4

Linear Power Amplifier Integrated Circuits

Introduction

The most convenient way to control power to a load is with a power op amp. These op amps have characteristics that are very similar to the low power ICs. However, they may be powered by over 50 V at 5 A.

Working with this much voltage and current requires that you accurately anticipate the power delivered to the load, the power provided by the dc supplies and the power that the op amp itself must dissipate. The power that the op amp dissipates is converted to heat. To move that heat from the silicon wafer requires effective heat sinking. Should a failure occur (by breakdown of a component, or because you botched the heat sink design), thermal shutdown allows the op amp to turn itself off. On-chip current limiting also allows you to set the maximum current the IC delivers to the load. This protects the load during a failure.

Audio power ICs have several special problems. Often you must run them from a single battery. Noise and total harmonic distortion are critical issues, as are circuit features such as bass or treble boost. You will see a low power tabletop amplifier IC and a 56 W boomer IC.

Objectives

By the end of this chapter, you will be able to:

- Determine the gain setting resistors and decoupling capacitors needed by a high voltage, high current, op amp based amplifier.
- Calculate the power delivered to the load, provided by the supply and dissipated by the IC.
- Calculate the IC and the case temperature and select the heat sink.
- Set the short circuit current limiting.
- Define special audio amplifier concerns and parameters.
- Properly apply a desktop amp, and a high power audio amplifier IC.

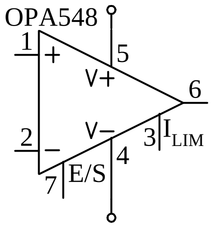

Figure 4-1 OPA548 symbol (*courtesy of Burr-Brown*)

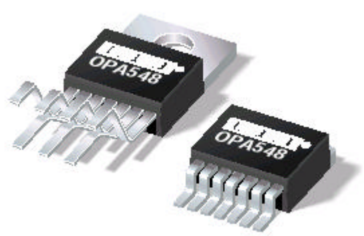

Figure 4-2 OPA548 connection diagram (*courtesy of Burr-Brown)*

Figure 4-3 OPA548 footprints (*courtesy of Burr-Brown)*

4.1 OPA548 Operational Amplifier IC

The OPA548 is a high voltage/high current operational amplifier made by Burr-Brown. Its schematic symbol is shown in Figure 4-1. It is available in two packages, a staggered lead, 7 pin TO-220 package, and a surface mount DDPAK. These are given in Figure 4-2. The circuit board footprints are shown in Figure 4-3.

If you want only to output positive voltage to the load, this op amp may be powered from a single supply, as high as +60 V. Connect V− to the circuit common. Unlike older designs, when powered from a single supply the OPA548 operates correctly with the input signal as much as a half of a volt *below* ground. The minimum single supply voltage is 8 V. So you will have to provide a separate, higher, more powerful supply if the rest of your system is running from +5 V.

To drive the load either positive or negative, reversing the direction of a motor, or to send audio to a loudspeaker, you can run the OPA548 from split supplies. Typically this means the dual supplies may range from ±4 V to ±30 V. But as long as the total difference between the power pins is 60 V or less, any combination of supply voltages is acceptable. Just remember to assure that the voltage on each input also always lies between V+ and V−.

Only CMOS implemented op amps are able to drive their output voltage all the way to the supplies. Typically the maximum output is several volts smaller than the supplies. This difference between supply voltage and maximum output voltage is called the **saturation voltage**. For the OPA548, the saturation voltage may be as large as 4 V. With supplies of ±28 V, the output voltage may be no more than 24 V_p.

The OPA548 can source or sink up to 5 A to the load. This is an instantaneous (peak) value. So, be sure to use the correct peak to root-mean-squared relationship and peak to average equations. These are summarized in Table 3-1. There are two other factors that limit the instantaneous current. You can connect a resistor between the I_{lim} pin (pin 3) and V− (pin 4). This resistor limits the maximum current to a value below 5A. This allows you to protect the load. The IC also has an on-wafer temperature sensor. Should the chip get too hot (>160°F), the op amp turns its output transistors off, until they cool down. This protects the IC. Later in this section, you will see how to set the current limit and to provide heat sinking to take advantage of the thermal protection feature.

There are two nonideal dc characteristics that affect how you use this IC. With proper negative feedback, an ideal op amp has no difference in potential between its inputs. However, in reality, the two input transistors cannot be made identically. So there is some small voltage between these two pins. This is the **input offset voltage**. For the OPA548 its worst case value is ±10 mV.

V_{ios} < 10 mV

To figure out the effect this has on the circuit, you can model the input offset voltage as a small dc supply in series with the noninverting input. A voltage follower is shown in Figure 4-4. The input offset voltage drives V_{out} to equal V_{ios}, instead of 0 V.

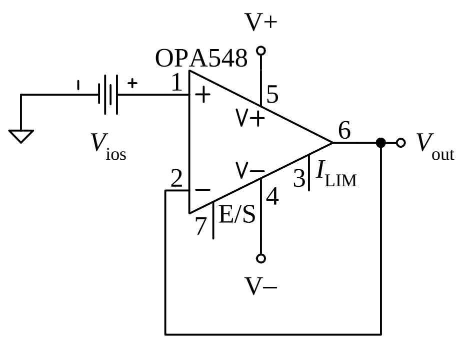

Figure 4-4 Voltage follower with input offset voltage

In some critical applications this ±10 mV output dc voltage could cause a problem. However, when you add gain to the circuit, the problem gets worse. Look at Figure 4-5. Ideally, with 0 V in, the output should also be 0 V. But since the input offset voltage is actually between the op amp's input and common, that voltage looks like an input signal. It is multiplied by the noninverting gain of the circuit.

$$V_{out} = \left(1 + \frac{R_f}{R_i}\right) V_{ios}$$

So, for reasonable gains, the output dc voltage could very easily be shifted significant parts of a volt, or more. If this shift in the output dc level causes a problem, you can add a coupling capacitor *immediately* before the load. Be sure to connect the feedback resistor, R_f, directly to the op amp's output. You could also add a voltage divider and potentiometer to the input, to allow you to tweak the output dc. Or, an integrator could be used to automatically sense any dc voltage at the output and send a small correction signal back into the OPA548. This is shown in Chapter 1, Figure 1-40.

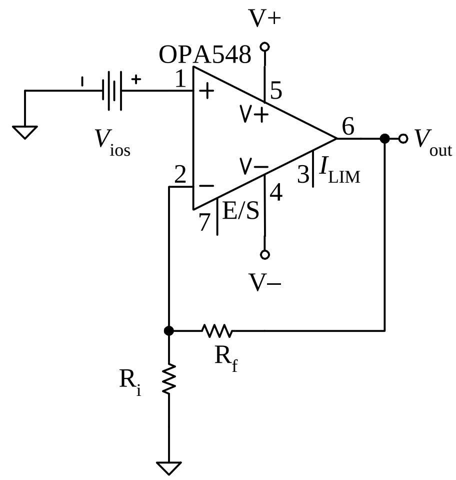

Figure 4-5 Amplifier with input offset voltage

$I_{bias} \leq 500nA$

The second nonideal dc characteristic that may cause you problems is the input current. You have assumed that there is no current flowing into the input of an op amp. But for the OPA548 both the input bias current and the input offset current may be as large as 500 nA. The results of this large an input current are shown in Example 4-1

Example 4-1

Calculate the output voltage for the circuit in Figure 4-5 with

$$R_f = 1\ M\Omega,\quad R_i = 10\ k\Omega,\quad V_{ios} = 0\ V,\quad I_{into\ pin\ 2} = 500\ nA$$

Solution

With $V_{ios} = 0$ V, the voltage at the noninverting input pin (pin 3) is

$$V_{NI} = 0\,V$$

Since negative feedback makes the inverting input track the noninverting (ignoring the input offset voltage),

$$V_{\text{INV}} = V_{\text{NI}} = 0\,\text{V}$$

This means that there is no voltage difference across R_i. So no current flows through it.

$$I_{\text{Ri}} = 0\,\text{A}$$

But, there is 500 nA of bias current flowing into the inverting input pin. It must come from somewhere. Since none of it can come through R_i, it must all come from the output of the op amp, flowing left to right through R_f. This current creates a voltage drop across R_f of

$$V_{\text{Rf}} = 500\,\text{nA} \times 1\,\text{M}\Omega = 500\,\text{mV}$$

Since the left end of R_f is held at 0 V, the output of the op amp must go up by 500 mV.

The simulation in Figure 4-6 confirms these calculations. Notice that it is necessary to edit the model of the op amp.

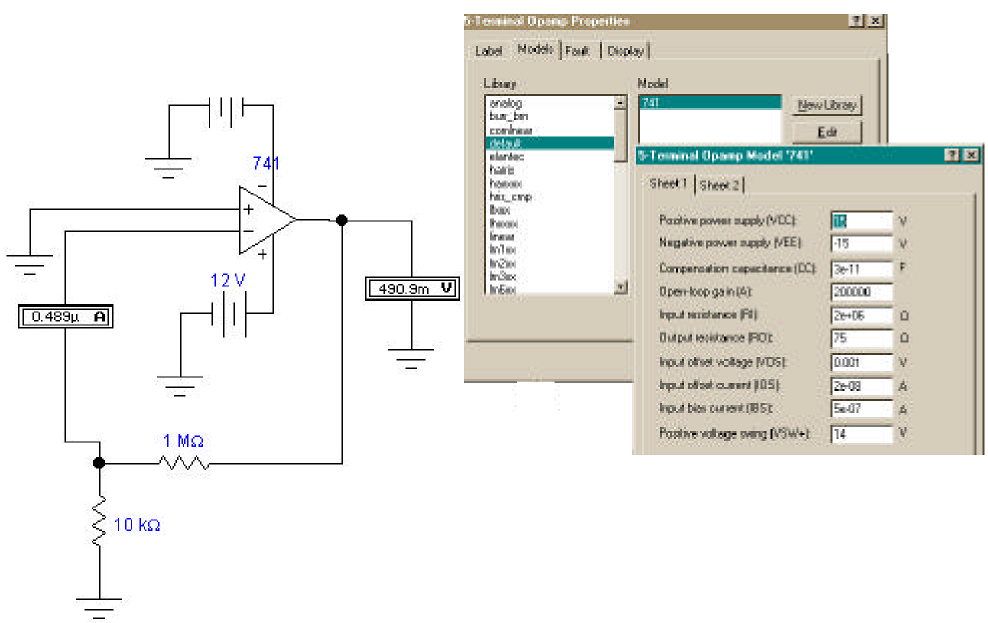

Figure 4-6 Multisim simulation of Example 4-1

Practice: What is the effect on the V_{out} of lowering the resistors to
$R_i = 100\ \Omega$, $R_f = 10\ k\Omega$

Answer: $V_{out} = 5$ mV

R_f < 10 kW

To minimize the effect of this unusually large bias current, keep the feedback resistor for the OPA548 as small as practical, typically a few kΩ.

The **gain bandwidth product** of the OPA548 is typically 1 MHz. This is the same as the 741 small signal amplifier. The gain bandwidth product is defined for *small* signals (1 V_p). It is

GBW = 1 MHz

$$GBW = A_o \times f_H$$

where

A_o = the amplifier's closed loop gain

f_H = the amplifier's high frequency cutoff, the frequency at which the gain has dropped to 0.707 A_o.

You may certainly input small signals into the OPA548. So you must be sure to consider the gain bandwidth product. But the main purpose of this op amp is to output large signals. For signals above 1 V_p, the op amp's speed is limited by its **slew rate**. The slew rate defines how rapidly the output may change.

SR = 10 V/ms

$$SR = \frac{dv_{out}}{dt}$$

For the OPA548 the slew rate is typically 10 V/μs when driving an 8 Ω load with a 50 V_{pp} signal.

If that output is a triangle wave, the slew rate defines the maximum slope of the output. For a rectangular output, the slew rate sets the smallest rise and fall times. But, for a sinusoidal output, you actually have to take the derivative of the signal, and look at that function at its maximum value. The result for a sine wave is called the **full power bandwidth**. This is the maximum frequency for a large undistorted sine wave output.

$$f_{max} = \frac{SR}{2\mathrm{p}V_p}$$

Example 4-2

An audio amplifier has an input of 300 mV_{rms} and is to deliver 35 W to an 8 Ω speaker. Can the OPA548 be used?

Solution

Assuming that the speaker is resistive, and that the signal is a sine wave,

$$P_{load} = \frac{V_{load\ rms}^{\ 2}}{R_{load}}$$

$$V_{load\ rms} = \sqrt{P_{load} R_{load}} = \sqrt{35\,W \times 8\,\Omega}$$

$$V_{load} = 16.7\,V_{rms} = 23.7\,V_p$$

$$I_{load} = \frac{23.7\,V_p}{8\Omega} = 3A_p$$

These levels are within the OPA548’s ability.

$$f_{max} = \frac{SR}{2pV_p}$$

$$f_{max} = \frac{10\frac{V}{\mu s}}{2\pi \times 23.7\ V_p} = 67.2\,kHz$$

Be careful with the units and the powers of ten. The slew rate is specified in V/μs. So the computed answer is 0.0672 MHz. Since the top of the audio band is only 20 kHz, the OPA548 has more than enough slew rate to pass an audio sine wave to the load.

$$A_o = \frac{V_{out}}{E_{in}}$$

$$A_o = \frac{16.7\,V_{rms}}{300\,mV_{rms}} = 55.7$$

$$GBW = A_o \times f_H$$

$$GBW = 55.7 \times 20\,\text{kHz} = 1.1\,\text{MHz}$$

The OPA548 has high enough voltage, current, and slew rate to serve for this 35 W audio amplifier. But it cannot amplify the high frequency signals enough. That is, its gain bandwidth product is too small.

