Amplifier Design Tips

Introduction

These notes summarize numerous circuit design techniques that have been used in several of the amplifiers that I have built. Many are described in greater detail in the "*Designing Audio Power Amplifiers*" book. These techniques help achieve high performance and quality sound in audio power amplifiers.

Input Circuits

Analog Ground

The clean analog ground is often separated by a small resistance of a few ohms to break ground loops and reduce ground noise. The shunt resistor leg of the feedback network is returned to this same clean analog ground.

Quasi-balanced Single-ended Input

A quasi-balanced input can be achieved with single-ended circuitry with an RCA input by allowing the input ground "signal" to act as the cold-side input to the differential input stage that configures the amplifier with its feedback loop as a closed-loop differential amplifier. This can be achieved by adding a resistor from the input to ground after the series resistor of the input LPF (often 2.2k) that creates the same amount of attenuation that a common-mode signal from the input signal ground. An example is shown in the BC-1 amplifier schematic.

Interconnect Impedance Matching and VHF LPF

A high-frequency low-pass filter is placed right at the amplifier input to suppress EMI. It that also acts as impedance interconnect matching at high frequencies where the shunt capacitance begins to look like a short. The series resistance in the LPF may be 68 ohms as a compromise between 50 and 75-ohm coaxial cable characteristic impedance. A typical LPF capacitor value might be 100-200 pF. This filter is not the LPF that is also normally seen in the input circuit of an amplifier, often with a corner frequency of a few hundred kHz. An example is shown in the BC-1 amplifier schematic.

True Balanced Inputs

Most power amplifiers are single-ended in nature, even if they have balanced inputs with XLR pin 2 hot and pin 3 cold. Sometimes pin 3 is just grounded. In other cases the pin 3 signal is inverted and added to the hot signal. In still other cases a single-op-amp differential amplifier is employed. The best way to implement true balanced inputs with excellent common-mode rejection, high input impedance and low noise is by use of a 3-op-amp instrumentation amplifier. This provides equal input impedances to ground for both the hot and cold signals. A switch selects the single-ended RCA input of the amplifier for unbalanced operation and selects the output of the instrumentation amplifier for balanced input operation.

Input Coupling Capacitors and high-impedance Input

In a JFET-input design, a relatively small film coupling capacitor on the order of 1-2 µF is used in combination with a high-value gate return resistor to provide a high-impedance load on the input coupling capacitor and the preamplifier driving the amplifier. An example is shown in the DH-220C amplifier schematic.

Input and Voltage Amplifier Stages

Unipolar Input Stage with Differential Push-pull VAS

A single-polarity differential input stage that is cascoded and loaded by two identical current sources whose current is controlled in a closed-loop fashion by feedback from the tail of a differential pair second stage. One side of the typically-cascoded differential stage passes through an ac ground-referenced cascode to a current mirror at the negative rail This provides a push-pull VAS. The current mirror employs a helper transistor and is typically cascoded. An example is shown in the MOSFET Power Amplifier with Error Correction schematic.

Cascoded JFET Differential Input Pair

A JFET input differential pair is used to achieve high input impedance and is cascoded to allow high voltage rails in spite of the lower voltage rating of JFETs. The high input impedance of JFETs allows smaller non-electrolytic input coupling capacitors and presents a higher-impedance load to the preamplifier source. An example is shown in the MOSFET Power Amplifier with Error Correction schematic.

Input stage tail current source

A feedback current source with high-value tail series resistance achieves high tail impedance for the input differential pair, even at high frequencies. This provides better common mode rejection at high frequencies and helps reduce EMI susceptibility. An example is shown in the BC-1 schematic.

Clamp Diodes

Back-to-back paralleled diodes are included across the input bases or gates for protection and across the collectors of the differential pair to limit signal excursion under clipping conditions to provide quick recovery and protection for the second differential stage. An example is shown in the BC-1 schematic.

Driven Cascode

The cascode bases are driven from a feedback replica network to apply the same signal as the feedback signal to the cascode bases to operate the input differential pair at a constant V_{ce} or V_{cb} to eliminate input stage common mode distortion and reduce input stage C_{cb} nonlinear capacitance effects. The emulating network is connected in such a way to a positive voltage to provide the desired amount of cascode DC base bias.

