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Noise and Distortion Mechanisms Encountered in Switching Audio Power Amplifier Design

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ABSTRACT

When designing a switching power amplifier, many phenomena are encountered which leave the designer wondering why performance falls short of what theory predicts. While many sources of non-linearity and noise in the conversion process are known and intrinsic to the sub-systems involved, other sources of error are more subtle. The intent of this paper is to outline the noise, distortion and error mechanisms commonly encountered in practice when designing a switching (Class-D) power amplifier. By understanding the root cause of these mechanisms, a more heuristic approach can be employed in switching power amplifier design. The focus will be on analog systems employing clocked, naturally sampled modulators, but the bulk of the material will be broadly applicable to any modulation scheme.

1 Introduction

There are many forms of switching amplifiers, differentiated by Class (AD, ABD, BD) and modulation scheme (clocked, self-oscillating, digital) but many share functional elements and error mechanisms.

In the context of this paper, distortion is meant to include both harmonically and non-harmonically related frequency artifacts, phase or frequency response shifts, added noise and settling errors (clicks and pops).

2 PASSIVE COMPONENTS

Except for sensitivity to high field strengths typically found inside switching amplifiers, the general guidelines presented here apply to any analog signal chain.

2.1 Capacitors

Capacitor induced distortion comes from several sources: voltage coefficient, temperature coefficient, ESR/dissipation factor (DF), frequency dependence, stability over time, and, to a lesser degree, dielectric absorption (DA). Capacitors with good performance in these areas will produce the best amplitude linearity.

Class 1 (C0G, NP0) ceramic capacitors are well suited for audio, having low voltage coefficients, low frequency dependence, low dielectric absorption and excellent temperature stability. Class 2 and 3 ceramics are poor in these areas and should never be used in signal chain. Higher voltage ratings offer superior distortion performance.[2]

Piezoelectric effects exist in all ceramic capacitors with ferroelectric dielectrics. Class 1 capacitors lack piezoelectric effects as these dielectrics are not ferroelectric. Class 2 or 3 used as pulsed DC or signal detection may produce audible noise. Lowering the stress with a higher voltage rated part may help.[3]

Film capacitors in general have low voltage coefficients, low DF, and good long-term stability but their temperature stability and DA are strongly related to their dielectric and construction technique.

The two film construction types are Metalized Film and Film-Foil (AKA Metal Foil). Film-Foil use actual metal foil whereas Metalized Film use vacuum deposited aluminum. Film-Foil has lower ESR and DF than Metalized Film and is preferred for audio use.

Wound films introduce a nonlinear inductive component which can vary reactance with amplitude and be sensitive to stray fields prevalent in switching amplifiers. Opt instead for stacked films.

The following dielectrics are available in film caps:

PE/PET	Polyester (Mylar)
PPS	Polyphenylene-sulfide
PP	Polypropylene
PS	Polystyrene
PEN	Polyethylene naphtholate
PTFE	Polytetrafluoroethylene (Teflon)
PC	Polycarbonate
Kapton	Polyimide

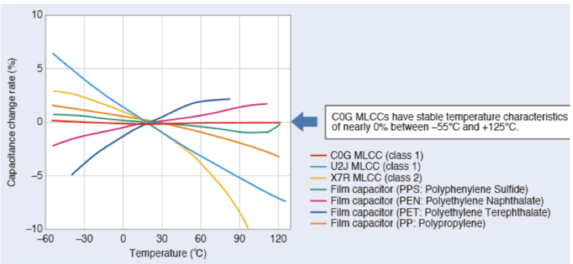

Figure 1. Shows how temperature coefficient varies among some popular capacitor types.[4]

Overall, PS, PE and PTFE are recommended for high performance analog design.[1] Where smaller capacitance values are required, several Class 1 ceramics in parallel perform better in many cases.

Where a large capacitance is needed, such as DC blocking, electrolytics are commonly employed. Having good voltage stability, they exhibit poor DA. When used as a DC block, fc should be set at least an order of magnitude lower than 20Hz. Too low a corner frequency can result in settling errors which manifest as start-up and shut-down clicks and pops. Metal cans of electrolytics can pick up stray fields.

To minimize temperature coefficient effects, choose components with low DF. Prevent small, low mass parts such as SMT ceramic or film capacitors from thermally coupling to resistors or active devices which may result in nonlinearities related to the capacitor's temperature coefficient.

2.2 Resistors

Resistor induced distortion comes from the resistor's voltage and temperature coefficients. While related, they exist as separate mechanisms.