Practice: Prove that the amplifier can be built with a small signal 741 op amp amplifier with a gain of 5, followed by the OPA548.

Answer: $V_{out\ 741}$ = 2.12 V_p, $SR_{741\ needed}$ = 0.27 V/µs, $GBW_{741\ needed}$ = 100 kHz, $GBW_{OPA548\ needed}$ = 223 kHz

4.2 Power Calculations

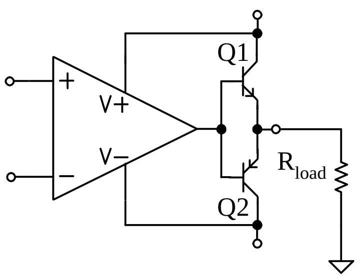

Figure 4-7 Simplified model of a power op amp

In considering the power that a linear power IC delivers to a load, it helps to consider the simplified model shown in Figure 4-7. Of course, the actual circuit is *much* more complex. But this highlights the key points. The traditional, low power op amp drives two power transistors. The npn transistor, Q1, turns on and **sources current** from V+ out of the output terminal, through the load, to circuit common. This produces a positive load voltage. On the negative load cycle, the pnp power transistor turns on. It **sinks current**, from circuit common, up through the load, through Q2 and to the negative supply, V−. All of the load current passes through either Q1 and/or Q2.

The power a signal can deliver to the load depends on several factors: the load's resistance, the op amp's power supply voltage, and the wave shape. These same factors determine the power that the supply must provide, and the power that the IC must dissipate. In Chapter 3, you saw how to calculate the power resulting from a wide variety of currents and voltages. These are summarized in Table 3-2. The two most prevalent wave shapes, DC and the sinusoid, will be applied to the power amplifier of Figure 4-7. But you can use these same techniques for any signal shape.

DC Signal to the Load

When a positive voltage is applied to the load, current flows from V+, through Q1, and to the load. The power that the load dissipates is

$$P_{\text{load}} = V_{\text{load dc}} \times I_{\text{load dc}}$$

Assuming that the load is purely resistive, this power equation can be combined with Ohm's law to give two alternate versions.

Load power

$$P_{\text{load}} = I_{\text{load dc}}^{\ 2} \times \text{R}_{\text{load}}$$

$$P_{\text{load}} = \frac{V_{\text{load dc}}^{\ 2}}{\text{R}_{\text{load}}}$$

This is the power that the load uses, converting it to heat, light, sound, or motion. Generally, that is the end product and the entire reason for the existence of the electronics.

This power is provided by the dc supply. Both V+ and V− are available to allow either positive or negative load voltages. If the load voltage only goes one direction, then the opposite supply just plays a small, biasing role. It does not deliver any significant power. The power provided by the supply is

$$P_{\text{supply}} = V_{\text{supply}} \times I_{\text{supply}}$$

Since the power supply, Q1, and the load form a series circuit,

$$I_{\text{supply}} = I_{\text{load dc}}$$

Combining these gives

Supply power

$$P_{\text{supply}} = V_{\text{supply}} \times I_{\text{load dc}}$$

Since the supply voltage is greater than the load voltage, the power supply's power is always greater than the power delivered to the load. The power that is provided by the supply but is not delivered to the load must be dissipated by Q1 (or Q2 if the output is negative).

IC power

$$P_{\text{IC}} = P_{\text{supply}} - P_{\text{load}}$$

This power is dissipated as heat in the IC output transistor, raising the temperature of the silicon. You will see in the next section how to provide the correct heat sink to protect the IC.

Example 4-3

Calculate the power delivered to the load, provided by the supply and dissipated by the op amp, for a circuit running from ±12 V_{dc}, delivering +5 V_{dc} to a 10 Ω resistive load.

Solution

The power delivered to the load is

$$P_{load} = \frac{V_{load}^{2}}{R_{load}}$$

$$P_{load} = \frac{(5\,V)^2}{10\,\Omega} = 2.5\,W$$

The current through the load, and therefore from the power supply is

$$I = \frac{5\,V_{dc}}{10\,\Omega} = 0.5\,A_{DC}$$

So, the power supply must provide

$$P_{supply} = V_{supply} \times I_{load\ dc}$$

$$P_{supply} = 12\,V_{dc} \times 0.5\,A_{DC} = 6\,W$$

The power supply is providing 6 W, but the load is using only 2.5 W. The IC dissipates the power that the load does not use.

$$P_{IC} = 6\,W - 2.5\,W = 3.5\,W$$

In this particular configuration, more power is going up as waste heat than is being delivered to the load. The simulation is shown in Figure 4-8.

Practice: What is the effect of decreasing the power supply to 9 V?

Answer: P_{load} = 2.5 W, P_{supply} = 4.5 W, P_{IC} = 2 W

Changing the supply voltage did *not* change the voltage or power delivered to the load. As long as the op amp has adequate head-room, the voltage passed to the load is set by the input. Changing the input voltage changes the load voltage, and that changes the power delivered to the load and the power provided by the supply. In turn these changes alter the power that the IC must dissipate, how hot the IC becomes, and the heat sink that you must provide. So in designing a power amplifier, you must consider two points of operation. The first is at the top end, at the maximum load voltage. Here, be sure to verify that the circuit can deliver adequate voltage and current to the load.

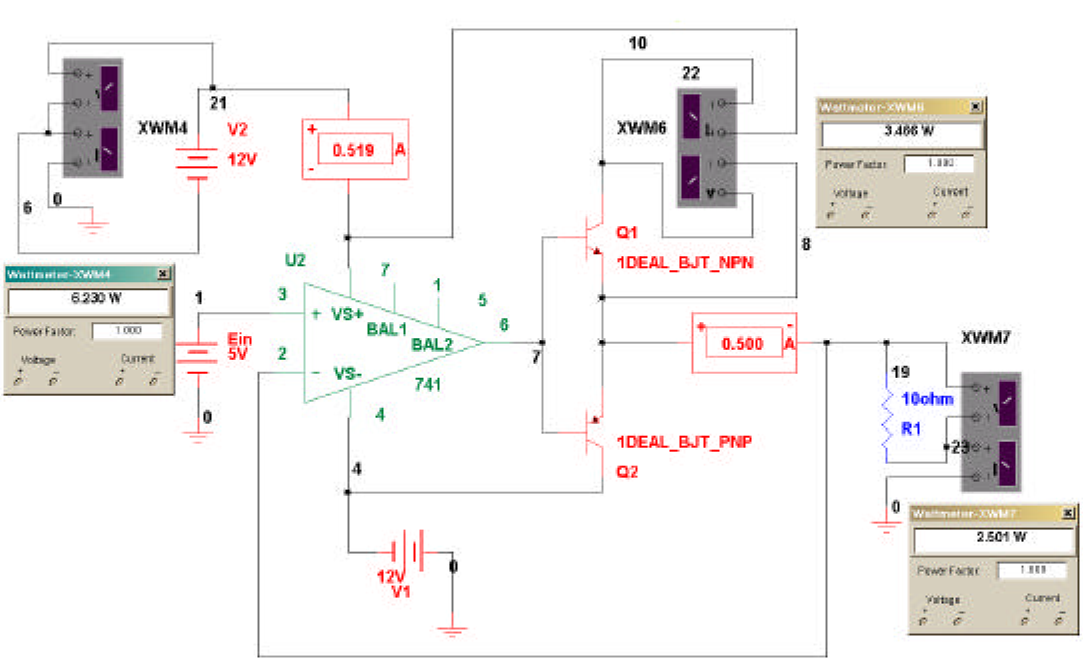

Figure 4-8 Simulation for Example 4-3

The second operational point to consider is the worst case power dissipation for the amplifier. At low output voltage, there is very little current flowing from the power supply through the op amp to the load. So the op amp is required to dissipate little power.

At the other extreme, where maximum voltage is being delivered to the load from the fixed supply voltage, the op amp's output voltage is driven very close to its supply voltage. This leaves only a small *difference* in potential between the collector and emitter of the op amp's power transistor. So, even though a lot of current is passing through the op amp, there is little voltage across it, so the op amp dissipates little power at the top end.

At the low end, there is little current through the op amp, so it does not have to dissipate much power. At the top end, there is little voltage *across* the op amp. So, again the IC does not dissipate much power. Precisely where is the worst case for the IC? Example 4-4 calculates the op amp's worst case operating point.

Example 4-4

Given a supply voltage of 12 V and a load voltage that varies from 0 V to 12 V, plot the IC power (*y* axis) versus load voltage (x axis), for a 10 Ω load.

Solution

Create a spreadsheet, with load voltage in the first column, load current in the second, load power in the third, supply power in the fourth, and IC power in the fifth.

Step the load voltage in each row from 0 V to 12 V, in 0.2 V increments.

"Pull down" all of the equations to fill the table. The result is shown in Table 4-1.

Table 4-1 Spreadsheet to determine the worst case IC power dissipation

V_{load} volts	I_{load} amps	P_{load} watts	P_{supply} watts	P_{IC} watts	
0.0	0.0	0.00	0.00	0.00	
0.2	0.0	0.00	0.24	0.24	
0.4	0.0	0.02	0.48	0.46	
0.6	0.1	0.04	0.72	0.68	
0.8	0.1	0.06	0.96	0.90	
4.8	0.5	2.30	5.76	3.46	
5.0	0.5	2.50	6.00	3.50	← matches Example 4-3
5.2	0.5	2.70	6.24	3.54	
5.4	0.5	2.92	6.48	3.56	
5.6	0.6	3.14	6.72	3.58	
5.8	0.6	3.36	6.96	3.60	
6.0	0.6	3.60	7.20	3.60	P_{IC} peaks & then drops
6.2	0.6	3.84	7.44	3.60	
6.4	0.6	4.10	7.68	3.58	
11.4	1.1	13.00	13.68	0.68	
11.6	1.2	13.46	13.92	0.46	
11.8	1.2	13.92	14.16	0.24	
12.0	1.2	14.40	14.40	0.00	

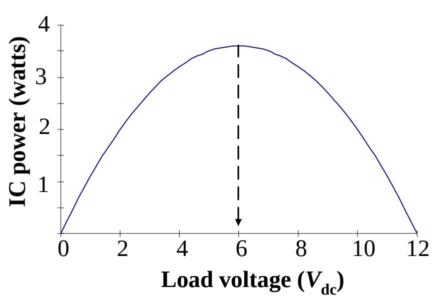

Figure 4-9 Maximum IC power

There are two points to notice from Table 4-1. The row that starts with V_{in} = 5 V duplicates the calculations in Example 4-3. This should give you confidence that the calculations in the table are correct.

Now, scan down the P_{IC} column. It starts low, grows as I_{load} increases, peaks, then decreases as the difference between V_{supply} and V_{load} falls. The maximum power that the IC must dissipate occurs when

Worst case IC power for a DC signal occurs when:

$$V_{load} = \frac{1}{2} V_{supply}$$

Figure 4-9 is a plot of the data from Table 4-1. It, too, shows a parabola with the IC power peaking when the load voltage is half of the supply voltage.

Practice: Duplicate Table 4-1 and Figure 4-9, with V_{supply} = 15 V, and R_{load} = 5 Ω.

Answer: $P_{IC\ max}$ = 11.3 W at V_{load} = 7.5 V

Sinusoidal Signal to the Load

The steps you used to determine the effects of a dc signal on the load, the supply, and the power IC can be applied to any wave shape. But the results are different for each different signal.

From the calculations in Chapter 3, you saw that the power delivered by a sine wave to a resistive load is

Load power

$$P_{load} = \frac{V_p I_p}{2}$$

In more familiar rms terms, for a sine wave,

$$P_{load} = \frac{V_p I_p}{\sqrt{2}\sqrt{2}} = \frac{V_p}{\sqrt{2}} \times \frac{I_p}{\sqrt{2}}$$

$$P_{load} = V_{rms} I_{rms}$$

During the positive half cycle, the upper *npn* transistor, Q1, inside the op amp turns on, sourcing a half-cycle sine wave current to the load. During the negative half-cycle, Q1 turns off. It passes no current. But Q2 turns on, sinking a half cycle current from the load. So, the positive power supply provides current to the load during the positive output half-cycle, and rests during the negative part of the cycle. Similarly, the negative power supply rests during the positive output half-cycle and sinks current during the negative part of the cycle.

Again, look back at Table 3-1. The two power supplies must be able to provide I_p. But, a dc ammeter indicates the average value.