DC Servo

A 2-stage non-inverting integrator controls output offset, eliminating the usual feedback shunt arm electrolytic capacitor, eliminating all electrolytic capacitors in the signal path. The DC servo signal path comprises an integrator followed by an inverter. This requires only one integrator capacitor as opposed to the two capacitors required by the single op-amp non-inverting integrator often seen in other amplifier designs. Dual JFET op amps are inexpensive and compact, often taking less space than the two quality capacitors required in single op-amp integrators. Always remember that the DC servo is effectively in the signal path. An example is shown in the DH-220C schematic.

Baker Clamps

Baker clamps are used on the VAS output to provide clean clipping and eliminate VAS transistor saturation. They are usually implemented with a diode connected between the VAS output and a reference voltage that is a couple of volts from the rail. Baker Clamps may be implemented with the reference voltage provided by emitter follower transistors whose collectors are connected to ground. This arrangement can handle the fairly high currents from the VAS transistor collectors during clipping (at least twice the VAS idle current). An example is shown in the Mosfet Power Amplifier with Error Correction schematic.

Baker Clamp Feedback

If the Baker clamps turn on under clipping conditions, and the diode voltage reference voltage is provided by an emitter follower, the emitter follower collector currents can be directed to a ground-referenced resistance across which a voltage is developed. That voltage can be routed as a parallel signal to the input stage feedback input, reducing closed-loop gain and softening clipping in the closed loop. Feedback stability must be assured when the closed loop gain is reduced under these conditions.

Miller Input Compensation

In Miller Input Compensation (MIC), the Miller compensation capacitance is connected from the VAS output node back to the input stage feedback node, rather than to the bases(s) of the VAS transistor(s), providing a single-path feedback compensation circuit in spite of a push-pull VAS that uses a differential pair. The MIC feedback compensation also provides much higher slew rate and feedback around the input stage at high audio frequencies. This longer high-frequency feedback loop is usually compensated by a series R-C network across the input differential pair cascode collectors. An example is shown in the MOSFET Power Amplifier with Error Correction schematic.

Transitional Miller Compensation

The Miller input compensation circuit can be configured to operate as Transitional Miller Compensation (TMC) just as with conventional Miller compensation. In the TMC circuit, the Miller compensation capacitance is split into two series-connected capacitors in a prescribed ratio. The junction of the capacitors is connected to the output signal through a resistor. This results in a 12-dB/octave roll-off in the open-loop transfer function over a prescribed frequency range that lies below the unity-loop gain frequency. This increases the in-band loop gain while preserving good feedback stability. An example is shown in the "*Designing Audio Power Amplifiers*" book.

Feedback Networks

Often consisting of a simple resistive divider, the feedback network is especially important because any distortion in it is not reduced by negative feedback. Resistors are imperfect, creating voltage-dependent and current-dependent distortions and having temperature coefficients that can cause low-frequency distortion as they heat up and cool down in response to low-frequency signal swings. The power dissipation rating of the feedback network resistors should be at least 10 times that experienced at full rated power. Two or more series feedback resistors can be wired in series to reduce voltage-dependent resistor distortion.

Output Stage

Bipolar Output Stage Triples

Many power amplifiers with bipolar output transistors have only a double emitter follower (Darlington) output stage. This provides inadequate current gain to provide high output current and reduce nonlinear loading the VAS. Three stages of current gain should be provided for the best amplifier performance and high-current output capability. Such an arrangement is the triple emitter follower, sometimes called the Locanthi T circuit. Other output triples can also be used, such as those incorporating a diamond buffer. An example is shown in the BC-1 schematic.

Metal Oxide Film (MOF) Emitter or Source Resistors

3-watt Metal Oxide Film (MOF) resistors (or multiples thereof if necessary) are used instead of non-inductive wire-wound resistors. MOF resistors are inherently non-inductive and can withstand very high peak current and brief intervals of high power dissipation. Ideally, these resistors are sized to withstand continuous full power operation into a 4-ohm amplifier load. An example is shown in the BC-1 schematic.

Distributed Zobel Networks

Tight, low-inductance Zobel networks are important for best high-frequency stability, so each output pair has its own local Zobel network connected from the output node to ground. This also allows the use of smaller MOF Zobel resistors to dissipate the total Zobel network dissipation at high frequencies. These multiple Zobel networks also damp the wiring inductance of the output rail. This is especially effective in designs employing a large number of output pairs spread over a considerable distance.

Load-side Zobel Network

A Zobel network is also placed on the output side of the series R-L network, preferably close to, or at, the output terminals for further damping and to suppress the entry of EMI from the speaker cables, which can act as an antenna. This network also suppresses large flyback output voltage swings in the event that a protection/muting relay is opened. An example is shown in the BC-1 schematic.

