The peak current delivered to the load is 10 A. This means that each emitter resistor must be capable of handling peak current of 5 A. In some cases, this will govern the required size of the emitter resistors. The peak voltage drop across the emitter resistors will be 1 V, and the peak power dissipation for each resistor will be 5 W.

### Inductance

It is usually recommended that the output stage emitter resistors be noninductive. However, there is little evidence that anyone has taken the trouble to measure the inductance of ordinary wire-wound emitter resistors and to quantify their effect. I am also unaware of any good technical analysis of emitter resistor inductance and its actual effect on output stage behavior. However, given the switching nature of a class AB output stage, one would instinctively assume that very low inductance in the emitter resistors is important.

The inductance of several typical inductive power resistors in the usual range of values used for emitter resistors was measured. The results indicate that conventional (inductive) wire-wound resistors in the 0.1- to 0.5-Ω range commonly used as emitter resistors in power output stages can be expected to have between 16 nH and 70 nH of parasitic inductance. Inductance appears to be smaller with smaller resistances, as expected. A safe worst-case estimate for typical modern output stages would be 120 nH for a 0.33-Ω wire-wound resistor. The axial and radial versions of the 0.33-Ω resistor had nearly identical values of inductance. At the other extreme, a pair of 0.68-Ω metal oxide 2-W resistors in parallel had a very low inductance of 25 nH. This is little more than that of a 1-inch trace.

One thing that must be considered in estimating the impact of small amounts of inductance in the emitter resistors is the expected current rate of change (ISR) in the resistor and the resulting inductive component of the voltage drop. The rate of change will be greatest near the crossover region, where the power transistor is in the process of turning on or turning off. Using ISR = 2.5 A/μs from the example above, each resistor will see 1.25 A/μs. If resistor inductance is 100 nH, we have an inductive voltage drop of 125 mV. This is not insignificant.

### Paralleled Emitter Resistors

One approach to reducing inductance and increasing power dissipation without resort to large wire-wound resistors is to parallel several smaller power resistors to achieve the necessary resistance and power dissipation. Two 3-W metal oxide resistors can be connected in parallel to obtain a suitable noninductive emitter resistor. The penalty here is an increase in occupied board space unless the resistors are stacked.

## 10.8 Output Networks

Emitter followers are the basis of most output stages. They can be picky about their load when it comes to local high-frequency stability. Emitter followers can become unstable if they are lightly loaded at high frequencies or if they are called on to drive a capacitive load.

A capacitive load can also introduce another pole into the output stage frequency response, possibly destabilizing the global negative feedback loop. For these reasons, most amplifiers incorporate an output network that controls the impedance seen by the

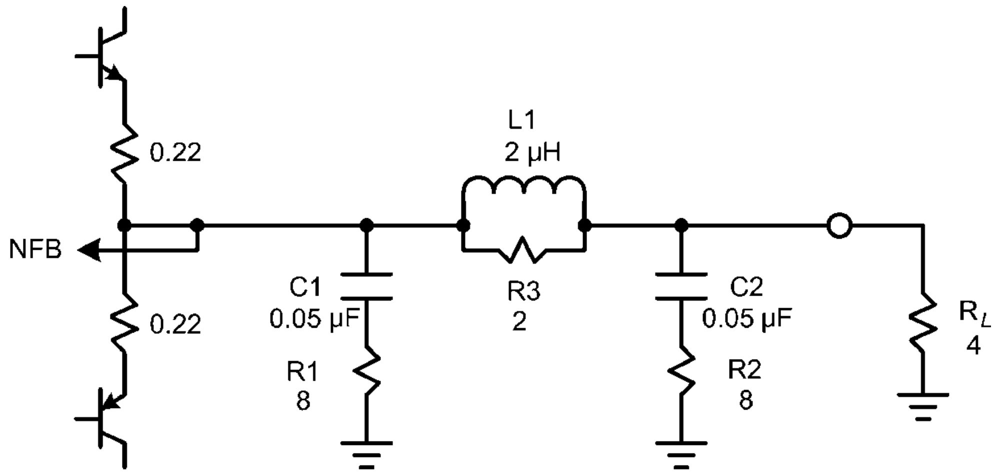


**Figure 10.13** An output network arrangement.

output stage and isolates the load from the output stage at high frequencies. This helps to make the amplifier stable with the great variety of unknown loads it may be presented with by speaker cables and loudspeakers.

Figure 10.13 illustrates a simplified output stage with an output network and a load. The network includes a series R-C Zobel network to ground on the input side and a parallel R-L network in series with the signal path to the load. For generality, a second Zobel network is shown on the output side of the network for variants that will be discussed later.

## The Zobel Network

The series combination of R1 and C1 shunting the output node is called a Zobel network. The purpose of the Zobel network is to ensure that the emitter follower output stage sees at least some resistive loading out to very high frequencies. This is important if the amplifier has no load or if the loudspeaker load becomes inductive at high frequencies.

Power dissipation in the Zobel network's resistor must be considered. At minimum, the resistor in the Zobel network should have a sufficient power dissipation rating to withstand continuous operation of the amplifier at full power at 20 kHz. Consider a 100-W/8-Ω amplifier with a typical Zobel network consisting of 0.05 µF and 8 Ω. This combination will be resistive at frequencies above about 400 kHz. The impedance of the capacitor will be about 159 Ω at 20 kHz. If the output voltage is 28 V RMS, the current in the network will be 176 mA. The power dissipation in the resistor will be 0.25 W. However, in the unfortunate event that the amplifier breaks into a high-power oscillation at ultrasonic frequencies, a small Zobel network resistor will likely get fried. For this reason, Zobel network resistors are often very oversized.