Supply current

$$I_{\text{p supply}} = I_{\text{p load}} = \frac{V_{\text{p load}}}{R_{\text{load}}}$$

$$I_{\text{dc supply}} = \frac{I_{\text{p supply}}}{p}$$

To determine the power that the supply is delivering, you must consider the wave shapes of both the voltage from the supply and the current it provides. The power supply outputs a steady, dc voltage. But the current is a half sine wave, positive sourcing on one half-cycle and negative sinking on the other half-cycle. For the positive supply this is shown in Figure 4-10. To determine the power provided by this combination of voltage and current, you must complete the integral

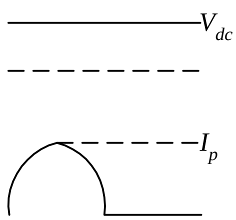

Figure 4-10 Power supply waveforms

$$P_{\text{each supply}} = \frac{1}{2p}\left(\int_0^p V_{\text{dc}} \times I_p \sin q \, dq + \int_p^{2p} V_{\text{dc}} \times 0 \, dq\right)$$

This was done in Chapter 3, and the result is in Table 3-2.

$$P_{\text{each supply}} = V_{\text{dc}} \frac{I_p}{p}$$

Since there are two supplies, the *total* power supplied is

Supply power

$$P_{\text{total supply}} = 2V_{\text{dc}} \frac{I_p}{p}$$

Finally, only some of $P_{\text{total supply}}$ is delivered to the load. The rest must be dissipated by the amplifier.

IC power

$$P_{\text{IC}} = P_{\text{total supply}} - P_{\text{load}}$$

Remember, this power is converted to heat at the IC's silicon wafer. The heat must be removed from the IC and passed on to the environment. The greater the heat, the larger the heat sink, and the hotter the inside of the equipment. Forced air (fans) may even be required. These thermal management components add cost and bulk to the equipment.

Example 4-5

Calculate the power delivered to the load, provided by the supply, and dissipated by the op amp, for a circuit running from $\pm 12\ V_{dc}$, delivering a $5\ V_p$ sine wave to a $10\ \Omega$ resistive load. Verify your calculations with a simulation.

Solution

The current through the load is

$$I_{load} = \frac{V_{load}}{R_{load}}$$

$$I_{load} = \frac{5\,V_p}{10\,\Omega} = 0.5\,A_p = 0.35\,A_{rms}$$

The power delivered to the load is

$$P_{load} = \frac{V_p I_p}{2}$$

$$P_{load} = \frac{5\,V_p \times 0.5\,A_p}{2} = 1.25\,W$$

Or, in terms of rms voltage and current,

$$P_{load} = \frac{5\,V_p}{\sqrt{2}} \times 0.35\,A_{rms} = 3.5\,V_{rms} \times 0.35\,A_{rms} = 1.23\,W$$

Each power supply must be able to provide $0.5\ A_p$. But this is in the shape of a half sine. So, the dc ammeter indicates

$$I_{dc\ supply} = \frac{I_p}{p} = \frac{0.5\,A_p}{p} = 160\,mA_{dc}$$

The power delivered by the two supplies is

$$P_{total\ supply} = 2V_{dc}\frac{I_p}{p}$$

$$P_{total\ supply} = 2 \times 12\,V_{dc}\frac{0.5\,A_p}{p} = 3.8\,W$$

The IC must dissipate the power that is provided by the supplies but not delivered to the load.

$$P_{IC} = P_{total\ supply} - P_{load}$$

$$P_{IC} = 3.8\,W - 1.3\,W = 2.5\,W$$

The simulation is shown in Figure 4-11. Look carefully at the values. The load's ammeter has been set to ac, and shows 0.354 A_{rms}. Load power also matches theory at 1.25 W. The dc current from the +12 V supply is shown as 158 mA_{dc}. Theory indicates 160 mA_{dc}. The wattmeter of the top supply indicates 1.93 W, for a total supply power of 3.8 W. This also matches theory. Finally the top transistor is dissipating 1.27 W, giving a total IC power of 2.5 W.

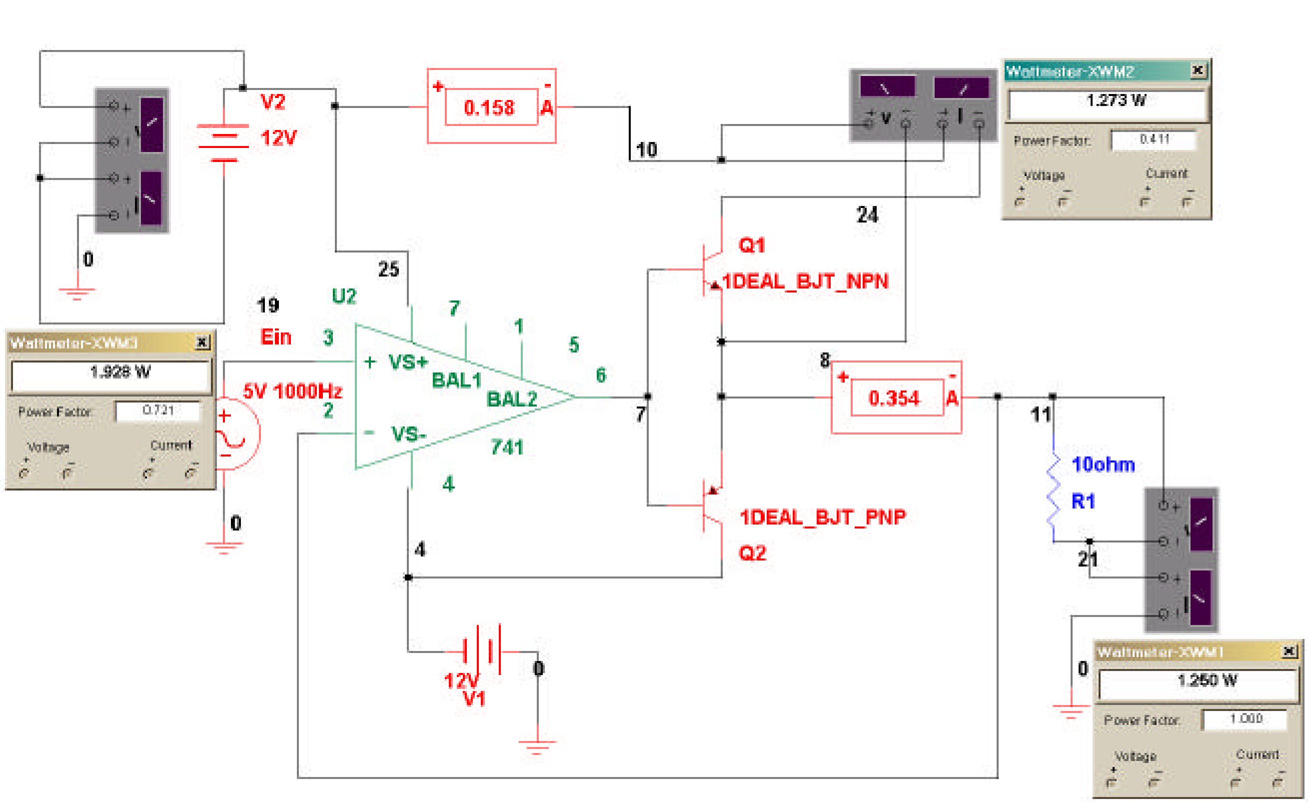

Figure 4-11 Simulation for Example 4-5

Practice: What is the effect of increasing the load voltage to 10 V_p?

Answer: I_{load} = 1 A_p, P_{load} = 5 W, P_{supply} = 7.6 W, P_{IC} = 2.6 W

As with a dc signal, the worst case power dissipation for the IC comes at moderate levels of output, not at the top end. However, since the wave shapes have changed, the maximum IC power point has also shifted. In Table 4-2, the appropriate equations for a sine wave have been entered into the spreadsheet and pulled down the column.

Table 4-2 Worst case IC power for a sinusoid

V_{load} volts	I_{load} amps	P_{load} watts	P_{supply} watts	P_{IC} watts	
0.0	0.0	0.00	0.00	0.00	
0.2	0.0	0.00	0.15	0.15	
0.4	0.0	0.01	0.31	0.30	
0.6	0.1	0.02	0.46	0.44	
4.6	0.5	1.06	3.51	2.46	
4.8	0.5	1.15	3.67	2.51	
5.0	0.5	1.25	3.82	2.57	← matches Example 4-5
5.2	0.5	1.35	3.97	2.62	
5.4	0.5	1.46	4.13	2.67	
5.6	0.6	1.57	4.28	2.71	
7.2	0.7	2.59	5.50	2.91	
7.4	0.7	2.74	5.65	2.92	
7.6	0.8	2.89	5.81	2.92	P_{IC} peaks & then drops
7.8	0.8	3.04	5.96	2.92	
8.0	0.8	3.20	6.11	2.91	
11.4	1.1	6.50	8.71	2.21	
11.6	1.2	6.73	8.86	2.13	
11.8	1.2	6.96	9.01	2.05	
12.0	1.2	7.20	9.17	1.97	

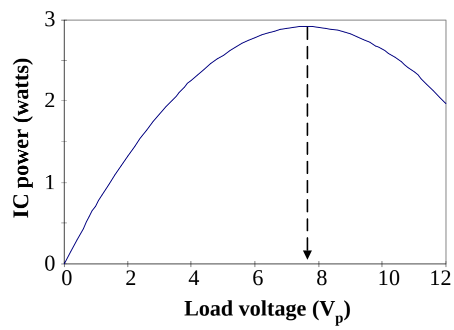

Figure 4-12 Plot of load voltage vs IC power for a sine wave

When the signal applied to the load is steady dc, the IC dissipates maximum power at

$$V_{\text{load p @ IC worst case}-\text{DC}} = 0.5V_{\text{supply}}$$

But, when the load voltage is a sine wave, the worst case for the IC occurs at a higher point, because the signal only spends a small part of each cycle near the peak.

$$V_{\text{load p @ IC worst case}-\text{sine}} = \frac{2}{p}V_{\text{supply}}$$

For other wave shapes, the worst case occurs at a different place. You have to complete the entire analysis for that particular shape. It will even involve some integrals, since the waveforms you are using are probably not in Table 3-2. Calculate

$$V_{\text{load p}}, I_{\text{load p}}, P_{\text{load}}, P_{\text{supply}}, P_{\text{IC}}$$

Then use a spreadsheet to investigate the effect of $V_{\text{load p}}$ on P_{IC}.

4.3 Heat Sinks

So what is to become of the power that the IC must dissipate? It is converted to heat by the resistance in the main transistors, Q1 and Q2. The hotter the IC gets, the poorer its performance, and the sooner it will fail. It is critical that you provide an adequate way to remove the heat from the silicon. Selecting the proper heat sink is central to the success of any electronic power device.

The key parameters are illustrated in Figure 4-13. Power dissipated at the silicon level produces heat that must flow through the IC packaging material, to the case, through the thermal interface between the case and the heat sink, to the heat sink, and finally into the surrounding air. These parameters combine to define the junction temperature.

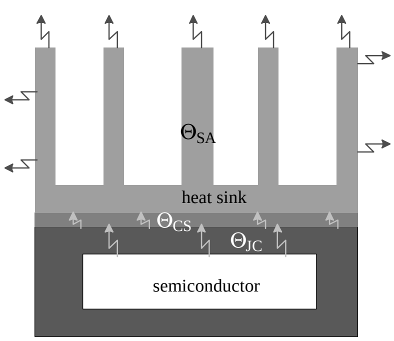

Figure 4-13 IC and heat sink layout and parameters

$$T_{\text{J}} = T_{\text{A}} + P\left(\Theta_{\text{JC}} + \Theta_{\text{CS}} + \Theta_{\text{SA}}\right)$$

T_{J} = silicon junction temperature of the IC–a specification
T_{A} = ambient temperature, *immediately* surrounding the package
P = power that the IC must dissipate
Θ_{JC} = thermal resistance between the *junction* and the *case*. This too is a specification of the IC.
Θ_{CS} = thermal resistance between the *case* and the heat *sink*.
Θ_{SA} = thermal resistance between the heat *sink* and the *air*. This is the key heat sink parameter.

The cooler you can keep the silicon, the longer the IC will run without a failure. But for even the worse case conditions, the manufacturer recommends that you must keep

$$T_J \leq 125°\text{C}$$

Thermal resistance tells you how much hotter the IC gets as heat flows through the packaging material. It is measured in °C of temperature rise for each watt of power dissipated. The thermal resistance, junction-to-case, Θ_{JC}, is set by how the manufacturer packages the silicon wafer. So, it is a specification. For the OPA548 TO220 package, typically

$$\Theta_{JC} = 2.5\frac{°\text{C}}{\text{W}}$$

For every watt of power the IC must dissipate in passing a signal to the load, its junction's temperature goes up 2.5°C as the heat flows out to the case.

The interface between the IC's case and the heat sink is critical. You must not ignore it. The simplest technique is to apply a liberal coat of heat sink **grease** or **compound** between the case of the IC and the heat sink. This fills in the surface imperfections and helps the heat transition to the heat sink. This is simple, inexpensive, and effective. But it is messy. Properly applied, a typical value is

$$\Theta_{CS} \approx 0.2\frac{°\text{C}}{\text{W}} \qquad \text{grease only}$$

Other forms of thermal adhesives and interface pads are also available. Be sure to verify their thermal resistance before selecting them.