Asymmetrical Source Resistors

For MOSFET output stages, series source resistors can be used, with a larger resistance in the sources of the N-channel devices to reduce their effective transconductance to better match the inherently lower transconductance of the p-channel output transistors, reducing crossover distortion by as much as a factor of 2. In some cases, the p-channel source resistors are eliminated entirely.

Output Transistor Physical Polarity Interleaving

Here output N/P pairs are located adjacent to each other on the heat sink, as opposed to all of each polarity located together. This tends to locally cancel the half-wave magnetic fields created by the class A-B output stage. Such nonlinear magnetic fields can create distortion in circuits exposed to them. An example is used in the BC-1 layout.

Shorted-turn Nonlinear Magnetic Field Suppression

If a 4-layer PCB is used, the top copper layer can be used to implement a conducting plane covering the output stage wiring traces on the inner layers. Similarly, such a conducting plane is also implemented on the bottom (writing side) of the PCB. Each end of these plane strips is connected together with numerous vias, forming a shorted turn encompassing the output stage wiring that is internal to it. This shorted turn suppresses the radiation of the class A-B magnetic fields created by the nonlinear output stage currents. The copper belt thus formed is connected to circuit ground at only one point. This arrangement is not unlike a copper transformer belly band (flux band), acting as a shorted turn to the stray magnetic flux.

DoubleCross Bipolar Output stage

For bipolar output stages consisting of 2 or more output pairs, one pair operates in a heavily-biased quiescent state that would create gm-doubling crossover distortion. A second pair is operated with retarded bias, so that as output current swing increases beyond the idle bias of the first pair, transconductance of the output stage is increased to compensate for the reduced transconductance as a result of the gm-doubling effect created by the over-biasing of the first output pair. This creates two crossover points that are displaced symmetrically about the zero-output current point, enabling the first pair to be heavily biased and violate the Oliver class A-B biasing criteria. However, the Oliver criteria can be enforced at each of the displaced crossover points by proper selection of the retarding of the second-pair turn-on. This arrangement permits an arbitrarily large class A region without incurring increased crossover distortion, relegating any crossover distortion to occurring at higher power levels where it will be less noticeable and smaller in comparison to the signal. The primary output pair acts as a conventional class AB output stage, albeit often over-biased beyond the Oliver criteria. The secondary output pair has retarded base drive and turns on just as one of the primary pair shuts off. In some output stages, like the Locanthi T circuit triple, DoubleCross operation can be achieved simply by connecting a resistor across the bases of the secondary pair after the base stopper resistors to retard turn-on. An example is shown in the "*Designing Audio Power Amplifiers*" book. This was tested on the BC-1 power amplifier.

Quasi Isothermal Output Stage

If a DoubleCross output stage is employed, the quiescent bias current can be arbitrarily high if thermal and other considerations are observed. This creates a larger class-A region and increases the power dissipation in the output stage. In a conventional class AB amplifier, power dissipation in the quiescent state is quite low and increases with power output until a maximum value occurs, often in the vicinity of 1/3 rated power. Beyond that, power dissipation decreases somewhat. At 1/8 power, dissipation is moderate and smaller than that at 1/3 power. In practice with music, average power dissipation will rarely exceed that at 1/8 continuous power, or lower. Heat sink temperature and output transistor junction temperature can thus change significantly between the quiescent state and moderate power. This can make it difficult to maintain optimum bias for least crossover distortion over these temperature ranges. If a significantly higher quiescent bias current is used in a DoubleCross output stage, the quiescent power dissipation can be increased to that value corresponding to 1/8 average power (or less), thus tending to flatten the power dissipation versus average power curve, pushing it in the direction of isothermal behavior. This can significantly reduce the heat sink and junction temperature swings.

Twin V_{be} Multipliers

In some designs the transistors comprising the output stage and affecting bias temperature dependence are in different thermal environments. This is the case with a triple emitter follower output stage (Locanthi T circuit) where the predriver transistors are not mounted on the heat sink while the driver and output transistors are mounted on the heat sink. In some cases, the predrivers will be mounted on a small heat spreader on the PCB along with an associated V_{be} multiplier transistor. An example is shown in the BC-1 schematic.