Because the function of the Zobel network is to maintain a resistive load, it is important that the resistor be noninductive. The load presented by the Zobel network should remain resistive up to at least the $f_T$ of the power transistors. An 8-Ω wire-wound resistor with 500-nH inductance will become inductive at frequencies above 2.5 MHz. This argues against the use of wire-wound resistors in the Zobel network unless they are noninductive. Metal oxide resistors with adequate dissipation are a better choice.

## Distributed Zobel Networks

The Zobel network is often built with fairly large components in order to dissipate the power that will be present under high-frequency conditions, especially sine wave testing. Such big components are not usually very good out to very high frequencies.

An attractive alternative is to use multiple smaller Zobel networks in parallel, where each Zobel network is placed very close to one output transistor pair. Smaller components can be used; they can be less inductive, and they can more effectively damp out high-frequency resonances. Such an approach provides a better high-frequency shunt path for output stages employing multiple output pairs in parallel. This can be more important when fast output transistors are being used. An output stage employing four pairs might include four Zobel networks, each consisting of a 33-Ω, 2-W metal oxide resistor and a 0.01-μF polypropylene film or COG ceramic capacitor.

## The Series L-R Network

Most amplifiers include a small inductor in series with the output, usually with inductance between 0.5 μH and 5 μH. At high frequencies the impedance of the inductor increases and isolates the output stage and the global feedback takeoff point from capacitive loads. The inductor is shunted by a small resistor (1–10 Ω) that helps damp out resonances that the inductor might have in combination with load capacitance.

A combination of 1 μH and 2 Ω might be employed in a high-performance amplifier. At very high frequencies the output stage will never see load impedance less than 2 Ω, even if the output is shunted by a large capacitance with low ESR. The impedance of the 1-μH inductor is 2 Ω at about 3 MHz. At frequencies above 3 MHz the load seen by the output stage will be substantially resistive regardless of what kind of load is connected to the amplifier output. The coil will reduce the amplifier's damping factor at high frequencies. The impedance of a 1-μH inductor at 20 kHz is about 0.13 Ω, implying a damping factor of 62 at 20 kHz.

Details of the amplifier output stage and global feedback compensation will govern how small an inductance can be used without risk of instability when driving difficult high-frequency loads. Amplifiers with low open-loop output impedance at high frequencies will usually permit the use of a smaller inductor.

## The Effect of the Coil on Sound Quality

Some high-end-amplifier designers claim that the presence of the output coil degrades the sound. It is hard to justify this solely on the basis of its impact on frequency and phase response when small inductances are used. A 1-μH output coil feeding a 4-Ω speaker load will cause a frequency response droop of less than 0.01 dB at 20 kHz. However, some amplifiers employ a 5-μH inductor in parallel with a 5-Ω resistor. Such a combination reduces the damping factor to only 13 at 20 kHz.

The coil must always be implemented as an air-core coil for best sound quality. Coils implemented with steel or ferrites will suffer nonlinearity, in some cases due to the approach of core saturation. Fortunately, air-core coils with values on the order of only 1 μH are quite small. The coil should be kept away from magnetic materials like steel for the same reason. The coil should also be kept away from devices or circuitry sensitive to radiation from it or from which it can pick up radiation, such as power wires carrying half-wave-rectified signal currents.

### Variations on the Networks

In some cases the shunt Zobel network will be placed on the output (downstream) side of the output L-R network, as shown with R2 and C2 present in Figure 10.13 and with R1 and C1 absent. This will normally work adequately, since at high frequencies the resistor across the coil will act as part of the series resistance of the Zobel network, ensuring loading of the output stage that extends to high frequencies.

Sometimes, the series resistance of the Zobel network in this position (R2) will be eliminated, allowing the shunt resistor across the output coil to effectively take on this duty as well. Placing the Zobel network on the downstream side of the coil can help with physical design, getting it off of the amplifier printed wiring board and perhaps out at the speaker terminals. However, this can also compromise the integrity of the load it provides for the output stage at very high frequencies due to the increased wiring inductance in the path to the Zobel network.

There may also be concerns about where the Zobel is returned to ground (local to the output stage or local to the speaker return). One advantage of the downstream Zobel network is that it provides some degree of high-frequency termination directly at the speaker terminals, possibly reducing the opportunity of EMI ingress from the external world via the speaker cables.

### The Pi Output Network

A further variation on output networks combines the advantages of the two approaches above. In this case a Zobel network is placed on both sides of the output coil as shown in Figure 10.13 when all of the components are present. The upstream Zobel network provides a low-inductance load for the output stage to very high frequencies and allows high-frequency currents to circulate local to the output stage. The downstream Zobel network provides a good resistive termination right at the speaker terminals at high frequencies, helping to reduce RFI ingress and damp resonances with, or reflections from, the speaker cables. Once again, in some cases the downstream Zobel is implemented without a series resistor, reducing it to merely a shunt capacitor.

### Eliminating the Output Coil

Some designers do not employ an output coil in an attempt to eliminate its perceived influence on sound quality. This incurs some risk of instability when driving unusually capacitive loads with little effective series resistance.

In seeking to do without the output coil, three things must be considered.

- Local output stage stability
- Global negative feedback loop stability
- How bad a capacitive load one is willing to tolerate

The likelihood of trouble operating without an output coil can be reduced by employing a large number of output devices operating in parallel so as to greatly reduce effective output impedance. In some cases, the judicious use of base stopper resistors can also help. Finally, amplifiers that have a stiff, high-speed output stage and do not have a high gain crossover frequency for their negative feedback may better tolerate the absence of a coil. I believe that the risk of eliminating the output coil does not justify the perceived gain as long as the value of the output coil is not greater than 1 μH.