In most power ICs the metal package is electrically connected to the most negative potential used by the IC. For the OPA548 the metal tab is tied to V−. If you connect the case directly to the heat sink, then the heat sink, too, is tied to V−. This most certainly can present a shock hazard, and a short circuit with destructive consequences if that heat sink ever touched anything else. So it is often a very good idea to *electrically* insulate the IC package from the heat sink, while keeping as good a thermal connection as you can. You can do this by inserting a wafer (often made of mica) between the IC and the heat sink. Be sure to also use an electrically *nonconductive* thermal grease as well. To provide a solid mechanical structure, either bond the sandwich together with an electrically *nonconductive* glue, or use a *nylon* bolt, nut, and washers. This provides the electrical insulation you need. But it raises the thermal resistance to, typically,

$$\Theta_{CS} \approx 2\frac{°C}{W} \text{ mica wafer , electrically insulated}$$

The most common way to determine the junction temperature is to measure the case temperature with a temperature sensor. You may do this during prototype testing to assure that the design meets its specifications. Or you may actually build a temperature monitor that measures the case temperature and takes some action to protect the electronics if things get too hot. With the sensor mounted on the heat sink,

$$T_J = T_C + P(\Theta_{JC} + \Theta_{CS})$$

So, measuring the temperature of the case, and knowing the specifications of the IC and the power that it is handling lets you determine the junction's temperature.

This leaves only the heat sink itself. The larger the heat sink, the more fins it contains, and the easier it is for heat to flow through it to the surrounding air. The thermal resistance is inversely proportional to the heat sink's surface area. A large heat sink has a small thermal resistance and heat flows through it easily, keeping the IC junction cool. This is the only part of the thermal elements over which you have much influence. If you want a different thermal resistance, pick a different heat sink. But be sure it fits into the space you have available. Rearranging the basic thermal equation to solve for the maximum allowable heat sink thermal resistance gives

$$\Theta_{SA\,max} = \frac{T_{J\,max} - T_{A\,max}}{P_{IC\ worst\ case}} - \Theta_{JC} - \Theta_{CS}$$

In still air, the temperature of the layer of air immediately surrounding the heat sink may be considerably higher than the air only a few centimeters away. This raises T_A, forcing you to obtain a larger heat sink with a lower thermal resistance. An alternative is to force air past the heat sink with a fan. This moves the heat away from the surface of the heat sink, rather than just relying on convection. The faster the air moves, the more heat is pulled from the sink. The heat sink's manufacturer gives the numerical effect of forced air cooling in a plot of the thermal resistance of the heat sink on the *y* axis, versus the speed of the air on the *x* axis. Figure 4-14 shows this effect for a TO220 heat sink by Avid.

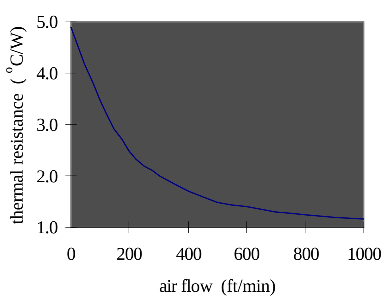

Figure 4-14 Air flow's effect on thermal resistance (*courtesy of Avid*)

You may see large areas of a printed circuit board with the copper left in place. The power semiconductor is then bent over and bolted to this expanse of metal. If you have large undedicated areas of your PCB, this may seem like a cheap and easy way to provide a heat sink. However, most printed circuit board material expands seven times more in thickness than it does in the plane of the surface, as it heats up. The coefficient of expansion for the board is also significantly different from that of the leads, the solder, and any nearby vias. So, as the heat transfers to the board, a great deal of force is exerted on the solder joint. After a surprisingly few cycles of heating and cooling, the leads break free from their solder connections, down inside the board (where you cannot see the break). And worse, the breaks separate when the parts heat up, but when you first turn on the equipment, to try to find the problem, everything is cool, and the broken ends are touching again. Do *not* use the printed circuit board as a heat sink unless you have PCB material specially designed for that purpose.

Example 4-6

Determine the heat sink's thermal resistance for the op amp from Example 4-5. Assume an ambient temperature of 40°C.

Solution

When picking a heat sink, you must consider the IC's worst case condition. From Table 4-2 this occurs at

$$P_{IC\ \text{worstcase}} = 2.92\,\text{W}$$

Solving the fundamental heat sink equation for Θ_{SA},

$$\Theta_{SA\ \max} = \frac{T_{J\ \max} - T_{A\ \max}}{P} - \Theta_{JC} - \Theta_{CS}$$

From the specifications for the OPA548, $T_{J\ \max} = 125°\text{C}$

$$\Theta_{JC} = 2.5\frac{°\text{C}}{\text{W}}$$

Since the metal package of the OPA548 is connected to V−, it is wise to isolate the case from the heat sink with a mica wafer.

$$\Theta_{CS} = 2\frac{°\text{C}}{\text{W}}$$

Make the substitutions.

$$\Theta_{\text{SA max}} = \frac{125°\text{C} - 40°\text{C}}{2.92\text{W}} - 2.5\frac{°\text{C}}{\text{W}} - 2\frac{°\text{C}}{\text{W}} = 24.6\frac{°\text{C}}{\text{W}}$$

This is the *largest* thermal resistance that can be used without the IC overheating.

Example 4-7

If a heat sink with a thermal resistance of $4\frac{°\text{C}}{\text{W}}$ is used on the OPA548, with ±24 V supplies, what is the largest sine wave that can be delivered to a 10 Ω load?

Solution

The basic thermal relationship is

$$T_{\text{J}} = T_{\text{A}} + P\left(\Theta_{\text{JC}} + \Theta_{\text{CS}} + \Theta_{\text{SA}}\right)$$

Solve this for *P*.

$$P_{\text{IC worstcase}} = \frac{T_{\text{J max}} - T_{\text{A max}}}{\Theta_{\text{JC}} + \Theta_{\text{CS}} + \Theta_{\text{SA}}}$$

$$P_{\text{IC worstcase}} = \frac{125°\text{C} - 40°\text{C}}{2.5\frac{°\text{C}}{\text{W}} + 2\frac{°\text{C}}{\text{W}} + 4\frac{°\text{C}}{\text{W}}} = 10\,\text{W}$$

Working the power equations backwards to determine the operating conditions that result in the IC dissipating 10 W becomes rather involved. A simpler solution is to alter the spreadsheet in Table 4-2, then look at the row that results in P_{IC} = 10 W. That row is shown in Table 4-3.

Table 4-3 Solution to Example 4-7

V_{load} volts	I_{load} amps	P_{load} watts	P_{supply} watts	P_{IC} watts
9.4	0.94	4.42	14.36	9.94
9.6	0.96	4.61	14.67	10.06

Practice: How much power can the IC dissipate and how much power can be delivered to the load if the heat sink's thermal resistance is raised to $8\frac{°C}{W}$ and the power supplies are lowered to ±18 V?

Answer: $P_{IC\ worst\ case} = 6.8$ W, $P_{load} = 6.5$ W

4.4 Protecting the OPA548

The OPA548 power op amp has internal **thermal protection**. When the semiconductor's temperature reaches about 160°C, the output transistors are automatically disabled. They are kept off until the wafer's temperature falls below approximately 140°C. This feature is intended to protect the IC from unexpected failures, enabling it to survive *occasional* problems. Allowing the IC to repeatedly operate above 125°C degrades its performance. This feature was *not* intended to replace proper heat sinking. Without the correct heat sink, as calculated in the previous section, the IC can never reliably deliver the required power to the load. This internal thermal protection is only a fail-safe.

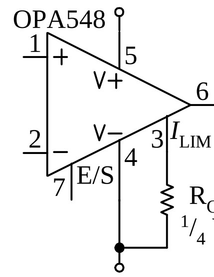

Figure 4-15 Current limiting with the OPA548 (*courtesy of Burr Brown*)

Thermal protection only activates when the power dissipated by the IC has caused its temperature to buildup over 160°C. This may take several cycles of the load current. If the load demands over 5 A from the OPA548, the IC, welds, and bonds may be damaged before the IC heats up enough to cause the thermal protection to activate. In addition, this excessive current flows from the power supply and through the printed circuit board traces, connectors, wires, and the load itself. Excessive current may damage all of these elements.

Adding a single, low power resistor to the OPA548 allows it to limit load current. The connection is shown in Figure 4-15. Select R_{CL} as

$$R_{CL} = \frac{15\,k\Omega \times 4.75\,A}{I_{LIM}} - 13.75\,k\Omega$$

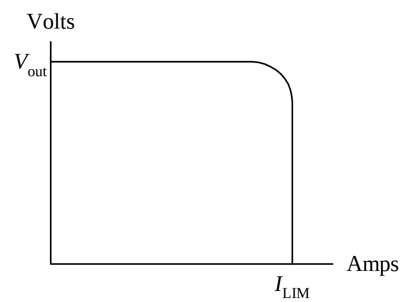

Figure 4-16 Current limiting characteristic curve

Current limiting is illustrated in Figure 4-16. When the load resistance is low, the output current is the value dictated by the output voltage and load resistance, as set by Ohm's law. But once I_{LIM} is reached, the output current is fixed. Since Ohm's law cannot be violated, once current limiting is entered, further reductions of the load resistance causes the load *voltage* to drop proportionally.

Current limiting is instantaneous. It affects only those parts of a waveform that result in currents above I_{LIM}. All load currents above I_{LIM} are held at I_{LIM}. This effectively shaves off the peaks.

Current limiting only limits the current. It does *not* prevent the amplifier from overheating. In fact, should the load be shorted, the load voltage goes to 0 V. This means that the load dissipates no power. The amplifier holds the current to I_{LIM}. The amplifier must now dissipate all of the power being delivered by the supply. If the heat sink is sized for normal operation, it cannot handle this excessive power. The IC's temperature rises. The OPA548 quickly goes into thermal limiting. Without thermal limiting, the IC would burn up. Current limiting does *not* protect the amplifier from overheating.

Do *not* try to test current limiting by shorting the load. You will just force the amplifier into thermal shutdown. Instead, raise the output voltage to its maximum. Then, gradually lower the load resistance until the peaks just begin to flatten. During that flattened part of the output signal, current limiting is being activated. The current limit is

$$I_{\text{lim measured}} = \frac{V_{\text{flattened peak}}}{R_{\text{load}}}$$

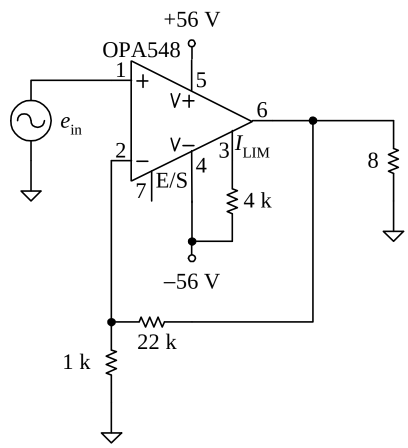

Figure 4-17 Schematic for Example 4-8

Example 4-8

a. Calculate the gain and the current limit for the circuit in Figure 4-17.

b. Accurately draw the output voltage waveform for an input of 2 V_p.

Solution

a.
$$A_v = 1 + \frac{R_f}{R_i} = 1 + \frac{22\,k\Omega}{1\,k\Omega} = 23$$

$$R_{CL} = \frac{15\,k\Omega \times 4.75\,A}{I_{LIM}} - 13.75\,k\Omega$$

$$I_{LIM} = \frac{15\,k\Omega \times 4.75\,A}{R_{CL} + 13.75\,k\Omega} = 4.0\,A$$

b. For an input of 2 V_p, the output should be

$$V_{out} = 2\,V_p \times 23 = 46\,V_p$$

But the maximum output current is 4 A_p. With an 8 Ω load, this current limit sets the maximum output voltage to

$$V_{ou\,I\,lim} = 4\,A_p \times 8\Omega = 32\,V_{max}$$

The output voltage is shown in Figure 4-18.

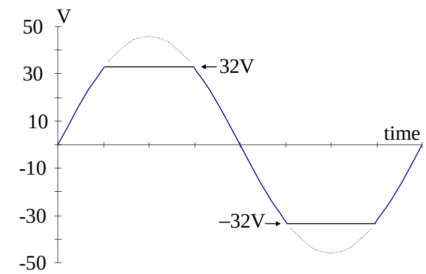

Figure 4-18 Clipped output for Example 4-8

Practice: How must you change the circuit in Figure 4-16 to deliver a 50 W sine wave to the 8 Ω load?

Answer: Change R_{CL} < 6.4 kΩ

4.5 Audio Power Parameters

Have you ever been told (or told some one) "Turn the volume down. It's too loud!"? Just how loud is loud enough? If the loudspeakers are on the stage, what happens to the volume as you move toward them? Will a more expensive loudspeaker make the music louder? How much power do you need from your amplifier? Music is not a sine wave. So what do you do about the peak-to-rms relationship? How do you rate the amplifier's power with a music signal? Before you can build an audio amplifier that actually produces the sound you want at the listener, you have to answer all of these questions.

Sound exerts a pressure on the eardrum. The higher that pressure, the louder the sound's volume. The softest sound that a young, undamaged ear can detect comes from a pressure of 20 μPascals. This level has been selected as a reference.

Softest detectable sound

$$p_{ref} = 20m\mathrm{P}$$

But, our ear responds logarithmically to amplitude. So loudness is measured in **sound pressure level** (**spl**). It is defined as

$$dB_{spl} = 20\log\frac{p_{ear}}{p_{ref}}$$

The softest sound generally detectable produces p_{ear}= 20 μP. The threshold of hearing, then, is at $dB_{spl\ threshold}$ = 0 dB_{spl}. A change of 1 dB_{spl} is barely perceivable, although it represents a 26% change in sound pressure. Your television remote control alters the volume by about 1.5 dB_{spl} each time you press the volume button. Most people can detect a 3dB_{spl} increase in volume. This requires *twice* the power from the amplifier.

Common volume levels are given in Table 4-4.