Emitter Follower Drive for MOSFET Output Transistors

Some MOSFET power amplifiers have the output transistors driven directly from the high-impedance output of the VAS, justifying this by the fact that the gate input impedance is very high. But this is so only at low frequencies. In high-quality designs, the output MOSFETs should always be driven by an emitter follower buffer or equivalent circuit like a diamond buffer. An example is shown in the DH-220C schematic.

Folded Emitter Follower Drivers for MOSFET Output Stages

A folded emitter follower comprises an emitter follower transistor of opposite polarity to that conventionally used in an application. It can be used to drive the gates of the MOSFET output devices. When driving an N-channel source follower output MOSFET, for example, a PNP emitter follower whose emitter is pulled up with a current source can be used. Rather than costing a V_{be} drop in drive voltage, it results in the addition of a positive V_{be} voltage drop to the DC level of the driving signal. This is not unlike the first stage of a diamond buffer. In the simple case, the collectors of the folded emitter follower transistors are connected to the opposite rail, requiring that these transistors withstand a maximum of twice the rail voltage. Alternatively, the collectors can be connected to the output node, thus being bootstrapped and having much lower peak voltage across them. The bootstrapping also reduces the capacitance seen by the VAS output. Since the bootstrapping is a feedback circuit, the collectors are preceded by a simple R-C low-pass filter with a 3-dB frequency well above the audio band. Diodes are connected from base to collector to keep the transistors out of deep saturation during over-current conditions. This circuit also limits the gate-source voltage applied to the MOSFET in either polarity, obviating the need for gate protection Zener diodes.

MOSFET Parasitic Oscillations

Both lateral and vertical Power MOSFETs can be very fast, since they are majority carrier devices and have no minority carrier charge storage. Their inherent speed is largely limited by their inter-electrode capacitances (C_{gs} and C_{dg}) and effective gate resistance. They also have gate inductance due to bond wires and external wiring. Resonant circuits can thus be formed that create oscillator topologies like Colpitts and Hartley oscillators. These can resonate at very high frequencies, often between 20 MHz and 100 MHz. These parasitic oscillation effects are discussed in the MOSFET Power Amplifier with Error Correction paper. Often these resonances are damped by the introduction of a resistor in series with the gate, reducing the Q of the associated gate inductance. One tradeoff is that the series gate resistance can slow down the MOSFET. Another thing making things tricky is the fact that the inter-electrode capacitances can change significantly as a function of signal swing. Paralleled MOSFETs can also be more prone to parasitic oscillation. The use of very short interconnect wiring is important.

Power Supply and Grounding

Star Grounding

Star grounding generally refers to returning all grounds to a single point, usually in the power supply where the ground ends of the reservoir capacitors meet. This in principle tends to keep ground currents flowing only in intended paths, reducing corruption in other grounds due to currents flowing in their ground paths. In reality, it is virtually impossible and impractical to fully realize star grounding. Instead, in some amplifiers, true star grounding is not observed, but one example might be taking the main circuit ground on a PCB back to the star ground point and taking the speaker ground back to the star ground point. In any case, the key concept is to manage where the currents flow. They will always take the path of least resistance. An approach that is effective is to route the main PCB circuit ground back to the star point and connect the speaker ground at the circuit ground on the PCB local to the output transistors. This is made more effective by including modest reservoir capacitors at the power transistors, such as 1000 uF, forming a local star ground in the vicinity of the output stage, where the speaker ground is connected. This closes the loop of large output signal currents at high frequencies right at the PCB. One might refer to this arrangement as a star-on-star grounding architecture. Earlier stages in the amplifier, where smaller linear currents flow, can get their ground from this on-PCB ground as well.

Quiet Rectifiers

Discrete soft-recovery rectifiers with Zobel network snubbers across each of the 4 rectifiers in a bridge rectifier can be used instead of the usual square four-terminal bridge rectifiers, which tend to be slow. Such individual rectifiers are available in TO-220 packages that can be attached to heat sinks or the chassis.

Progressive Decoupling with Zobel Network Arrangement

In this approach, the main power rails are connected to the output stage and include local 1000-uF reservoir capacitors whose grounds are connected together by a small copper island whose center is connected to the circuit ground at a single point, resolving their half-wave class AB currents locally without dumping them into the circuit ground. A low-impedance decoupling low-pass filter passes the rail voltage to the driver transistors. The low impedance of the LPF also acts as a Zobel network to damp any resonances on the mail rails. Similarly, another such decoupling network of somewhat higher impedance supplies rail power to earlier stages in the amplifier circuit. An example is shown in the BC-1 schematic.

