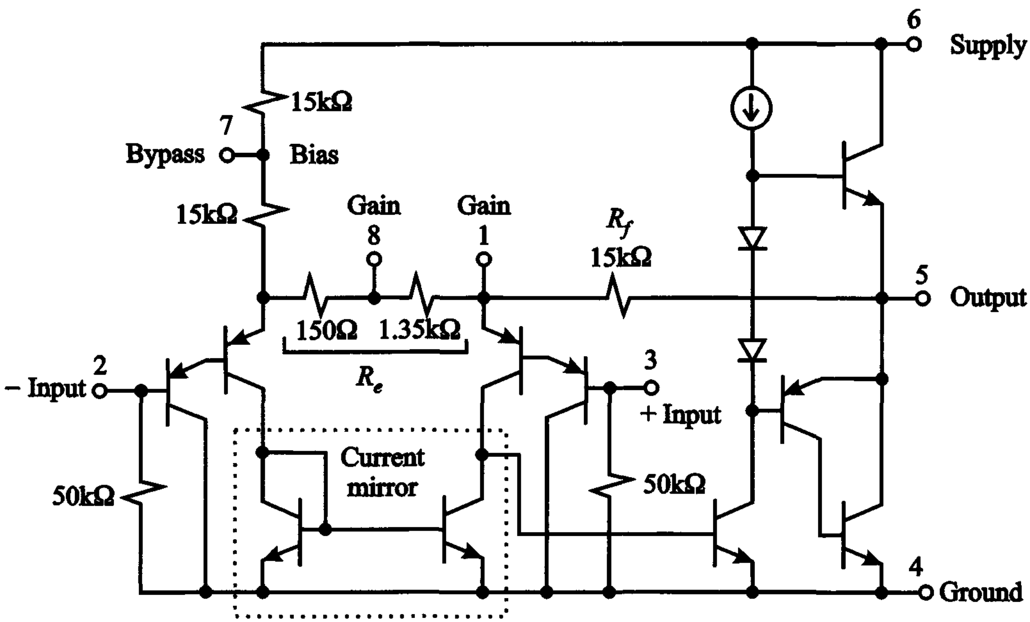


Figure 13.1. Schematic for the LM386N-1 Audio Power Amplifier, from the National Semiconductor data sheet in Appendix D.

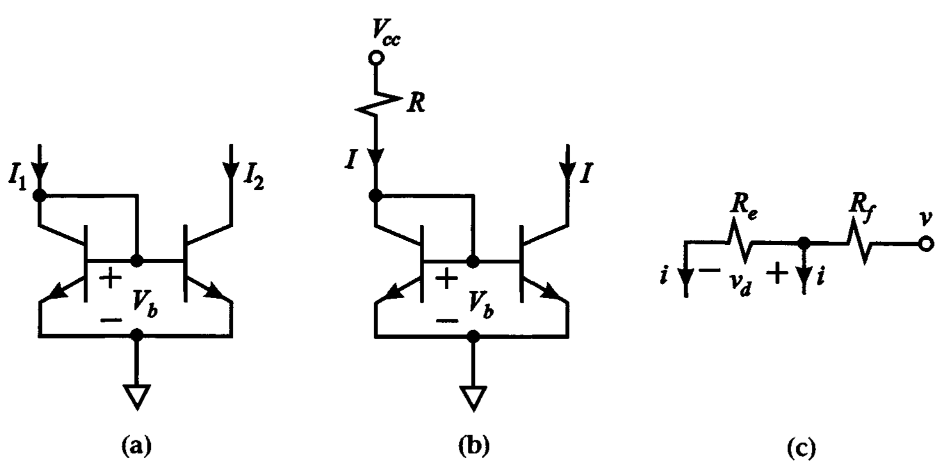


Figure 13.2. (a) Current mirror. (b) Making a current source with a current mirror. (c) Gain calculation for the Audio Amplifier. The two currents labeled i are forced to be equal by the current mirror.

transistors close together on the same piece of silicon, I_{cs} can be matched closely. Therefore

$$I_1 \approx I_2, \tag{13.2}$$

provided β is large, so that the base currents are much smaller than the collector currents.

One application of a current mirror is to make current sources (Figure 13.2b). We can set the current with a resistor to the supply. The current in the resistor is given by

$$I = (V_{cc} - V_b)/R. \tag{13.3}$$

The current in the other transistor is now forced to be I.

The current mirror forces the collector currents on each side of the differential amplifier to be the same. This property of the current mirror allows us to calculate the gain of the Audio Amplifier. A simplified circuit is given in Figure 13.2c. Here v is the AC output voltage. The currents labeled i at each end of the emitter resistance R_e are forced to be equal by the current mirror. The voltage across R_e is the differential input voltage v_d. We can understand this if we consider the base–emitter voltage drops in the pnp transistors on each side of the differential amplifier. Since the drops are the same on both sides, the difference in voltage between the two inputs is the same as the voltage across R_e.

The current that flows through the feedback resistor R_f is approximately $2i$. We can neglect the current that flows in the two 15-kΩ bias resistors, because these have a much higher impedance than the pnp emitters, which are basically forward-biased diodes. Consequently, the feedback current will flow in the emitters and not in the bias resistors. We write

$$2i \approx v/R_f. \tag{13.4}$$

Here we have assumed that the output voltage v is much larger than the input voltage v_d because of the gain of the amplifier. We can also write an expression for the current in R_e:

$$i = v_d/R_e. \tag{13.5}$$

If we eliminate the current between these two equations, we get the voltage gain

$$G_v = v/v_d = 2R_f/R_e. \tag{13.6}$$

One thing that is interesting about this expression is that the gain only depends on the feedback and emitter resistances, and not on the β of the transistors, which is quite variable. The gain is fixed even if β varies with the drive level, which ordinarily would cause distortion. In this amplifier, $R_e = 1.5$ kΩ and $R_f = 15$ kΩ, and so we expect a voltage gain of 20. We can reduce the effective value of R_e to 150 Ω by connecting a bypass capacitor between pins 1 and 8. This increases the gain to about 200. In addition, we can provide high-frequency roll-off by connecting a capacitor in parallel with R_f.