Table 4-4 Typical sound pressures of various sources (*courtesy of Yahmaha's Sound Reinforcement Handbook*)

dB_{spl}	sound
140	.45 ACP colt pistol at 25 feet
130	Siren at 100 feet
	Threshold of pain
120	Rock music at 10 feet
110	
	Film musical score at 20 feet
100	Loud classical music
90	Heavy street traffic at 5 feet
80	Cabin of a jet aircraft
70	
	Average conversation at 3 feet
60	
50	Average suburban home at night
40	Quiet auditorium
30	
	Quiet whisper at 5 feet
20	
	Rustling leaves
10	
0	Threshold of hearing

Since a sound wave usually spreads out both vertically and horizontally as it travels away from the source, sound pressure level decays as the square of distance. As compared with the level at 1 meter, the sound *x* meters away has changed by

$$\Delta dB_{spl} = 10\log\left(\frac{1\text{m}}{x}\right)^2$$

The square of the argument of a log is the same as twice the log.

Effect of distance on sound

$$\Delta dB_{\text{spl}} = 20\log\left(\frac{1\text{m}}{x}\right)$$

Example 4-9

A singer wants to be "loud enough" 8 m from the loudspeakers. The sound from a loudspeaker is rated at 1 m. How loud must the music be 1 m in front of the loudspeaker?

Solution

"Loud enough" is interpreted as 90 dB_{spl}. Softer would not be "commanding." Much louder could be painful to the people closer to the stage.

$$\Delta dB_{\text{spl @15m}} = 20\log\frac{1\text{m}}{8\text{m}} = -18\,\text{dB}_{\text{spl}}$$

The sound drops −18 dB_{spl} as it travels from the loudspeaker to the listener, 8 m away. So, at 1 m from the loudspeaker the sound pressure must be

$$dB_{\text{spl @1m}} = 90\,\text{dB}_{\text{spl}} + 18\,\text{dB}_{\text{spl}} = 108\,\text{dB}_{\text{spl}}$$

This at the top end of acceptable. Much louder would too loud for the audience close to the loudspeaker.

Practice: A teacher can project a sound of 85 dB_{spl} in a class room. Given that the listener in the back of the room must hear the sound at 70 dB_{spl}, how large can the room be without needing a sound reinforcement system?

Answer: The room may be 5.6 m = 18.5 ft deep.

Loudspeakers convert electrical energy into sound pressure. How effectively they do this is indicated by their rating:

dB_{spl} @ 1 m @ 1 W

The power delivered to the speaker can also be rated in dBW:

$$dBW = 10\log\frac{P}{1\text{W}}$$

This allows the direct conversion between sound pressure level and power delivered to the loudspeaker.

Example 4-10

In Example 4-9, it was decided that 108 dB_{spl} is needed at 1 m in front of the loudspeaker. How much power must be provided by the amplifier if the loudspeaker is rated at 95 dB_{spl} @ 1 m @ 1 W?

Solution

When 1 W of power is applied to the loudspeaker, it outputs a 98 dB_{spl} sound. But you want the sound of 108 dB_{spl}.

$$\Delta dB = 108\,\mathrm{dB} - 95\,\mathrm{dB} = 13\,\mathrm{dB}$$

The power to the loudspeaker must be increased by 13 dBW above 1 W.

$$dBW = 10\log\frac{P}{1\,\mathrm{W}} = 13\,\mathrm{dBW}$$

Solve this equation for *P*.

$$P = 1\,\mathrm{W} \times 10^{\frac{13}{10}} = 20\,\mathrm{W}$$

Practice: How much power is needed if it is decided to lower the volume at the listener by 6 dB_{spl}?

Answer: The needed power drops to 5 W, a four fold decrease.

Most testing is done with a sine wave. It is well defined, its shape is not altered by linear components, distortion is easy to detect, and it is commonly available. However, audio program content is *not* sinusoidal. It is **random**. That is exactly what makes it interesting to listen to. You have seen repeatedly that the peak of a sine wave is 1.414 times its root mean squared value. And it is this rms value that is used in determining the power delivered to a resistive load (the loudspeaker). The ratio of peak to rms is called the **crest factor**.

$$crest\ factor = \frac{V_{\mathrm{p}}}{V_{\mathrm{rms}}}$$

Table 4-5 Crest factors

	crest factor	
sound	voltage	power
sine	1.414	
speech	1.73	x 2
music	3.2	x 10

The rms value is used to determine the power that the signal delivers to the load. This in turn sets the average sound pressure level that the loudspeaker produces and that the audience hears. However, the amplifier must be able to provide a signal whose random, instantaneous, peak voltage is up to three times larger than the rms voltage. This peak is not repetitive. It happens occasionally and unpredictably during the program. The duration of the peaks also vary widely, but the peaks are a very small percentage of the entire program.

The amplifier's power rating is based on a sine wave. Knowing the gain and maximum power rating of the amplifier, you can input a sinusoidal tone, deliver the amplifier's rated maximum power to the loudspeaker, and provide a known sound pressure level at 1 m and at any given spot in the audience. The tone sounds loud and clear. However, as soon as you connect the same rms speech or music source, the peaks are far above that of the sine wave. The amplifier is already at its maximum. So the peaks from the audio source are clipped off. During the clipped peak, the amplifier's output goes to a high, constant level. The loudspeaker's cone moves out and stays there during the clipping. The sound is distorted. In addition, since the cone is not moving it does not cool itself. There is a danger that the loudspeaker may be damaged. The loudspeaker is damaged because the amplifier is *under*powered!

The solution is to buy a bigger amplifier than needed to provide the sound pressure level calculated in Examples 4-9 and 4-10. Generally, sound professionals recommend that the amplifier's power be increased by the signal's crest factor. If the amplifier from Example 4-10 is to be used in a classroom, select a 2x20 W = 40 W amplifier. This assures that the continuous volume meets the levels set in Example 4-9, but that there is plenty of **head room** when the teacher's peaks occur. If you want to play music through the same system, producing the same sound levels, then the amplifier must be 10x20 = 200 W to assure that there are crisp, clear, undistorted peaks.

The amplitude from the audio signal processor (mixer) is usually measured in **dBu**.

$$dBu = 20\log\frac{v_{\text{rms}}}{0.775\text{V}_{\text{rms}}}$$

The reference voltage of 0.775 V_{rms} is the amplitude needed to deliver 1 mW into 600 Ω. Signals coming from professional sound reinforcement equipment are typically set at about 4 dBu. This translates into 1.23 V_{rms}. The **line out** from consumer electronics is usually −8 dBu, 0.31 V_{rms}.

Example 4-11

What output voltage and what gain are needed by an amplifier that delivers 20 W to an 8 Ω loudspeaker?

Solution

To deliver 20 W to 8 Ω:

$$P = \frac{V^2}{\text{R}}$$

$$V = \sqrt{P \times \text{R}} = \sqrt{20\ \text{W} \times 8\,\Omega} = 12.7\ \text{V}_{\text{rms}}$$

From a professional mixer, the line level is 1.23 V_{rms}, so

$$gain = \frac{v_{\text{out}}}{v_{\text{in}}}$$

$$gain = \frac{12.7\,\text{V}_{\text{rms}}}{1.23\,\text{V}_{\text{rms}}} = 10.3$$

Practice: What range of gain must you provide if this amplifier is also to work with consumer electronics.

Answer: 10–40

4.6 Low Power Audio Amplifier IC

The LM386 is a low voltage audio power amplifier. It has been optimized to require a minimum of components while delivering as much as 1 W to a loudspeaker. Its schematic is shown in Figure 4-19.

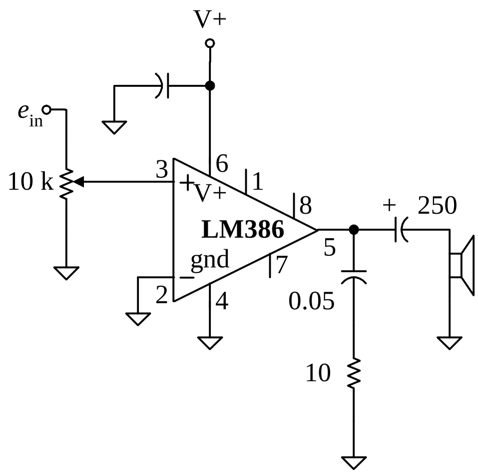

Figure 4-19 Low power audio amplifier (*courtesy of National Semiconductor*)

Unlike the op amps that you have seen, the LM386 has been designed to operate from a *single* power supply voltage, rather than ±V. This voltage may range from 4 V to 12 V for most versions. The -4 version allows a supply voltage as large as 18 V. This supply requirement allows you to power the amplifier from three 1.5 V batteries, from the +5 V of your computer, from a 9 V battery, or from your car battery (which may rise to 18 V).

However, without a negative supply voltage, what happens when the output signal needs to swing down? The LM386 biases its output pin to half of whatever voltage is provided as the supply. So, when the input is 0 V, the output is at half of the supply. The output can then swing up toward the supply, or down toward circuit common. For a 5 V supply driving an 8 Ω load, the output voltage can swing up to within 1 V of the supply, and down to within 1 V of circuit common. As the supply voltage and resulting load current increase, this saturation level also increases. With a 12 V supply and 8 Ω load, the output can swing up to 9.5 V and down to 2.5 V. Refer to the manufacturer's specifications for a detailed graph of supply voltage versus output peak to peak swing for various loads.

The bias voltage at the output must be blocked from the load, while the signal should be passed. That is the role of the 250 μF capacitor just before the loadspeaker. These two form a high pass filter, blocking the dc bias voltage (0 Hz) and passing the signal. The low frequency cut-off is

Low frequency cut-off

$$f_l = \frac{1}{2\pi R_{load} C}$$

For the components in Figure 4-18, signals below 80 Hz are attenuated. If you want to pass more bass, increase this output capacitor. If you are working with speech rather than music, set f_l = 300 Hz. This allows you to reduce the size and cost of that capacitor.

Internal gain = 20

Another major difference between the LM386 and the general purpose op amp is that negative feedback is provided internally by the LM386. Apply the input signal directly to the noninverting pin and tie the inverting input to circuit common. This provides a gain of 20. To invert the signal, apply the signal to the inverting pin and connect the noninverting input to circuit common. This sets the gain to −20.

Input impedance = 50 kΩ

With this gain and an output swing of less than 10 V_{pp}, you must restrict the input amplitude. The manufacturer rates the maximum input as ±0.4 V. That is the purpose of the input potentiometer. Even though the IC is powered only with a positive voltage, the input may swing both positive and negative 400 mV, without an *RC* input coupler. Either input may be referenced directly to analog common. Each input provides a 50 kΩ resistor to common. Unlike the op amp, the input impedance of the LM386 is not extremely large. It is 50 kΩ. The input potentiometer is set to 10 kΩ to reduce the loading effect of this 50 kΩ input impedance.

The internal negative feedback is provided by a 15 kΩ resistor between the output (pin 5) and pin 1. The lower part of the negative feedback voltage divider is provided internally by a 1.35 kΩ resistor (between pins 1 and 8) and a 150 Ω resistor. The gain is

External gain adjust

$$A = 2\frac{15\,\text{k}\Omega}{R_{\text{pin}\,1-8} + 150\,\Omega}$$

Increase the gain above 20 by placing a resistor and a dc blocking capacitor between pins 1 and 8. This resistor parallels the 1.35 kΩ internal resistor. If you place only a capacitor between pins 1 and 8, the gain rises to 200. Remember to account for the effect of the internal 1.35 kΩ resistor. Select the capacitor's value so that at the lowest frequency of interest, its reactance is small (1/7) compared to the resistor it affects.

$$C > \frac{1}{2\text{p}f_1 \dfrac{R}{7}}$$

Example 4-12

Determine the resistor and capacitor you must add between pins 1 and 8 to set the gain at 40, with f_1 = 80 Hz.

Solution

The gain is

$$A = 2\frac{15\,\text{k}\Omega}{R_{\text{pin}\,1-8} + 150\,\Omega}$$

Solve this for $R_{\text{pin 1-8}}$.

$$R_{\text{pin}\,1-8} = 2\frac{15\,\text{k}\Omega}{A} - 150\,\Omega$$

$$R_{\text{pin}\,1-8} = 2\frac{15\,\text{k}\Omega}{40} - 150\,\Omega = 600\,\Omega$$

Pick a 620 Ω resistor.

The capacitor in series with the 620 Ω resistor should be

$$C > \frac{1}{2p \times 80\text{Hz} \times \dfrac{620\Omega}{7}} = 22m\text{F}$$

Pick a 27 μF capacitor.

Practice: How much gain error would using a 620 Ω resistor produce?

Answer: A = 39 This is an error of 2.5 %.

It is often desirable to boost the low and the high frequency signals. This may be used to compensate for an inexpensive loudspeaker, or to implement the *loudness* feature. It is usually enough to give these bass and treble signals twice the gain that the middle frequency signals.

You can boost the bass by placing an RC series pair between pins 1 and 5. At low frequencies, this capacitor looks like an open, and the gain is 20. As the frequency goes up, the capacitor begins to look like a short. This places the external resistor between pins 1 and 5 in parallel with the 15 kΩ internal resistor. Setting this external resistor to 15 kΩ then reduces the gain to

$$A_{mid} = 2\frac{15\,k\Omega // 15\,k\Omega}{1.35\,k\Omega + 150\,\Omega} = 10$$

This is the lowest stable gain that the amplifier produces.