Thermal modulation is the dominant source of resistors distortion, typ. 3rd harmonic.[2] Physically small resistors or those run close to their power limit, can thermally track signal excursions. The problem generally occurs in the 5 to 200Hz range. Related to V^2/R, smaller values inherently perform worse. This runs counter to noise considerations, where smaller values produce less noise. Use larger SMT packages and limit the power to SMT devices to <20mW peak buy using series-parallel devices.

Resistors have voltage coefficients, where the voltage gradient causes the resistivity to change, independent of power. Keep the voltage across the resistor low by using multiple resistors in series.

SMT resistors are available as either thick film or thin film. Thin film resistors are more accurate, have better temperature coefficient, are more stable and exhibit lower current noise and frequency stability compared to their thick film counterparts.

Metal foil resistors are a good choice for DC but show greater thermal modulation than there temp co may suggest. Metal films are akin to thin films and share many of the same advantages.

Wire would resistors are not recommended for audio due to their ability to pick up stray fields. Non-inductive winding technique such as Ayrton-Perry still exhibit some inductance and should be avoided.

The Barkhausen effect produces low level magnetic domain induced distortion responsible for resistor induced noise measured in excess of the predicted thermal value.[4]

2.3 Inductors

An air core inductor is the most linear core possible, though large inductance values require the use of relatively nonlinear, high permeability cores to minimize turns and leakage inductance. When air core inductors are used, they should be distanced from ferromagnetic materials which affect linearity.

Ferrites on amplifier inputs should be distanced from ferromagnetic materials such as screws, connectors and chassis. Keep adjacent inductors at 90-degree to each other to minimize coupling.

For audio distribution transformers where high permeability is desired, high Nickle content alloys are used. High resistivity of the magnetic material and low hysteresis and eddy current loss are desirable so that overall core losses are minimized.[5]

Inductors used in crossover networks use air cores and, for larger inductances, laminated iron bars. Thought the core is nonlinear, most of the energy is stored in the air gap, which dominates the linearity.

Switching amplifier reconstruction filters use either powdered iron or gapped ferrites. Typical Powdered Iron materials are Micrometals #2 and #14 which have low core and hysteresis loss and high BH linearity. Toroidal construction is typically employed to contain magnetic fields. Multiple inductors should be kept apart or at 90 degrees from each other.

Using powdered iron cores, an amplifier's THD+N measures lowest on a new core then settles to a slightly higher value with subsequent measurements. It's been proposed that the mechanism behind this observed phenomenon is residual flux in the core, but this has not been substantiated to my knowledge.

Inductors employing gapped ferrite store the majority of the energy in a large air gap. This technique exploits the linearity of air, while retaining the high permeability of the Ferrite. The fringing flux associated with the large air gap can couple to the winding, increasing losses and introducing nonlinearity through proximity effects. The situation is manageable by distributing the gap or spacing the winding sufficiently away from the gap(s) to avoid being affected.

Compared to Powdered Iron designs, the gapped ferrite is free of residual flux concerns, promises slightly better linearity but tends to be slightly larger and potentially less space efficient given its form factor. It can also utilize self-shielding cores.

3 DIODES

Input TVS diodes used to protect against ESD may begin to partially conduct as the voltage approaches their breakdown rating. Ensure these parts have ample voltage margin to avoid conduction through the full intended voltage and temperature range. A similar concern is the leakage of input clamping diodes. Low leakage types should be chosen or use a diode connected transistor instead.

4 OP AMPS

Phase inversion can occur when the input stage is driven outside it's specified range. Causes include using progressive stages run from different supplies or those having OP swings greater than the following part's IP stage range. Input clamping diodes can be used. Ensure there is a current limiting element to protect these diodes during overload.

Inverting topologies will show lower 2nd harmonic distortion above 5KHz.[1] Having one input leg grounded also helps reject common mode noise. If a NI topology is used, balance the source impedance on both legs to help reject common mode noise, lower distortion and reduce current induced offsets.

Op amp THD+N curves are measured at specific levels and may be meaningless at higher currents and loads which the part may also be rated for.

Pull any signal detection networks directly at output of op amps, before coupling caps. The transient loading of these types of circuits will pull against any finite source impedance and create distortion.

AM modulated noise can get onto the output of an op amp above its loop crossover frequency where the output impedance is very high. Noise passes unimpeded through the feedback network to the input where, due to the P-N junctions if the bipolar input stage, act as an AM demodulator. The lower frequency demodulated components then reappear on the output. This same mechanism is equally applicable to noise getting in through other paths.

An effective solution is to use FET input op amps which are free of demodulation effects. Alternately, resistance can be added in series with each input leg to limit currents and work with the op amp's input capacitance. HF filtering can lower the loop bandwidth and make the op amp more sensitive. A PI filter can be added directly at the op amp output.