13.2 Op Amps

For the Audio Amplifier, we found that the gain is determined by the feedback resistance. This is negative feedback, and it reduces the gain. This is in contrast to the positive feedback that we used to make an oscillator. Negative feedback is one of the most important ideas in electrical engineering, and it is due to Harold Black of the Bell Telephone Laboratories. You might wonder why we would want

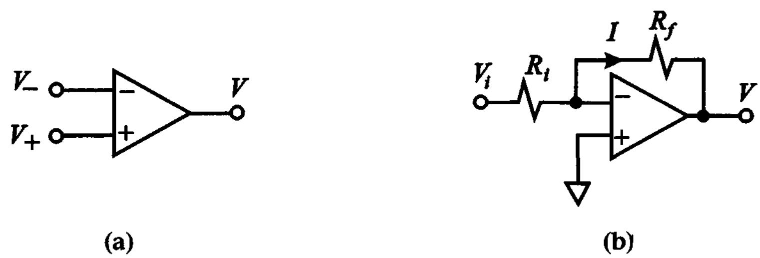


Figure 13.3. (a) Schematic symbol for an op amp, and (b) inverting amplifier circuit.

to reduce gain, but it turns out that it is relatively easy to build amplifiers with a lot of gain. It is more difficult to control the gain, reduce distortion, increase the input impedance, and reduce the output impedance. Negative feedback can help us with all of these.

This approach is taken to an extreme in operational amplifiers, or op amps, which are differential amplifiers with very high gain, like the LM393N comparator in the RIT circuit we built in Problem #27. Op amps typically have a voltage gain of 100,000 and they would not be used as an amplifier without negative feedback because the outputs would saturate. In addition, they have high input impedance and low output impedance. We will consider an example to see how the feedback works. Figure 13.3 shows the schematic symbol for an op amp. There are differential input terminals labeled – and +. In analyzing op amps, it is common to make two assumptions. Horowitz and Hill call these the Golden Rules.

Rule I. The differential gain is extremely high, and we will call it ∞. This means that if the output V is not at the ground or supply (as it would be in a comparator), then the difference between V_- and V_+ is infinitesimal. We write

$$V_- = V_+. \tag{13.7}$$

Rule II. The impedance of each input is extremely high, and we will call it ∞. This means that the inputs draw no current, and we can write

$$I_- = I_+ = 0. \tag{13.8}$$

We show an inverting amplifier in Figure 13.3b. If the + input is grounded, then $V_- = 0$ (Rule I). We call this a *virtual ground*. Moreover, since the – input draws no current, the current in both resistors is the same. We can therefore write two expressions for the current I:

$$I = V_i/R_i \tag{13.9}$$

and

$$I = -V/R_f. \tag{13.10}$$

If we eliminate the current between these two expressions, we get the voltage gain:

$$G_v = V/V_i = -R_f/R_i. \tag{13.11}$$

Notice the similarity to the gain calculation for the Audio Amplifier (Equation 13.6). The output voltage is proportional to the value of a feedback resistor. The input voltage is proportional to the value of the resistor in the input circuit.

13.3 JFETs as Variable Resistors

When we studied bipolar transistors, we considered two different regions of operation. If the collector voltage is more than a few tenths of a volt, the output impedance is large, and the output current is relatively independent of the load. In our circuit models, we used a current source for the output. We called this the active region, and we used it for our Class-A amplifier. However, we found that when the base current is large and the collector voltage is small, the effective output impedance is small. We used this "on" mode for the switches and the Class-C amplifier.

JFETs also have two modes of operation. Figure 13.4 shows a plot of drain current versus drain voltage with gate voltage as a parameter. In the active region, the current is relatively independent of the drain voltage. The current increases with gate voltage from zero at the cut-off voltage V_c to I_{dss} at $V_{gs} = 0$. In FETs, the active region is also called the saturation region, which is quite confusing, because it does not correspond to the saturation region for a BJT.

If $V_{ds} < V_{gs} - V_c$, the drain current is no longer independent of drain voltage. This is called the *linear* region because the current is approximately linear in the voltage. This means that the JFET acts like a conductance that is controlled by the gate voltage. The current is usually written approximately as

$$I_d = V_{ds}\left(\frac{2I_{dss}}{V_c^2}\right)(V_{gs} - V_c - V_{ds}/2). \tag{13.12}$$

This is different from BJTs where the current is quite nonlinear at low collector voltages. The JFET can also be used with negative drain voltages and currents.