The low frequency boost point is set by the capacitor in series with the 15 kΩ resistor between pins 1 and 5. The precise equation is rather *complex* since it involves a series-parallel combination of two resistors and a capacitor. Select its initial value near

$$C_{bass\,boost} \approx \frac{1}{2p \times 15\,k\Omega \times f_{bass\,boost}}$$

Then test select the final value by substitution at the bench.

This RC pair between pins 1 and 5 has dropped the gain above $f_{bass\ boost}$ to 10. To raise the gain back up to 20 for the treble signals, you must add the RC pair between pins 1 and 8. But because the resistor between pins 1 and 5 is now paralleling the internal 15 kΩ resistor, the equation changes to

$$R_{pin1-8} = 2\frac{15\,k\Omega // 15\,k\Omega}{20} - 150\,\Omega = 600\,\Omega$$

But instead of selecting the capacitor to look like a short at 80 Hz, pick it to pass the signal to $R_{pin1\text{-}8}$ at the treble boost frequency. Below that frequency, the capacitor looks like an open, and the gain is 10. Above that frequency the capacitor looks like a short and the gain is 20.

$$C_{treble\,boost} \approx \frac{1}{2pR_{treble\,boost}\,f_{treble\,boost}}$$

The schematic, with both bass and treble boost, and the resulting frequency response are given in Figure 4-20.

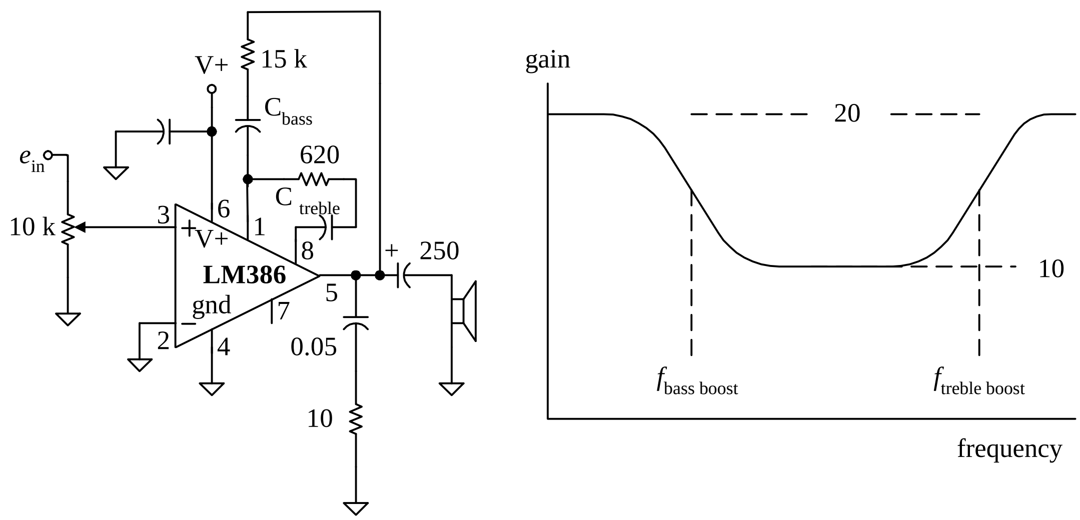

Figure 4-20 LM386 with bass and treble boost

All of the power and heat sinking relationships that you used for the power op amp of the previous section apply equally to the LM386. They are demonstrated in the following example.

Example 4-13

Calculate the maximum power you can deliver to an 8 Ω loudspeaker, the worst case power that the LM386 must dissipate, and the heat sink's thermal resistance using a +5 V supply.

$T_{J\,max} = 150°C$ $\Theta_{JC} = 37°C/W$ $\Theta_{JA\,no\,sink} = 107°C/W$

Solution

The output dc voltage centers at half of the supply.

$$V_{out\,dc} = 2.5\text{ V}$$

This output voltage can rise to within 1 V of the supply.

$$V_{out\,max} = 4\text{ V}$$

The ac peak swing, then is

$$V_{p\,out} = 4\text{V} - 2.5\text{V} = 1.5\text{V}_p$$

Assuming that this signal is a sine wave means that

$$V_{\text{rms out}} = \frac{1.5\,\text{V}_\text{p}}{\sqrt{2}} = 1.06\,\text{V}_\text{rms}$$

The loudspeaker dissipates

$$P_{\text{load}} = \frac{(V_{\text{rms}})^2}{\text{R}_{\text{load}}}$$

$$P_{\text{load}} = \frac{(1.06\,\text{V}_{\text{rms}})^2}{8\,\Omega} = 140\,\text{mW}$$

In terms of dBW, this is

$$dBW = 10\log\frac{140\,\text{mW}}{1\text{W}} = -8.5\,\text{dBW}$$

How loud this sounds depends on the efficiency of the loudspeaker and how close to it you are. Having a +5 V supply suggests that this circuit is to be used for a desktop computer monitor. So, a distance of 1 m is reasonable.

The loudspeaker from earlier examples was rated at

$98\ \text{dB}_{\text{spl}}$ @ 1W @ 1 m

The sound heard, then is

$$dB_{\text{spl}} = -8.5\,\text{dBW} + 98\,\text{dB}_{\text{spl}} = 89.5\,\text{dB}_{\text{spl}}$$

Table 4-4 suggests that this is not quite as loud as heavy street traffic at 5 ft. That certainly should be loud enough for a computer monitor on your desk.

The worst case output level for the IC (assuming a sine wave) is when the signal is at 63% of the supply voltage. Since the signal swings up and down from 2.5 V, the worst case for the IC is when

$$V_{\text{p worst case}} = 0.63 \times 2.5\,\text{V} = 1.6\,\text{V}_\text{p}$$

But the maximum signal is only 1.5 V_p. So the worst case for the IC is at maximum signal. The current from the supply is

$$I_{\mathrm{p\ supply}} = \frac{1.5\,\mathrm{V_p}}{8\,\Omega} = 188\,\mathrm{mA_p}$$

This current flows from the supply, charges the capacitor, and then flows to the load, when the output voltage swings positive. On the negative half-cycle, the IC's sourcing power transistor turns off, and its sinking transistor is turned on. Current flows from the capacitor, through the IC's lower transistor to ground, and then up from ground through the load to the negative side of the capacitor. This is how current reverses direction through the load without a negative supply voltage.

The key point is that current flows from the supply only during the positive half-cycle. The power delivered comes from a dc voltage and a half sine current. From Table 3-2 that power is

$$P_{\mathrm{supply}} = V_{\mathrm{dc}}\,\frac{I_{\mathrm{p}}}{\mathrm{p}}$$

$$P_{\mathrm{supply}} = 5\,\mathrm{V_{dc}}\,\frac{188\,\mathrm{mA_p}}{\mathrm{p}} = 299\,\mathrm{mW}$$

The IC must dissipate the power that is provided by the power supply but is not passed to the load.

$$P_{\mathrm{IC}} = P_{\mathrm{supply}} - P_{\mathrm{load}}$$

$$P_{\mathrm{IC}} = 299\,\mathrm{mW} - 140\,\mathrm{mW} = 159\,\mathrm{mW}$$

The maximum allowable thermal resistance is

$$\Theta_{\mathrm{JA\ max}} = \frac{T_{\mathrm{J\ max}} - T_{\mathrm{A}}}{P}$$

For an amplifier that sits on a desk, without forced cooling, it is reasonable to expect that the air next to the enclosed IC gets no hotter than about 50°C.

$$\Theta_{\mathrm{JA\ max}} = \frac{150^\circ\mathrm{C} - 50^\circ\mathrm{C}}{0.159\,\mathrm{W}} = 629\,\frac{^\circ\mathrm{C}}{\mathrm{W}}$$

This is the *maximum* allowable thermal resistance. Any value below this will keep the junction temperature below 150°C. The specifications of the thermal resistance for the IC without a heat sink is 107°C/W for the DIP package. So the IC needs no heat sink.

Practice: Calculate the maximum power you can deliver to an 8 Ω loudspeaker, the worst case power that the LM386 must dissipate, and the heat sink's thermal resistance if this amplifier is to be used in a car (+12 V supply).

Answer: $V_{load\ p} = 3.5\ V_p$, $P_{load} = 0.77$ W, 97 dB_{spl} in the front seat, 91 dB_{spl} in the back seat, $I_{supply\ p} = 438\ mA_p$, $P_{supply} = 1.7$ W, $P_{IC} = 0.9$ W, $\Theta_{JA} = 111°C/W$.

With *good* loudspeakers, the LM386 delivers reasonable sound levels if you are close, *and* if you ignore the fact that music produces peaks that are 10 times its rms value. To keep from clipping these peaks, distorting the sound and damaging the loudspeakers, the amplifier must be able to provide more power. The **bridge amplifier** of Figure 4-21 provides up to four times the power without a larger power supply voltage.

The loudspeaker is *not* tied to circuit common. Both ends are driven, one by U1, and the other by U2. The second IC, U2, is configured as an inverting amplifier. So, when U1 drives the left side of the load to its maximum level, the right amplifier, U2, drives that end down

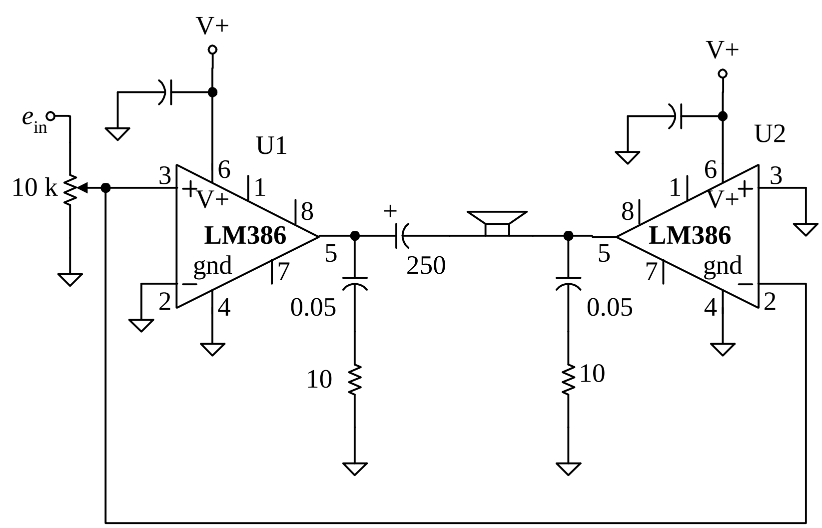

Figure 4-21 Bridge amplifier

just above circuit common. So the total positive peak across the load is almost the supply voltage, not half of the supply as it is when the loudspeaker is tied to common. On the negative half-cycle the left end is driven down near common, while the right end goes close to the supply. However, the current is flowing in the opposite direction. The current has reversed direction without having a negative power supply.

Example 4-14

Calculate the maximum power delivered to an 8 Ω load by a bridged amplifier using two LM386s running from a 5 V supply.

Solution

On the positive input peak, U1's output goes to

$$V_{\text{left max}} = 5\,\text{V} - 1\,\text{V} = 4\,\text{V}$$

U2 drives the right end of the load close to common.

$$V_{\text{right min}} = 1\,\text{V}$$

The *peak* across the load is

$$V_{\text{p}} = 4\,\text{V} - 1\,\text{V} = 3\,\text{V}_{\text{p}}$$

Assuming a sine wave,

$$V_{\text{rms}} = \frac{3\,\text{V}_{\text{p}}}{\sqrt{2}} = 2.1\,\text{V}_{\text{rms}}$$

The power delivered to the load is

$$P_{\text{load}} = \frac{\left(2.1\,\text{V}_{\text{rms}}\right)^2}{8\,\Omega} = 551\,\text{mW}$$

Practice: Calculate the maximum power delivered to an 8 Ω load by a bridged amplifier using two LM386s running from a 12 V supply. At this supply level, there is a 2.5 V saturation.

Answer: 3 W

4.7 High Power Audio Amplifier IC

The few watts available from the LM386 are fine for personal listening. But to be heard more than a meter or two from the loudspeaker, a sound must be delivered at much higher power levels. The LM3875 can deliver much more power.

Up to 56 W of continuous power can be provided to an 8 Ω speaker. At that power level, the gain is flat from 20 Hz to 20 kHz and there is typically no more than 0.1% of distortion and noise. The IC also provides a variety of protection circuits. It monitors its internal temperature, turning itself off if the junction temperature exceeds 165°C, allowing operation to begin again once it has cooled to 155°C. Output current is limited to a peak of 4 A. Output protection is also provided for under voltage and over voltage transients.

A typical schematic is shown in Figure 4-22. At first glance, it looks just like an op amp. However, the IC has been optimized to deliver a lot of power, over a narrow frequency range, through long leads, at low noise and distortion levels. It handles these jobs much better than a general purpose power op amp.

The pin out diagram is given in Figure 4-23. It is a staggered lead power package, with the case tied to V−. The leads are spaced less than 0.1″ apart, so be careful if you plan to use a traditional universal breadboard with solderless connections.

