Douglas Self's 8 Distortions (and a Few More)

In 1996, Douglas Self published his now famous 'Audio Power Amplifier Design Handbook', in which he described the 8 key distortion mechanisms in audio power amplifiers, using the very well understood Lin topology to demonstrate how these mechanisms affected measured performance. To avoid controversy in a field as subjective as hi-fi , he purposefully did not call it the 'perfect' or 'ultimate' amplifier, but simply the 'blameless' amplifier because he showed that all of the distortion mechanisms could be reduced to such low levels that they could effectively be disregarded as having any deleterious effect on the sound when contrasted with the effect of other components in the signal chain – source, speaker/cable system, speaker/room interface. This appendix lists the 8 distortions plus a few additional ones and also includes some information on the magnitude of the distortion, and a very brief description of the cure. For the problem magnitude figures, I gleaned these directly from his book, and in some cases I investigated and arrived at the numbers I show using LTSpice modeling. I included some comments on the level of distortion to be expected after implementing the cure as well.

#1: Input Stage Distortion
Problem Magnitude: As much as 1% open loop distortion in a badly unbalanced LTP
Cure: ensure input stage LTP current is well balanced between the two halves – means <0.1% current imbalance. How? Use a mirror load on single ended designs; tweak LTP collector load resistor values on balanced designs, or use a current mirror and CMCL techniques.
Effectiveness of Cure: Open loop distortion of the front end can easily be made <0.01% i.e. up to 2 orders of magnitude improvement

#2: VAS Distortion
Problem Magnitude: As much as 0.5% open loop distortion
Cure: Ensure high VAS local loop gain by using a two transistor beta enhancement circuit or by cascoding (conventional or Hawksford). Use low Cob (3pF max) transistors for the main Vas transistor, or cascode. Use a high quality capacitor for Cdom – a 500V silver mica component is a good choice for this task.
Effectiveness of Cure: open loop distortion reduced to under 0.1% (no VAS load condition)

#3: Output Stage Cross-over Distortion (class B and class AB amplifiers) plus additional 2nd order output distortion mechanisms
Problem Magnitude: anything from just plain sub-optimal at 0.5% to 3 or 4% open loop at rated load but this can be much higher if the output is biased heavily away from the ideal class B quiescent current.
Cure: Set output bias current at 26mV across the associated emitter degeneration resistors; For the 2nd order mechanisms, use the Locanthi 'T' topology and employ a speed up cap across the resistor that ties the bases of the PNP and NPN output pairs together to reduce or obviate switch-off artifacts. Ensure that the driver and pre-driver always remain operating in class A mode under all load conditions. Ensure output stage bias conditions are stable over temperature; use base stoppers to ensure no emitter follower parasitic oscillation, or use an RC base stopper in the driver bases – often required in triple followers (this is used in the e-Amp -27 Ohm and 1nF cap networks in the bases of the drivers)
Effectiveness of Cure: Open loop distortion well under 0.5% at rated load (resistive), with 0.2% possible

#4: VAS Loading Distortion
Problem Magnitude: In the closed loop condition 0.3% would be a typical figure going from 8 Ohm to 2 Ohm load on a EF double
Cure: Buffer the VAS. For the ultimate performance, use an EF triple; additionally, use 'sustained beta' output devices (MJL1302/1381); use multiple output pairs in parallel (this last cure is however expensive)
Effectiveness of Cure: A triple along with sustained beta devices can reduce the problem to 2ppm to 3ppm in the closed loop condition going from 8 ohms to 2 ohms load. This is at least 3 orders of magnitude improvement over a simple buffer solution.