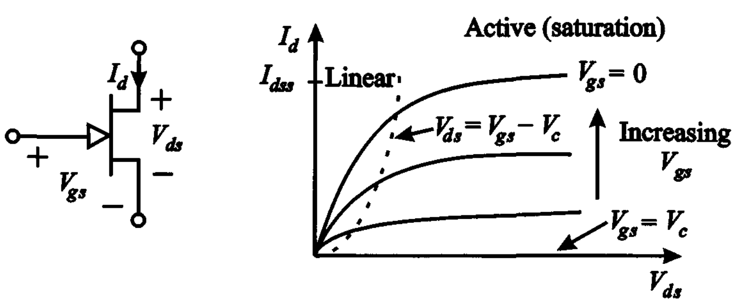
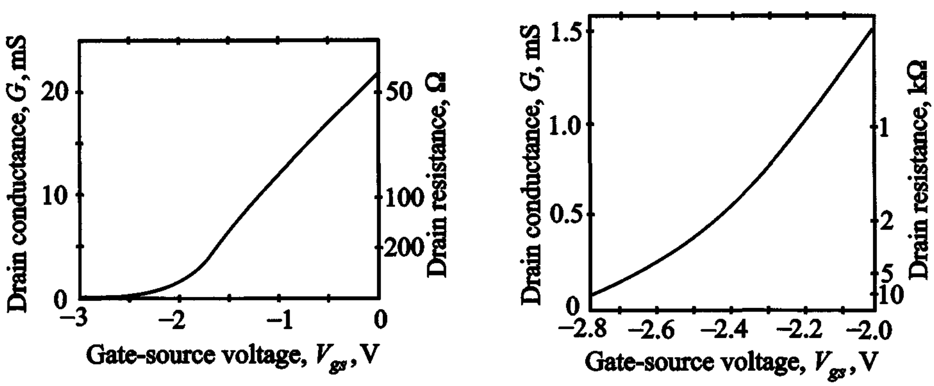


Figure 13.4. Drain current characteristics for a JFET.



(a) (b)

Figure 13.5. Drain conductance in the linear region for the J309 JFET as a function of the gate voltage (a), and the high-resistance region near cutoff (b).

This is like swapping the role of the source and drain. JFETs work well this way, although usually g_m drops somewhat and the Miller capacitance increases because the gate is usually placed closer to the source than the drain. This is quite different from BJTs, which usually work poorly backwards. We use JFETs in the linear region as a variable conductance in the Automatic Gain Control. To see how this works, let us calculate the conductance G as

$$G = \frac{I_d}{V_{ds}} = \left(\frac{2I_{dss}}{V_c^2}\right)(V_{gs} - V_c). \tag{13.13}$$

We have neglected the term $V_{ds}/2$, which is small in the linear region. This equation predicts a linear relation between the gate voltage and the conductance. This is only approximately true in practice. Figure 13.5a shows the measured conductance versus gate voltage for the J309 JFET that is used in the AGC. For gate voltages above -1.5 V, the relationship is relatively linear, covering a resistance range from 200 Ω to 50 Ω. Figure 13.5b shows the high-resistance region of the same plot. This covers the range where the resistance is greater than 500 Ω. The curvature is quite noticeable.

FURTHER READING

Horowitz and Hill cover JFET circuits in Chapter 3 and op amps in Chapter 4 in *The Art of Electronics*, published by Cambridge University Press.

PROBLEM 31 - AUDIO AMPLIFIER

We build the Audio Amplifier in three stages, so that we can see how different components determine the frequency response. The final result will be an amplifier with a band-pass characteristic that eliminates both high-frequency hiss and low-frequency rumble. In the first stage (Figure 13.6), we consider how the output circuit affects the gain. The output

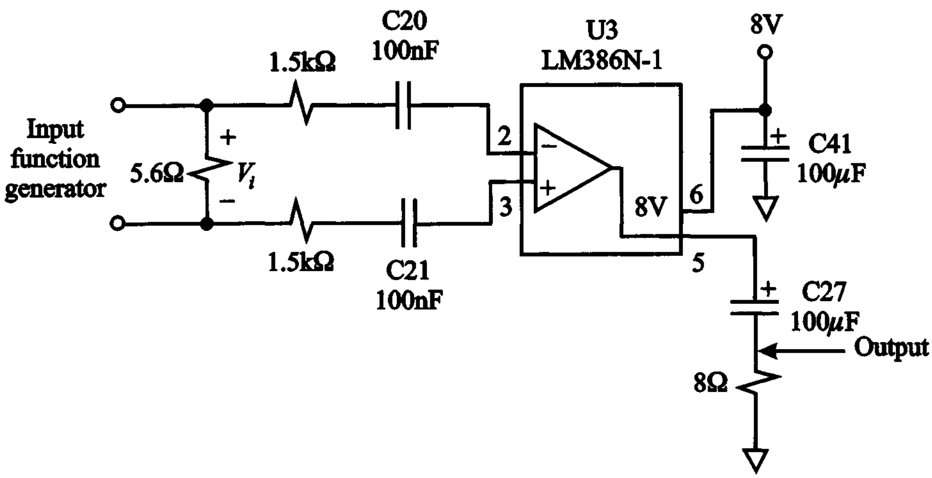


Figure 13.6. Measuring the frequency response of the output network of the Audio Amplifier.

voltage is taken from pin 5. The DC voltage there is half the supply voltage. Because we do not want DC current in the speaker we use a large electrolytic capacitor C27 (100 μF) to couple the output to the speaker. In the same way, we have coupling capacitors C20 and C21 (100 nF) at the input so as not to upset the input bias conditions. We will use an 8-Ω resistor in place of the speaker temporarily. The speaker impedance varies with frequency, and this would confuse the measurements.

Install the amplifier U3, the coupling capacitors C27, C20, and C21, and the supply bypass capacitor C41 (100 μF). For the load, solder an 8-Ω resistor across the outer holes of the R8 outline. Leave enough lead length that you can get probes on C20, C21, and the 8-Ω resistor. Connecting a function generator is complicated because the audio amplifier has a lot of gain, and even low input voltages can saturate the output. We use a potential-divider circuit to reduce the input voltage to prevent the output from saturating. Connect a 5.6-Ω resistor and a pair of 1.5-kΩ resistors as shown in Figure 13.7. The drain holes in the Q2 and Q3 outlines are convenient for this. Connect the function generator leads at the input, and connect the multimeter and scope probes at the output. Be careful when connecting the scope ground, because one can often cause oscillations by hooking up the scope leads backwards. Since the multimeter measures rms voltage, it is convenient to use rms amplitude settings on the function generator. This way, you do not have to worry about factors of $\sqrt{2}$ in the gain calculations.