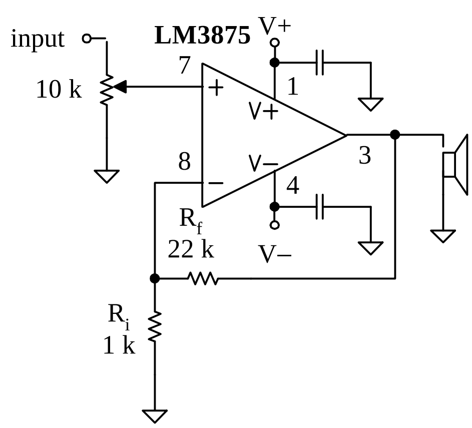

Figure 4-22 High power audio amplifier (*courtesy of National Semiconductor)*

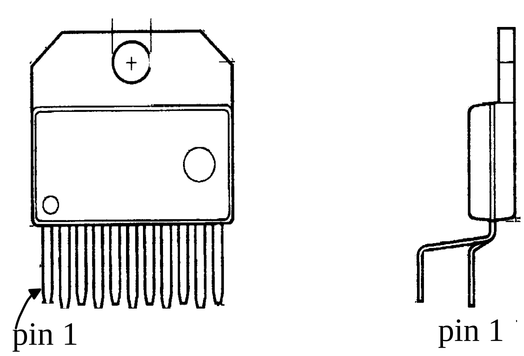

Figure 4-22 LM3875 pin out diagram (*courtesy of National Semiconductor*)

There are several key specifications that affect how you use the amplifier. These are shown in Table 4-6

Table 4-6 LM3875 key parameters

Parameter	Value	Unit
Power supply voltage	20–84	V
Output drop out voltage	5	V
Output current limit	4	A
Junction temperature	150	°C
Thermal resistance Θ_{JC}	1	°C/W
Gain bandwidth product	2	MHz

The power supply voltage is the difference between V+ and V−. You can run the IC from either split supplies (±10 V to ±42 V) or from a single supply (usually +20 V to +84 V with V− connected to common). If you choose to use a single supply be sure to provide appropriate biasing and RC coupling at the input and output. The minimum supply of 20 V means that you cannot power this IC *directly* from a car's 12 V battery, or the four D cells in a boom box. The maximum voltage (84 V or ±42 V) sets the upper limit on the largest voltage you can deliver to the load.

The output drop out voltage indicates how close to the power supplies the output can be driven before the transistors saturate. Although under certain conditions it may be less, it is wise to count on being able to drive the output no closer to the supplies than 5 V. So, if you are using the maximum ±42 V supplies, the largest output peak is ±37 V_p.

The output current typically is limited internally to 6 A. But the guaranteed limit is 4 A (or more). So you can count on being able to deliver at least 4 A to the load, assuming the part does not overheat.

The highest temperature on the silicon wafer that the IC can reliably run is 150°C. Even though there is internal temperature monitoring and shutdown, repeatedly pushing the chip over 150°C degrades its performance and may eventually cause its failure. So provide the appropriate heat sink to assure that under worst case, normal operation (i.e., not a failure in the system), the wafer temperature does not exceed 150°C. To determine this heat sink, you need to know the thermal resistance between the junction and the case, Θ_{JC}. It is no larger than 1°C/W.

Finally, the maximum closed loop gain is determined by the highest frequency to be amplified and the IC's gain bandwidth product. Although the GBW is typically 8 MHz, the worst case guaranteed value is 2 MHz. So, for a sine wave at the upper end of the audio range, 20 kHz, you can have a closed loop gain of 100. But, remember, at that frequency, the *actual* gain has dropped by 0.707 (–3 dB).

In addition to the limitations dictated by these specifications, there are several precautions you must observe to assure that your amplifier works well. Review Chapter 2 on the proper methods to breadboard and to lay out a printed circuit board for a power amplifier. *All* of the techniques and warnings presented there apply when you are using the LM3875. Be sure to:

- Keep the input and the output connections well separated.
- Rigorously decouple each power supply pin, as close to that pin as possible with a 10 μF electrolytic and a 0.1 μF film capacitor.
- Connect the speaker return *directly* to the analog common in its own separate lead, not back to the amplifier board's common.

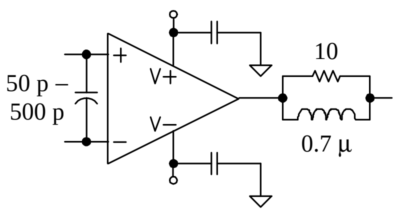

Figure 4-24 Input and output compensation (*courtesy of National Semiconductor*)

The leads that run from the output of the amplifier to the loudspeaker may be quite long. Running two conductors, side by side, creates a capacitor. The longer the distance, the greater is the capacitance to common. At high frequencies, this capacitance may cause the amplifier to oscillate. The parallel *RL* circuit shown in Figure 4-24 looks like a short at audio frequencies, but forms a low pass filter, blocking the high frequency oscillations.

In many applications, long leads may also be connected to the input, as the customer runs a cable to the CD player on another shelf. Noise coupled into this cable from the large amplitude output may cause the circuit to oscillate. The capacitor *directly* across the input leads prevents this, without degrading the audio signal.

Example 4-15

Using the LM3875, with a sinusoidal signal, and assuming an ambient temperature of 35°C, calculate the maximum power you can deliver to an 8 Ω load and the heat sink needed for worst case operation.

Solution

The supply voltages limit the power to the load. The maximum voltages for the LM3875 are

$$V_{\text{max supply}} = \pm 42\text{V}$$

The maximum output voltage from the LM3875 is the drop out voltage below its supply.

$$V_{\text{max out}} = 42\,\text{V} - 5\,\text{V} = 37\,\text{V}_\text{p}$$

This is the peak voltage for the output wave. Assuming a sinusoid,

$$V_{\text{p load}} = 37\,\text{V}_\text{p}$$

$$V_{\text{rms load}} = \frac{37\,\text{V}_\text{p}}{\sqrt{2}} = 26.2\,\text{V}_\text{rms}$$

The 8 Ω load dissipates

$$P_{\text{max load}} = \frac{(26.2\,\text{V}_\text{rms})^2}{8\,\Omega} = 85.5\,\text{W}$$

This is a very impressive amount of power from an integrated circuit. What must be done to assure that the IC does not overheat? From Table 4-2 and Figure 4-11 you saw that the worst case for the IC, assuming a sine wave, is *not* at the maximum load voltage. The worst case for the IC is at

$$V_{\text{p load @ IC worst case−sine}} = 0.63 \times V_{\text{supply}} = 26.5\,\text{V}_\text{p}$$

Repeat the sequence of calculations above. This leads to

$$P_{\text{load @ IC worst case}} = 44\,\text{W}$$

At this level, the current that the power supply provides is

$$I_{\text{supply @ IC worst case}} = \frac{26.5\,\text{V}_\text{p}}{8\,\Omega} = 3.3\,\text{A}_\text{p}$$

The power delivered by these two supplies is

$$P_{\text{supplies}} = 2V_{\text{dc}}\frac{I_\text{p}}{\text{p}}$$

$$P_{\text{supplies@IC worstcase}} = 2 \times 42\,\text{V}_{\text{dc}} \frac{3.3\,\text{A}_{\text{p}}}{\text{p}} = 89\,\text{W}$$

The IC must dissipate the power that is not delivered to the load.

$$P_{\text{IC@worstcase}} = 89\,\text{W} - 44\,\text{W} = 45\,\text{W}$$

The basic temperature relationship is

$$T_{\text{J}} = T_{\text{A}} + P\left(\Theta_{\text{JC}} + \Theta_{\text{CS}} + \Theta_{\text{SA}}\right)$$

Solve this for the thermal resistance of the heat sink, Θ_{SA}.

$$\Theta_{\text{SA}} = \frac{T_{\text{J}} - T_{\text{A}}}{P} - \Theta_{\text{JC}} - \Theta_{\text{CS}}$$

$$\Theta_{\text{SA}} = \frac{150°\text{C} - 35°\text{C}}{45\text{W}} - 1\frac{°\text{C}}{\text{W}} - 0.2\frac{°\text{C}}{\text{W}} = 1.4\frac{°\text{C}}{\text{W}}$$

Although this is a low thermal resistance, with proper forced air flow, even the simple TO220 heat sink from Figure 4-13 can reach this level. A larger heat sink may not require a fan.

Practice: Calculate the maximum power you can deliver to an 8 Ω load with the LM3875 powered from ±28 V supplies. What heat sink is needed?

Answer: $P_{\text{load max}} = 33.1$ W, $\quad \Theta_{\text{SA}} = 4.6\frac{°\text{C}}{\text{W}}$

Summary

The OPA548 power op amp allows a supply voltage up to 60 V. You can set the load current limit with a single, low wattage, high resistance resistor. Should there be a failure, the IC turns itself off when its temperature exceeds 160°C. The input offset voltage, offset current, gain bandwidth, and slew rate all can have a significant effect on the output, so do not forget to consider each.

Power depends on the signal's shape. The two most common shapes are dc and sinusoidal. The power dissipated by the load is

$$P_{\text{load}} = \frac{\left(V_{\text{dc load}}\right)^2}{\mathrm{R}_{\text{load}}} \text{ or } \frac{\left(V_{\text{rms load}}\right)^2}{\mathrm{R}_{\text{load}}}$$

The power supply to the amplifier provides

$$P_{\text{supply}} = V_{\text{dc}} \times I_{\text{dc}} \quad \text{or} \quad 2V_{\text{dc}} \frac{I_{\text{p}}}{\text{p}}$$

The amplifier must dissipate the power that is provided by the supply but not delivered to the load.

$$P_{\text{amp IC}} = P_{\text{supply}} - P_{\text{load}}$$

Calculate these power levels at the maximum load power to assure that the supply can provide enough voltage and current, and that the load can indeed dissipate the power that reaches it. But the worst case for the amplifier IC is not at maximum load power. So, you must repeat the analysis again at IC worst case

$$V_{\text{dc load}} = 0.5V_{\text{supply}} \text{ or } V_{\text{p load}} = 0.63V_{\text{supply}}$$

The more power that the IC must dissipate, the hotter it becomes. Its precise temperature depends on the ambient temperature, how much power it is dissipating, the thermal resistance between the wafer and the case, how the heat sink is mounted to the IC, and the characteristics of the heat sink. The air flowing over the heat sink lowers its thermal resistance.

One of the major uses of power ICs is as an audio amplifier. The loudness of a sound is measured in dB_{spl}, ranging from 25 dB_{spl} for a whisper to 140 dB_{spl} for a pistol shot. Sound decreases logarithmically as you move beyond the 1 m specification of the loudspeaker. Power may also be rated logarithmically in dBW. Audio signals are random, not sinusoidal. The crest factor varies from 1.7 for speech to 3.2 for music. Typically, signal levels from professional consoles are centered around 4 dBu, 1.23 V_{rms}. Consumer electronics output signals of about 310 mV_{rms}.

Tabletop applications require little more than a watt. This can be accomplished by the LM386. It is optimized for single supply operation from 4 V to 12 V. It has a fixed internal gain of 20. But this gain can be altered with external resistors, or its frequency response can be shaped with external RC networks. Bridging two LM386s allows you to deliver four times the power to the load.

For more power (over 50 W), consider the LM3875. It is configured very much like an op amp. It may be run from a single supply or from split supplies (20 V to 80 V). The load current is internally limited to at least 4 A, and the junction temperature is monitored and automatically limited.

The power ICs that you have seen in this chapter are convenient. But convenience is purchased at the expense of flexibility. Different voltage and power levels, increased frequency performance, custom current foldback, current output (to drive particularly low load resistances), and load power in the hundreds of watts require that you design the amplifier yourself. In Chapter 5 you will build on the fundamentals introduced here to construct custom MOSFET linear power amplifiers.

Problems

OPA548 Power Op Amp

4-1 For the circuit in Figure 4-25, calculate the dc and rms values of each of the four indicated voltages.

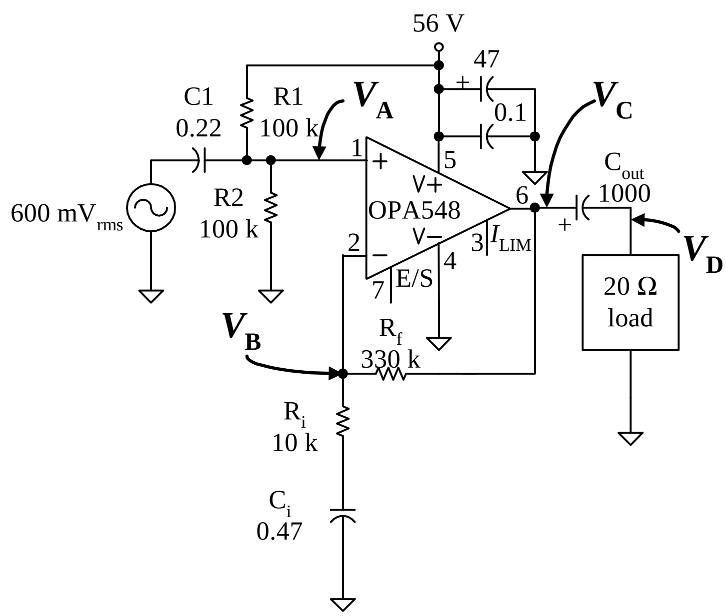

Figure 4-25 Schematic for Problem 4-1

4-2 Explain the purpose of each of the following components in Figure 4-25: C1, R1 R2, C_i, and C_{out}

4-3 The nonideal input offset voltage, bias currents, and offset currents are shown in Figure 4-26. Calculate the indicated voltages and currents. Hint: do the calculations in the indicated order.