Independent IPS/VAS Power Supply

Fed in parallel with the main rail rectifier and reservoir capacitor network, a smaller rectifier and reservoir capacitor network can be implemented to supply rail voltage to the driver and earlier stages of the amplifier. Its voltage is much less subject to brief main-rail droop and ripple.

Boosted Rails

In similar fashion to the above, a boosted low-current supply can be implemented by feeding the rectifier from additional low-current low-voltage windings connected in series with the main high-voltage windings. If desired, these additional windings can be implemented by adding some turns to the perimeter of a toroidal power transformer (which will usually yield 0.5 to 1 V/turn). Providing boosted rails to the earlier circuits in the amplifier provides extra headroom for those circuits, permitting slightly higher signal voltages to the output stage. This is especially helpful in amplifiers employing MOSFET output stages, where higher forward gate voltages are needed to drive the output transistors to high current. This can be especially important for amplifiers employing output stage error correction. If desired, the boosted rails can be regulated. An example is shown in the MOSFET Power Amplifier with Error Correction schematic.

Local Reservoir Capacitors

Additional reservoir capacitors of 1000-2200 µF can be placed on the PCB immediately adjacent to the output power transistors to provide local very low impedance power rails. The grounds of these capacitors should be close to each other and connected with a wide trace whose center tap is connected to circuit ground. An example is shown in the BC-1 schematic.

Pi Network Reservoir Capacitor Network

The main reservoir capacitors for each rail can be split and separated by a low-value series resistance of a few tenths of an ohm. This arrangement further reduces ripple and reduces rectifier spike feedthrough. For example, a 15,000 µF reservoir capacitor preceded by a 0.5-ohm series resistor will form a 20-Hz LPF. Such an amplifier might have a total of 30,000 uF for each rail.

Rail-reversal Protection Diodes

If fuses are used in the power supply rails, and one opens, the associated rail can be driven to the opposite polarity by current still flowing in the amplifier from the opposite rail. This reversal of rail polarity on one side can damage components in some cases. Rail reversal diodes from each rail to ground can prevent this situation from occurring.

Protection Circuits

Natural Current Limiting

In a bipolar amplifier, diodes connected from either side of the Vbe multiplier to the output rail will limit maximum current when the voltage drop across the power transistor emitter resistor exceeds approximately the voltage of the Vbe multiplier plus one diode drop. Two diodes or a diode plus a Zener or LED can be used if a larger voltage threshold is desired. A similar arrangement can be used with MOSFET output stages, modified a bit when the MOSFET gates are driven by folded emitter followers, as discussed above. The latter arrangement naturally protects the gate-source voltage from over-voltage, obviating the need for gate Zener diode gate protection circuits. This limits the current during the brief interval before a protection circuit opens the speaker relay. Examples are shown in the BC-1 and DH-220C schematics.

Speaker Relay Muting and Fault Disconnect

A speaker relay is often used to open the circuit to the loudspeaker to prevent thumps during power-on and power-off intervals and to protect the loudspeaker from faults like DC at the output from damaging the speakers. The relay will close at turn-on after a delay and turn off immediately after power is turned off or once the power supply rail voltages fall below a certain value. The relay swinger is normally connected to the loudspeaker load, with the NO contact connected to the amplifier output and the NC contact connected to ground. Connecting the NC contact to ground tends to suppress flyback voltages at the loudspeaker when the relay is opened while current is flowing. ICs are available that monitor circuit conditions to control the relay. An example is shown in the BC-1 schematic.

Post-relay Zobel Network

Suppression of flyback voltages during the speaker relay contact transition period to the open state is also helped by the use of a Zobel network placed on the load side of the relay. An example is shown in the BC-1 schematic.

Printed Wiring Board Material

Most power amplifiers are implemented by using ordinary FR4 printed wiring board material. The FR4 dielectric is a bit nonlinear, resulting in what has been called "hook" in sensitive circuits, first described by Tektronics. Better PCB material can be used for amplifiers of the highest quality. Sometimes Teflon is mentioned, but more cost-effective materials are available that can better withstand the higher reflow temperatures required for use of ROHS lead-free solder. These have higher glass transition temperatures and lower dissipation factor than FR4. These materials include Nelco N4000-6, Panasonic Megtron 6, 7 or 8 and Rogers RO3000 or RO4000. These materials are often used in high-frequency applications up to 10 GHz and above. In some amplifier designs, the use of 4-layer PCBs can provide more routing opportunities to provide better signal integrity, lower inductance and local ground islands or global ground planes.