A. Calculate how the input voltage V_i relates to the amplitude setting on the function generator, assuming that the input impedance of the amplifier is very high. You will need this ratio later to calculate the gain of the amplifier and the loss of the input network.

B. The output coupling capacitor gives a high-pass characteristic. Measure the voltage gain G_v at a frequency that is high enough that you get full gain. Also measure the 3-dB roll-off frequency f_l. Now calculate what you expect for G_v from Equation 13.6. Calculate the value you expect for f_l, assuming that the output impedance of the amplifier is small.

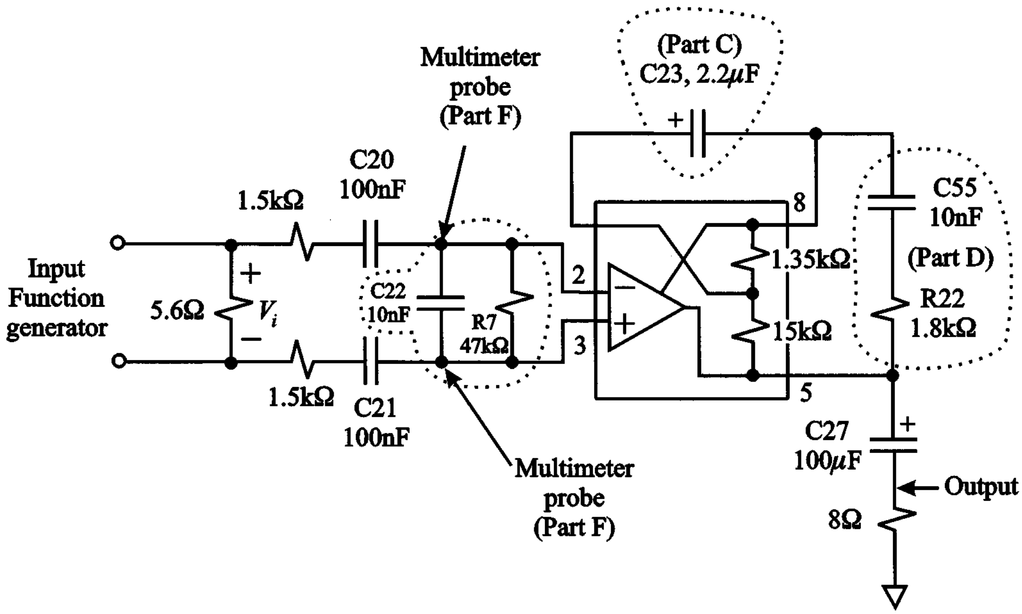


Figure 13.7. Adding C23 (2.2 μF) to increase gain (Part C). Adding C55 (10 nF) and R22 (1.8 kΩ) for a low-pass response (Part D). Adding the input network C22 (10 nF) and R7 (47 kΩ) for low- and high-frequency roll-off (Part F).

C. Now we increase the gain by bypassing the internal 1.35-kΩ emitter resistor. Install C23 (2.2 μF). C23 connects between pins 1 and 8 of the amplifier (Figure 13.7). Study Figure 13.1 to see how this affects the operation of the amplifier. You should work with a low input voltage now because the gain is large. Check frequently that the output is a clean sine wave and not saturated. The bypass capacitor only shunts the internal resistor at high frequencies, so this also gives a high-pass characteristic, but at a higher roll-off frequency than the output circuit. Measure G_v and f_l again. Now calculate the values that you would expect, neglecting the effect of the internal 1.35-kΩ resistor.

D. Next we add a low-pass response to the amplifier by installing the bypass network C55 (10 nF) and R22 (1.8 kΩ) for the internal 15-kΩ feedback resistor. These connect between pins 5 and 8 (Figure 13.7). You will need to study Figure 13.1 again to understand how it works. Combined with the high-pass response we have already measured, we get a band-pass characteristic. Make a plot of the gain in dB as a function of frequency from 100 Hz to 10,000 Hz, making sure that the input voltage is low enough that the output does not saturate. For the input power P_+, use the available power from the function-generator and resistor network. For the output power P, use the power that is delivered to the 8-Ω load. The plot will be compressed at the low-frequency end if you use a linear frequency scale. For this reason, for the frequency axis, you should plot $\log_{10} f$. This will give a more symmetric plot. This kind of plot is called a Bode plot, and it is convenient because the capacitive roll-offs show up as straight lines with a slope of 1. Bode plots are widely used for studying

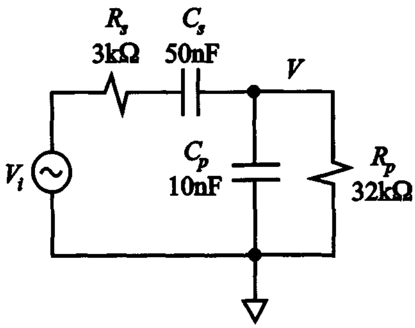


Figure 13.8. Simplified version of the input circuit.

amplifier response and checking stability against oscillation. Incidentally, a log plot should also guide you in choosing frequency increments. You should use much bigger increments at higher frequencies, or the plots will take a long time. One way to do this is to use equal increments of $\log_{10} f$, for example, the sequence, 2.0, 2.2, 2.4, ..., 3.6, 3.8, 4.0. This lets you make an excellent plot from 100 Hz to 10,000 Hz with only 11 data points.