#5: Rail Coupling Distortion
Problem Magnitude: 100's of PPM in a bad case (closed loop condition)
Cure: STRICT grounding order: Ensure the decoupling capacitors on the output stage and on the small signal front end stages are correctly ordered; do not mix power and ground decoupling capacitor return paths – keep then separate; ensure the Zobel network ground return is separate from the PCB decouple ground; Ensure the speaker return is taken back to the common ground, and not back to the PCB and thereby connected to the decouple ground.
Effectiveness of Cure: Problem reduced to low 10's of PPM typically, but with enough care can be into single digit PPM levels

#6: Induction Distortion
Problem Magnitude: 100's of PPM typically in closed loop condition
Cure: Keep supply lines (which are full of half wave rectified currents with high, wide bandwidth harmonics) well away from the decoupling ground, the front end and the speaker output.
Effectiveness of Cure: low 10's of PPM typically

#7: Negative Feedback Takeoff Distortion
Problem Magnitude: 10's of PPM typically in closed loop condition
Cure: take negative feedback point off from AFTER the output rail and just before the Zobel network, or, if this is not possible, ensure the feedback pick-off point is at the exact electrical center of the output rail.
Effectiveness of cure: single digit PPM levels in closed loop condition

#8: Electrolytic Capacitor Distortion (this refers specifically to DC blocking electrolytic capacitors coupling audio signals)
Problem Magnitude: Typically low single digit % distortion in the closed loop condition at low frequencies. Distortion rises as frequency drops
Cure: Use large values for the feedback decoupling capacitor (e.g. 500uF) in order to reduce the AC voltage across the capacitor; use a unipolar device or create one by using two back to back electrolytic devices (1000uF x 2); bypass the main cap with a good quality polystyrene capacitor that is specified for HF operation. Typical value would be 0.1uF to 1uF.
Effectiveness of Cure: in closed loop condition, distortion is reduced by all counts to midband distortion of amplifier – so 10's of PPM

Additional Distortions (non – Self)

#9: Slewing Induced Distortion and Transient Inter-modulation Distortion
Problem Magnitude: Only occurs on fast rise time music signals, and generally not an issue on modern amplifier designs due to awareness of mechanisms that cause it
Cure: Ensure amplifier slew rate is at least 2x to 3x the worst case input signal rise time and/or limit the input signal bandwidth such that it is 2 to 3 times less than the power amplifier feedback loop unity gain frequency which is typically around 850KHz
Effectiveness of Cure: completely avoidable

#10: Phase Inter-modulation Distortion
Problem Magnitude: It can be measured but is still being debated – is it really a problem, and even if so, is it audible?
Cure: Use adequate levels of negative feedback and/or increase the small signal loop bandwidth (or the open loop bandwidth) by applying degeneration to the LTP. See Robert Cordell's definitive article on this subject at
Effectiveness of Cure: Completely avoidable

#11: Additional Component Distortions
1. Polyester Capacitor Distortion. (10's of PPM distortion). Avoid them and use polystyrene or polypropylene which completely obviate the problem. See 'Small Signal Audio Design' by Douglas Self page 54 for details.
2. Thick film resistor non-linearity – specifically SMD types (10's to 100's of PPM). These are highly non linear and their resistance varies with applied voltage - the problem gets worse as the size decreases. Always use metal film resistors for signal handling which do not show these distortions (under 1ppm). See the reference above, pages 42-51 for an important discussion on resistor linearity.

Summary and Overview

In general terms if we assume a moderately badly biased class AB output stage, and a 20KHz loop gain of 30db, the 20KHz THD in an amplifier that does not attend to all of Self's mechanisms, a closed loop distortion figure of between 0.5 and 1% at nominal output can be expected. In a well designed amplifier in which all of Self's mechanisms have been attended to, a figure in the region of 20 to 30ppm is achievable at the same output power, with the output stage distortion accounting for at least 60 to 70% of this figure. This assumes conventional Miller compensation. Lower figures are achievable using TMC or TPC compensation. The small signal and pre-diver and driver stages alone (so the class AB/B output stage is excluded) can easily achieve single digit PPM levels of 20KHz THD at the full voltage output swing.

For a very illuminating and instructive walk through on amplifier distortion reduction, see Robert Cordell's book '***Designing Audio Power Amplifiers'***