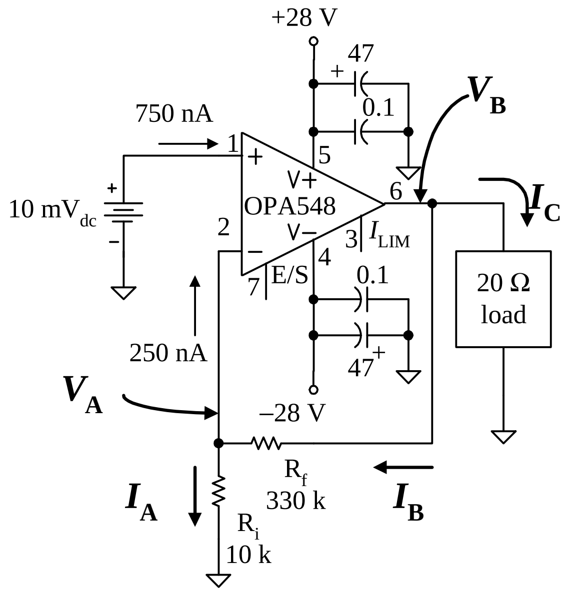

Figure 4-26 Schematic for Problem 4-3

4-4 For the circuit in Figure 4-26, if the 10 mV_{dc} offset voltage source is replaced with a 500 mV_{rms} sinusoid,

a. calculate the high frequency cut-off, f_H.

b. What is the output amplitude at f_H?

c. Is the output signal distorted by the op amp's slew rate limit? Prove your answer with a calculation.

d. Can a larger input be applied without distorting the output? Explain your answer with calculations.

Power Calculations

4-5 An OPA548 is powered from ±28 V, and is driving a 20 Ω resistive load. For a dc input signal, calculate the following at the maximum *load* power: P_{load}, P_{supply}, P_{IC}.

4-6 Repeat Problem 4-5 at the operating point that causes the IC to dissipate maximum power.

4-7 An OPA548 is powered from ±28 V, and is driving a 20 Ω resistive load. For a sinusoidal input signal, calculate the following at the maximum *load* power: P_{load}, $P_{both\ supplies}$, P_{IC}.

4-8 Repeat Problem 4-7 at the operating point that causes the IC to dissipate maximum power.

Heat Sinks

4-9 For the following conditions, determine the OPA548's junction temperature:

$$T_A = 35°C,\ P_{IC} = 10\ W,\ \Theta_{SA} = 4\frac{°C}{W}\text{, mica wafer}$$

4-10 For the following conditions, calculate the largest acceptable heat sink thermal resistance for a OPA548.

$$T_A = 35°C,\ P_{IC} = 10\ W\text{, mica wafer}$$

4-11 Locate the specifications for a heat sink that full-fills the requirements from Problem 4-10, in still air.

4-12 For the following conditions, calculate the maximum power that can be delivered by a sinusoidal signal: to a 20 Ω load, by a OPA548 and a sinusoidal signal from ±28 V supplies.

$$T_A = 35°C,\ \text{mica wafer},\ R_{load} = 20\ \Omega,\ \text{OPA548},\ V_{supply} = \pm 28\ V$$

Audio Power Parameters

4-13 A sound level meter indicates 105 dB_{spl}.

- **a.** How loud is that in qualitative terms?
- **b.** How much pressure is being exerted on the eardrum?
- **c.** If you wanted to lower the volume to that of average conversation, how many TV remote clicks does it take?

4-14 If the 105 dB_{spl} is measured 20 feet from the loudspeaker, how far must you move from the loudspeaker for the sound to drop to 70 dB_{spl}?

4-15 The loudspeaker producing the 105 dB_{spl} at 20 feet is rated at 90 dB_{spl} @ 1 W @ 1m. How much power must you provide to the loudspeaker to produce the 105 dB_{spl} at 20 feet?

4-16 An audio amplifier is capable of outputting 24 V_p. How much music power can be delivered to an 8 Ω loudspeaker without distorting the sound?

4-17 To deliver 10 W to a 4 Ω loudspeaker, how much gain must the audio amplifier have if it is to be driven from a typical consumer electronics signal?

Low Power Audio Amplifier IC

4-18 Design an amplifier circuit using the LM386 to run from a 5 V supply, driving a 4 Ω loudspeaker. Select all components. Determine the heat sink's thermal resistance assuming an ambient temperature of 35°C.

4-19 Repeat Problem 4-18 using a 12 V power supply.

4-20 Alter your design from problem 4-18 to allow a 20 mV_{rms} input to produce 0.5 W into the 4 Ω loudspeaker.

High Power Audio Amplifier IC

4-21 Design an amplifier circuit using the LM3875 to run from ±28 V supply, driving an 8 Ω loudspeaker. Assume that an input signal of 500 mV_{rms} produces the maximum output power. Select all components. Determine the heat sink's thermal resistance assuming an ambient temperature of 40°C.

4-22 Complete the design of the bridge amplifier shown in Figure 4-27. Set the gain to allow a 500 mV_{rms} signal to produce the maximum output power. Calculate the power delivered to the load and the heat sinks' thermal resistance assuming an ambient temperature of 40°C.

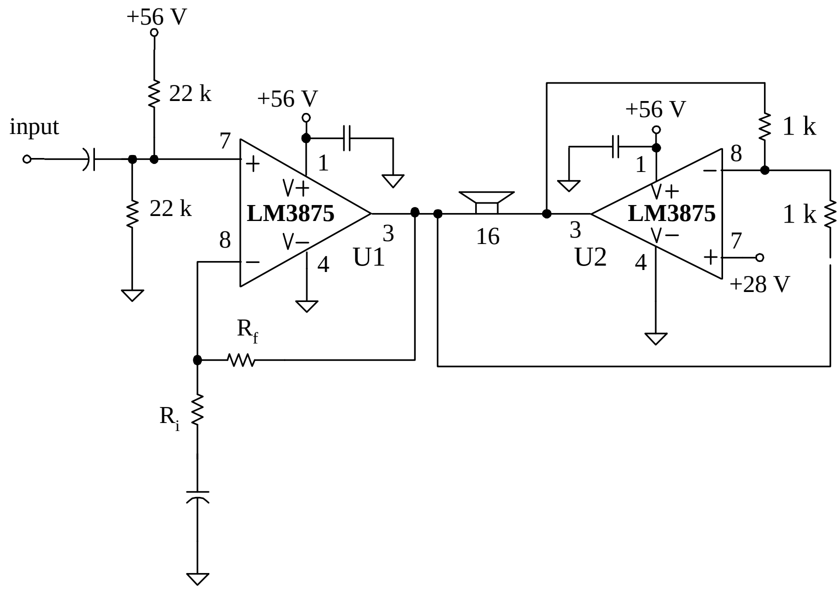

Figure 4-27 Bridge amplifier for Problem 4-22

Power Op Amp Lab Exercise

Prototyping

The pins of the OPA548 are *not* spaced on 0.1″ centers. They also do not tolerate repeated bending. Power supply and load currents of 3 A are required in this exercise. For these reasons it is recommended that a printed circuit board for the OP548 be developed, rather than using the traditional universal breadboard with 0.1″ solderless connections. The layout in Figure 4-28 works well. Notice that the power and load are brought onto the board through screw terminals, and traces are sized to handle the current. But 0.1″ spaced pins are provided to allow you to breadboard the other connections. Decoupling capacitors are provided on the PCB because it is important to keep them as close as possible to the IC's power pins. The diode protects the IC if you reverse the power supply polarities.

This exercise *can* be run without the PCB. Be sure to handle the op amp's leads with great care, and keep all connections between the op amp, power, and the load as short as possible.

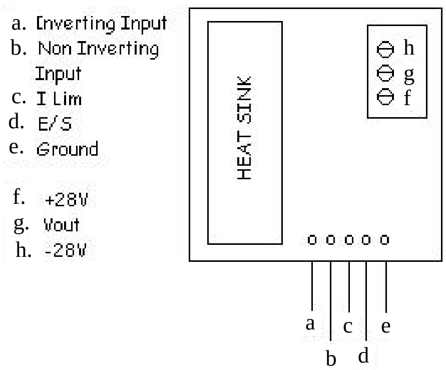

Figure 4-28 OP548 board connections

A. Voltage Follower

1. **1.** Build a voltage follower using the OPA548. Be sure to *rigorously* follow the procedures for prototyping power electronic circuits explained in Chapter 2.
2. **2.** Replace e_{in}, the input signal generator, with a short to common.
3. **3.** Assure the load is set to at least 100 Ω.
4. **4.** Position the board as close as practical to the power supply. Use simple 22 AWG wires from the power supply *directly* to the IC. Keep the leads as short as practical. Apply the ±18 V power.
5. **5.** Measure the input and the output voltage with your digital multimeter. Record *all* stable digits. The output voltage, with the input tied to common, is the **input offset voltage**. It should be a few millivolts. If your output voltage is significantly larger, there is a problem. Do *not* continue until the circuit is working correctly.

6. Replace the short to common at the input with a sine wave of 5 V_{rms}, 100 Hz as measured on the digital multimeter.
7. Display the input and the output on the oscilloscope.
8. When the output is an *undistorted* sine wave, with little offset, measure the input and the output with your digital multimeter. Record all stable digits.
9. Set the input to 0 $V_{rms.}$
10. Switch the power connections to a ±28 V, high current supply.
11. Turn the power supply on while monitoring the supply current.
12. Set the input to 5 V_{rms}. Gradually lower the load's resistance until the supply current is 1 A_{dc}.
13. When the output is an *undistorted* sine wave, with little offset, measure the input and the output with your digital multimeter. Record all stable digits.
14. Return the load to its maximum resistance and turn the power supply off.
15. Calculate the gain and compare it to theory.

B. Noninverting Amplifier

1. Build a noninverting amplifier with the OPA548. Set R_f = 33 kΩ, and R_i = 1 kΩ. Carefully review your layout to assure that it closely follows the guidelines from Chapter 2.
2. Measure the value of R_f and R_i. Record all stable digits.
3. Using these *measured* resistor values, calculate and record the amplifier's theoretical gain.
4. Replace e_{in}, the input signal, with a short to circuit common. Apply ±18 V.
5. Measure the input and the output V_{dc} with your digital multimeter. Record all stable digits.
6. Compare this offset voltage with that from the voltage follower. Is it the same, or did it go up by 34? Is the input offset voltage affected by the gain?

7. Replace the short to common with a sine wave of 100 mV_{rms}, 100 Hz as measured on the digital multimeter. Also display the input and output signals on the oscilloscope.

8. When the output is an undistorted sine wave, with little offset, measure the input and the output V_{rms} with your digital multimeter. Record all stable digits.

9. Calculate the measured gain and compare it to the theoretical gain calculated (with actual resistor values) in step B3.

10. Set the input to 0 $V_{rms.}$

11. Switch the power connections to a ±28 V, high current supply.

12. Turn the power supply on while carefully monitoring the supply current.

13. Set the input to 0.5 V_{rms}. Gradually lower the load's resistance to 8 Ω. The supply's current should indicate about 1 A_{dc}.

14. When the output is an *undistorted* sine wave, with little offset, measure the input and the output with your digital multimeter. Record all stable digits.

15. Calculate the gain at full load, and compare it to theory (step B3).

16. Calculate the power being delivered to the load.

C. Amplifier High Speed Performance

1. Lower the input amplitude to 20 mV_{rms}.

2. Raise the input signal's frequency until the *gain* has fallen to 0.707 of that measured in step B15. Be sure that the input amplitude remains constant.

3.

4. This frequency is the high frequency cut-off, f_H. Calculate the amplifier's gain bandwidth product.

$$GBW = f_H \times A_{\text{low frequency}}$$

5. Change the input to a square wave with a 600 mV_p amplitude and a 5 kHz frequency.

6. Measure the *slope* of the output. This slope is expressed in V/μs. This is the amplifier's slew rate.

$$f_{\text{large signal max}} = \frac{slew\,rate}{2pV_{\text{p out}}}$$

7. **7.** Using your amplifier's slew rate, calculate the highest frequency a 24 V_p sine wave output can obtain before distortion begins.

8. Change the input to a sine wave and adjust its amplitude to 0.5 V_{rms}, at 100 Hz.

9. Raise the frequency slowly until the output begins to distort, changing into a triangle. Record that frequency and compare it to that calculated in step C7.

D. Audio Amplifier

1. Set the input signal generator to 0. Turn the power supplies off.

2. Replace the 8 Ω resistive load with a loudspeaker capable of dissipating at least 50 W.

3. Turn the power supplies on.

4. *Gradually* increase the input amplitude until the output is a clean 100 Hz, 2.83 V_{rms} sine wave. This signal is delivering 1 W to the loudspeaker.

5. Measure the volume in dB_{spl} at 1 m directly in front of the loudspeaker.

6. Increase the input amplitude until the volume is slightly uncomfortably loud.

7. Measure the rms voltage delivered to the loudspeaker. Calculate the power being delivered to the loudspeaker.

8. Measure the volume in dB_{spl} 1 m in front of the loudspeaker. Compare the expected increase in volume with that which you just measured.

9. Move to a point 4 m directly in front of the loudspeaker. Measure the volume. Did the dB_{spl} decrease according to theory?

10. Repeat steps 4 through 8 at 1 kHz and 5 kHz. Discuss the effect of the signal's frequency (tone).

11. Reduce the input signal's input to 0. Replace it with a music source, with the volume all the way down.

12. Gradually increase the music source's volume until the sound is slightly uncomfortable. Repeat steps 7 and 8. Discuss the differences in the power and sound from a sine wave and from a music source.