E. Find the peak gain in dB and the corresponding frequency. What are the upper and lower 3-dB frequencies, f_u and f_l? Now calculate what you would expect for f_u. In this calculation, ignore the effect of R22. The role of R22 is to help prevent oscillations at high frequencies.

Now we turn to the input circuit. Install C22 (10 nF) and R7 (47 kΩ) (Figure 13.7). These provide additional roll-off at both low and high frequencies. Inside the amplifier, each input effectively has an internal 50-kΩ resistor in parallel with the pnp transistor pair. This adds a 100-kΩ resistor in parallel with R7. We can draw a simplified version of the input circuit (Figure 13.8). I have combined the input resistance of the amplifier, 100 kΩ, and R7 (47 kΩ) to make an equivalent resistance R_p given by

$$R_p = R7 \parallel 100\,\text{k}\Omega = 32\,\text{k}\Omega. \tag{13.14}$$

In addition, the coupling capacitors C20 and C21 are combined to make an equivalent capacitor C_s. The voltage V_i is the input voltage from Part A.

F. Find an expression for the loss of the network V_i/V. You should be able to put it in the form

$$\frac{V_i}{V} = L\left(1 + \frac{jf}{f_u} + \frac{f_l}{jf}\right), \tag{13.15}$$

where L is the loss in the pass band and f_u and f_l are the 3-dB roll-off frequencies. Find expressions for L, f_l, and f_u, and calculate the values for our circuit. Now measure them. It is convenient to do this with the multimeter probes attached to the amplifier side of the coupling capacitors C20 and C21. This is a differential input, and so you should not attach the scope ground there. When you finish the measurements, remove the 5.6-Ω and 1.5-kΩ resistors that you used to drive the Audio Amplifier. However, leave the 8-Ω load resistor in place, because we will need it for the next two exercises.

PROBLEM 32 - AUTOMATIC GAIN CONTROL

The AGC attenuates large signals to try to keep the audio output at reasonable levels for a wide range of inputs. The NorCal 40A uses a pair of JFETs as variable resistors in front of the Audio Amplifier. The AGC is a complicated circuit, with an attenuator, detector, and a keying section, and we will take it in several stages in this exercise and the next.

We start with the attenuator, or more precisely, dual attenuators (Figure 13.9). Install Q2 and Q3, R5, D5, D6, and R6. Leave enough room at the anode connection of D5 that you can attach a multimeter probe. Each JFET forms an attenuator for an audio amplifier input. R5 is a network of four identical 2.2-MΩ resistors in 2:1 potential dividers at the gates of the two JFETs. The input voltage for the attenuators is set by the AGC Threshold pot R6. The diodes prevent the gate voltage from rising above the JFET source voltage.

Once again, the function-generator voltage is too large, and it would cause the Audio Amplifier to saturate if we do not attenuate it first. Install a 300-kΩ resistor in one of the C19 holes, and attach the function-generator probe to the other end of the resistor. Either hole can be used. The function-generator ground should be attached to one of the ground loops on the side of the board.

Attach the oscilloscope and the multimeter to measure the output voltage of the Audio Amplifier as you did in the last problem. The function-generator setting should

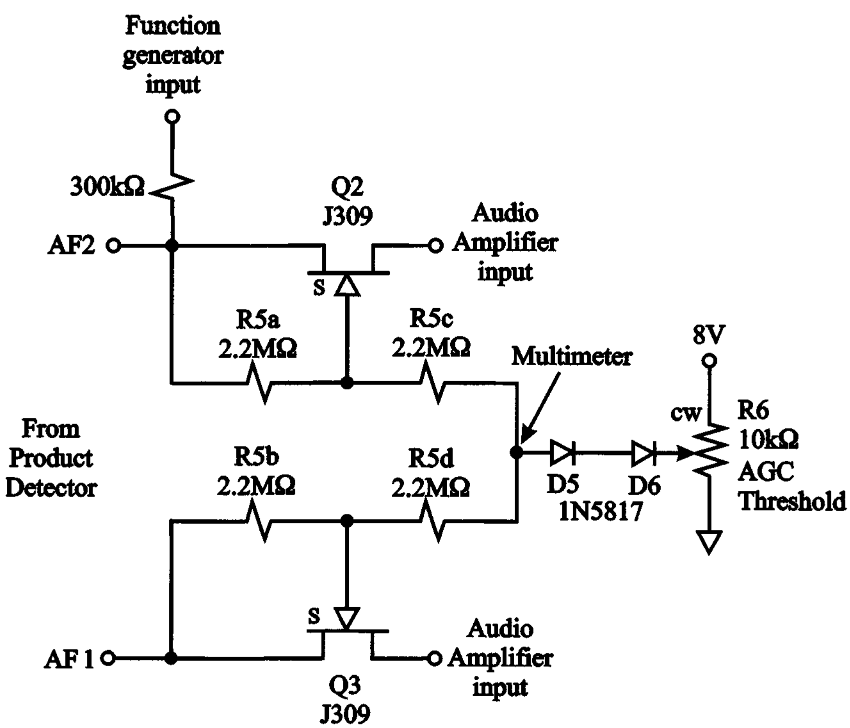


Figure 13.9. The AGC attenuators.

be for a 620-Hz sine wave. R6 should be set fully clockwise. This turns the attenuator off by setting the gate-source voltage to zero and leaves the JFETs with minimum resistance.

Adjust the amplitude setting of the function generator until the output voltage of the Audio Amplifier is 1 Vrms.

A. In the next set of measurements, you will need to move the multimeter lead that is not grounded back and forth between the 8-Ω load resistor and the anode of D5 (Figure 13.9), which is the control voltage for the attenuator. You will also need to switch back and forth between AC and DC voltage measurements. Make a plot with the audio output voltage on the y axis and the DC control voltage (the anode of D5) on the x axis. You should plot the audio voltage on a log scale because it varies over a wide range. This plot requires care and thought, because you will find that sometimes large changes in the control voltage make little change in the output, whereas at other times small changes in the control voltage cause large changes. You should try to keep a reasonable spacing between the points on the graph.

B. What is the maximum control voltage that you measure? What device supplies this voltage? Use this voltage and your plot to infer the cut-off voltage V_C for the JFET.

C. What is the minimum control voltage that you measure? D5 and D6 are Schottky diodes rather than pn diodes. Can you think of what could go wrong with the circuit if we used pn diodes instead?

D. Your plot should show that the range of control voltages that change the output is only a small part of the total range. For this reason we must set the AGC Threshold pot R6 at the beginning of the region where changes in the control voltage make a difference. Adjust the pot so that the audio output is reduced by 1 dB from its value at the full clockwise position. This is the setting that we use for the later measurements.

Now we can install the AGC capacitor C29 (10 μF) and the coupling capacitor C30 (2.2 μF) (Figure 13.10). C30 couples a portion of the output audio voltage to the AGC. When the audio voltage is sufficiently negative, it pulls down C29 through the rectifier diode D5. This reduces the input control voltage to the attenuator and increases attenuation. D6 prevents R6 from shunting D5, by turning off when the audio output voltage is negative.

E. The input network consists of the function generator, the 300-kΩ resistor, and a 1.5 kΩ resistor in the Product Detector. How does the open-circuit voltage for this network relate to the amplitude setting of the function generator? This open-circuit voltage should be the input voltage for the next plot. Plot the audio output voltage as the input voltage varies from 0.3 mVrms to 30 mVrms. Both the input and output voltages should be plotted on a log scale. You should find that the AGC has little effect at low voltages, but it should reduce the output at high voltages. Find the slope of the plot in the high-voltage region. Leave the 300-kΩ resistor in place; we will need it for the next exercise.

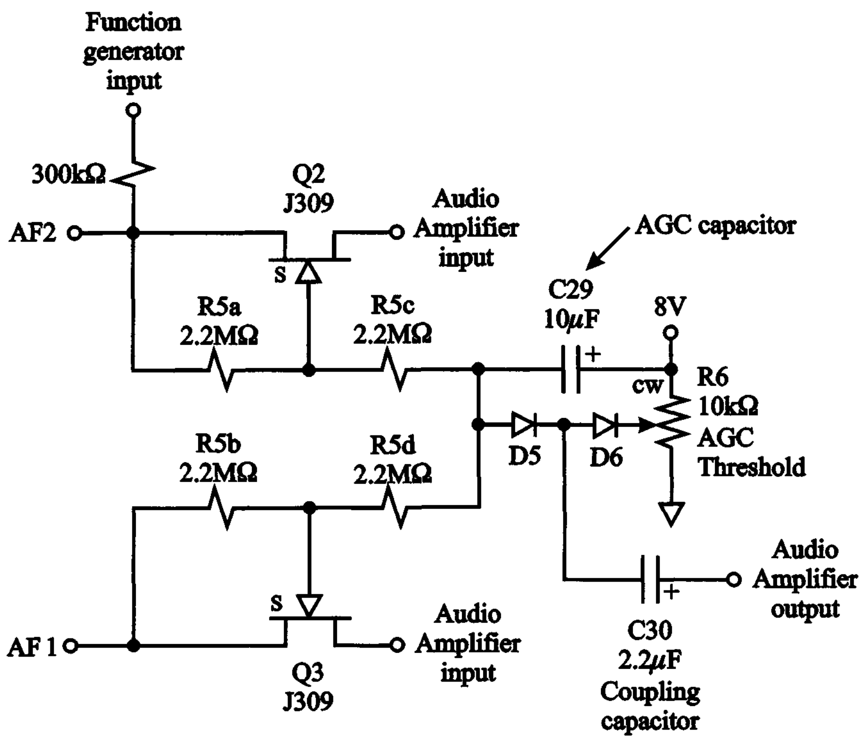


Figure 13.10. Adding the AGC capacitor C29 and the coupling capacitor C30.

PROBLEM 33 – ALIGNMENT

In this exercise we finish the transceiver, and do a checkout and alignment. We start with a measurement of AGC timing. We know from our transmitter measurements that the rise time for a pulse is in the range of 1 to 3 ms. The audio tones are at 620 Hz. Hence the rise time is only one audio cycle. The AGC should attenuate a strong signal on that time scale. People call this the *attack*. The attack for the NorCal 40A AGC is shown in Figure 13.11. The first cycle shows distortion at both the top and the bottom, indicating that the amplifier is overloaded. On the bottom half of the second cycle the amplitude is still large but the distortion is gone. On the top half of the second cycle the attack is complete, and the output is much reduced. The high volume at the beginning of an attack has an annoying pop.

When a signal ends, the AGC capacitor C29 *recovers* by discharging through the gate potential-divider network R5. Because the resistors and the capacitor are large, recovery is much slower than attack. This ensures that the AGC does not have to attack at each pulse, which would be quite irritating.

A. We can make a qualitative measurement of the recovery time. Set up the function generator to drive the AGC and audio amplifier through the 300-kΩ resistor as in the previous problem, and set up the oscilloscope to see the output of the Audio Amplifier. Use a snail's pace sweep speed of 0.5 s/division. Start with a 620-Hz,

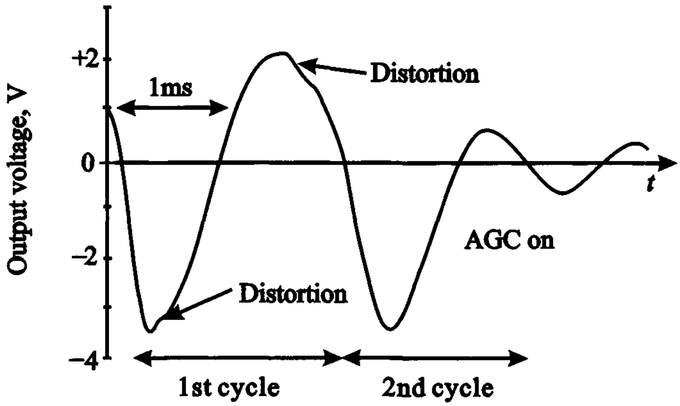


Figure 13.11. The attack for the NorCal 40A AGC. A 50-mV_{rms} signal is applied suddenly at the input of one of the AGC JFETs. The plot shows the audio output. During the attack, the audio amplifier charges the AGC capacitor in the bottom half of each cycle.

0.1 Vrms setting on the function generator and find an appropriate voltage scale for the scope. You should see a vertical band sweep slowly across the screen. Now change the amplitude setting to 3 Vrms, but do not change the scope scale. This should give a much larger output voltage, and the band should shoot off the screen in both directions. Now change the amplitude setting back to 0.1 Vrms. Initially the scope voltage will be small, because the AGC attenuates the signal. However, eventually the AGC capacitor will discharge, and the scope voltage will increase. Measure the time it takes for the scope voltage to reach the final value. This is the recovery time. The measurement is a little tricky, and you may need to repeat it several times before you have confidence that you have the time right.

B. Now calculate approximately how long the recovery should take. You may assume that the AGC capacitor C29 will discharge 1 V during the recovery.

Before we add the final parts, you should take out the temporary resistors. Remove the 300-kΩ resistor that we used for the function-generator input and the 8-Ω resistor that we used for the audio output. Replace the 1-Ω resistor in the S1 holes with a bare wire jumper.

Now we can complete the assembly. The parts that we need to install are circled in Figure 13.12.

Install C19. This capacitor provides additional high-frequency roll-off.

Install the Audio Frequency (AF) Gain pot R8 (500 Ω). This pot allows us to adjust the output volume. It should be set fully clockwise. This gives the maximum output voltage for multimeter measurements.

Install the Speaker jack J4 and C26. The capacitor provides additional high-frequency audio roll-off for removing hiss.

The remaining parts are for muting while transmitting. Even with the Receiver Switch on, the transmitter gives a larger voltage in the receiver mixers than any signal that would be received by an antenna; therefore, the designer does not try to handle this with the AGC alone. The muting circuit includes the three diodes D1, D2, and D3 and

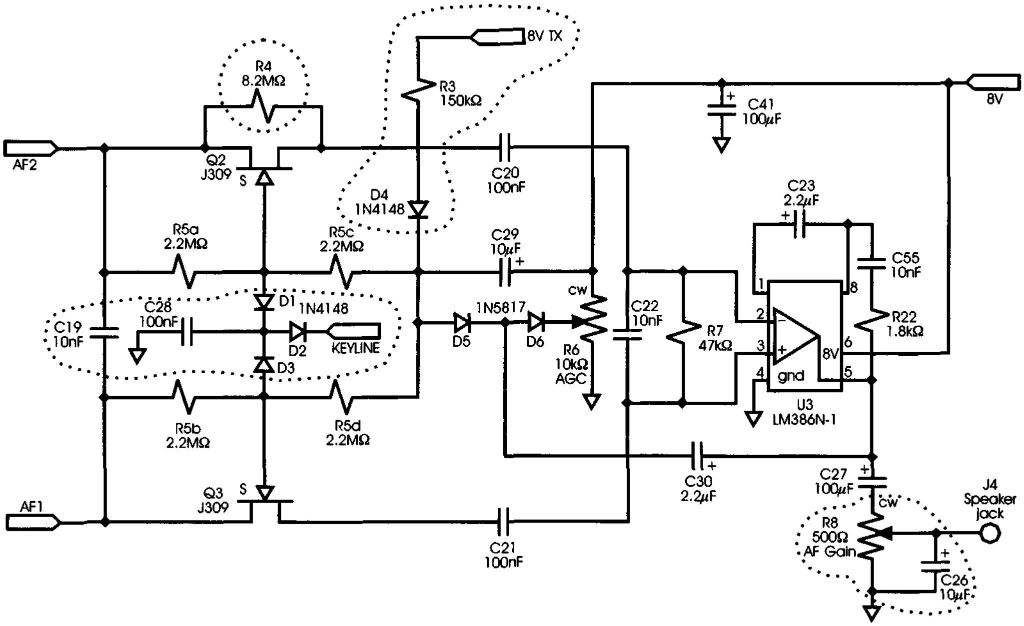


Figure 13.12. The final parts to install in the NorCal 40A.

the mute capacitor C28 (100 nF). We can understand what they do if we keep in mind what happens to KEYLINE during a pulse. At key down, KEYLINE goes low. This pulls the two gates of the JFETs all the way down to two diode drops above ground, cutting them off completely. In key up, KEYLINE rises, and this turns off D2. C28 charges through R5a and R5b. The gate voltages rise, the JFETs go into the linear region, and we are ready to receive again. The charging time for C28 has to be long enough to allow the transmitter to shut down completely. D1 and D3 ensure that the two gate circuits do not interact.

Install R3 (150 kΩ) and D4. This charges the AGC capacitor C29 during transmit so that the AGC recovers. The diode D4 prevents the AGC capacitor from discharging in reception when 8 V TX is low.

This leaves only one component, R4 (8.2 MΩ). R4 allows a little bit of the transmitter signal to leak around the JFET, so that you can hear your sending. This tone is called a *sidetone*. The volume is determined by the resistance. Some people find the sidetone with this resistor too loud and that a 15-MΩ resistor gives a better level.

Check the board to make sure that you have not forgotten to put in any components. You should mount the board in its box, add the knobs, and plug in your speaker.

Check that the AF Gain pot R8 is fully clockwise. This sets the volume to the maximum level.

Set the RF Gain pot R2 fully clockwise. You should not move this pot during the measurements. This position gives the maximum signal.

The RIT pot R16 should be centered.

The VFO Tune pot R17 should also be centered.

Plug in the power supply and turn it on. You should hear a hiss from the speaker. The function generator should be set for a sine wave at 20 mVrms. You will need an attenuator to reduce the level well below this. Set a frequency between 7,020 and 7,030 kHz. If you work in a lab where others also make measurements, you should set the kilohertz digit to the bench number. This ensures that the frequency at each bench differs by at least a kilohertz. Otherwise it can be difficult to tell the difference between your function generator and someone else's transmitter. Connect the attenuator to the Antenna jack J1 with a coaxial cable. It is a good idea to keep the cables separated so that signals do not couple around the attenuator.

A good place to start is with 80 dB of attenuation. Adjust the VFO Tune pot carefully to try to find the signal. If you cannot find it, reduce the attenuation to 50 dB or 30 dB. Once you find the signal, adjust the RIT to give maximum volume. Then take some time to enjoy the sound. There is almost no better feeling in electrical engineering than hearing the first tones out of a receiver you built, unless it is hearing someone answer your transmitter.

Now we tune the RF Filter. Hook the scope probes onto the speaker leads so that you can see the audio signal. Remember that one of the speaker leads is grounded. If you get the leads backwards you will short out the signal. Now tune the RF-Filter capacitors C1 and C2 for a maximum signal on the scope. They should be already well tuned, but this is a good time to check. Now we need to check the BFO frequency. Adjust the RIT pot for a maximum signal on the scope. This puts the signal through the center of your IF Filter. Hook up the counter to the output and check the audio frequency with a counter. Adjust the BFO capacitor C17 for an audio frequency of 620 Hz.

C. Next we find the receiver gain. Attach the multimeter leads to the speaker so that you can measure the output AC voltage. There is only a limited range of input powers that we can use to measure the gain. If the attenuation is set too high, stray coupled voltages dominate the input. If the attenuation is set too low, the AGC will kick in, and that will also upset the measurement. One way you can check the stray voltage is to switch all the attenuation in, and see what voltage is left on the multimeter. You need to work at an output voltage that is much higher than this, as high as you can get without provoking the AGC. Start with 80 dB of attenuation and try switching in an additional 6 dB. This would be 86 dB in all. If the voltage drops by a factor that is close to 2, then you have a good place to work. If the signal does not change at all, you may be picking up an AM station or another student's transmitter. You may need to shift the function-generator frequency a kilohertz or so to avoid this interference. Once you find a 6-dB range where the response is linear, go ahead and calculate the power gain, assuming that the speaker has a resistance of 8 Ω. You should get around 100 dB. If it is less than 90 dB, you have a problem, and you will need to check the signal levels at different stages in the receiver, taking into account the fact that the RF Filter and IF Filter have a loss of about 5 dB each and the mixers have a gain of about 18 dB.

D. One of the most important spurs is the response to the wrong sideband. This is the image of the Beat-Frequency Oscillator. The reason this is a problem is that if you hear a signal in the wrong sideband and transmit there, the other operator is unlikely to hear you. How much should you have to shift the frequency to hear a 620-Hz tone from the wrong sideband? Set the function generator to this frequency. You will probably not hear the signal, but if you decrease the attenuation, eventually you should hear it. Keep reducing the attenuation until the output voltage is the same as it was during the gain measurement. By how many dB does the IF Filter suppress the spurious sideband response?

The next two alignment steps are critical. The transmitter frequency needs to be adjusted so that it is the same as the signal being received. Otherwise another operator would not be able to hear the transmission. For this we need to set the sidetone frequency and find the center for the RIT knob. To start, connect the scope to the Antenna jack J1 with a 50-Ω load. Connect a switch to the Key jack J3 and turn the switch on to key the transmitter. You should peak the output by adjusting the Transmit Filter capacitor C39. Then set the Drive pot R13 to give 2.25 W output. You should also hear a sidetone at a reasonable volume level. Check the frequency of the sidetone with a counter. Set it to 620 Hz by adjusting the Transmit Oscillator capacitor C34.

Now we need to find the center position for the RIT pot R16. This is the position where the receive frequency matches the transmit frequency. Start by measuring the transmitter frequency. You should use the 50-Ω load in parallel when you connect the counter. You might need the counter's filter and attenuator because the transmitter voltage is large. Write the transmitter frequency down. Next we need to set the function generator to this same frequency. Often counters and function generators do not agree on the frequency, and so you should plug the function generator into the counter, and set it to match the transmitter. Now go back and connect the function generator to the radio through the attenuator. Adjust the RIT until the audio frequency is 620 Hz again. Use an indelible pen to put a center mark above the white dot on the knob, so that you can find this position again. This procedure is complicated enough that it is a good idea to check that the transmit and receive frequencies match when the RIT is set to the center mark.

Make marks with an indelible pen around the VFO Tune knob to indicate the frequencies 7,000, 7,010, 7,020, 7,030, and 7,040 kHz. This will make it convenient to set the transmitter and receiver to these frequencies in Problem 35.