5 COMPARATORS

Pulse width distortion (PWD) occurs when the switching transitions from L→H or H→L do not occur at the same relative points in time. PWD results from the *difference* in propagation delay between H and L going edges. This effect is greatest with small signals operating near 50%D and is a function of temperature, loading and overdrive.

Propagation delay changes the phase response of control loops, affecting self-oscillator switching frequency and clocked modulator control dynamics.

Both absolute and relative propagation delays are functions of input overdrive and vary as the driving signal moves through its voltage range.

A comparator is effectively a high gain op amp with no internal frequency compensation. Ein and Iin noise sources are intrinsic but rapid and well-defined crossing over of inputs negate their effects. Where noise comes into play is when relatively slow-moving signals exist at the comparator input. The trigger tracks the voltage of the noise, causing PWM jitter which translates to amplifier output noise.

Use relatively large signals at the comparator input for best noise and distortion. A triangle waveform using the maximum comparator input range minimizes noise and contributes to increased effective overdrive, helping to minimize propagation delay.

The output swing of an op amp may exceed the input common mode (IPCM) range of the comparator it is driving. Input transitions occurring outside this range can be non-deterministic and may change with temperature or device lot. Pad the op amp output if necessary.

6 MODULATOR DISTORTIONS

Foldback distortion is inherent to the modulation process. Intermodulation products manifest as sidebands on either side of fs at integer multiples of the modulating signal. Spectra differs somewhat between class AD and BD amplifiers, but the fundamental mechanism remains (Fig. 2).

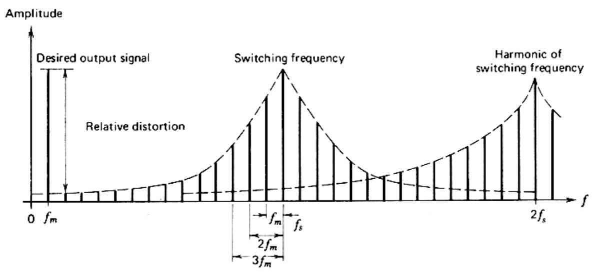

Figure 2: Intermodulation products spectral content

Intermodulation products are a function of fs and fm and are not necessarily harmonically related to fm. Increasing the switching frequency pushes higher order IM terms farther out of the audio spectrum.

Amplitude of these foldback distortion products, especially high order components which lie closest to the audio spectrum, increase with increasing duty cycle (Fig 3).

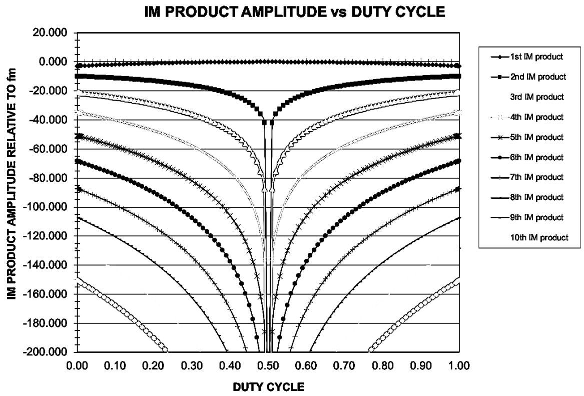

Figure 3: Intermodulation product amplitude v D

In clocked systems, non-linearity of the triangle wave directly contributes to distortion. To convert an ideal square wave to an ideal triangle wave requires zero phase shift *changes* from the fundamental upwards. If the fundamental lies within the integrator's stopband transition, where phase is still moving from 0 to -90 degrees, distortion will result. Signals below the fundamental only contribute to the noise floor exiting the comparator.

Clock jitter directly contributes to noise exiting the comparator. If many stages of asynchronous division are used, uncertainty of the successive gates adds up and increases noise. Use a low frequency, low jitter clock and a synchronous counter for divisions.

7 CONTROL LOOP DISTORTION

An open loop naturally sampled modulator is theoretically perfect. When feedback is applied around the modulator, two distortion mechanisms appear: a DC nonlinearity caused by pulse width distortion and a nonlinear time shift of the pulse edges.[7] Schemes exist to address this issue.[7,8,9]

Post-filter global feedback reintroduces any ripple present on the output back to the input of the modulator, reducing the linearity of the modulator.

To minimize the noise introduced by the control loop, the largest amount of gain in the loop should be placed as close as possible to the beginning of the forward signal chain. The closer this gain is placed to the output, the less ability the loop has to correct inter-stage noise sources.

A switching amplifier is a sampled data system and is subject to the same Nyquist limitations any such system is bound by. Care should be taken to incorporate some form of anti-aliasing filter to the signal entering the amplifier and to suppress noise outside the Nyquist frequency from entering the feedback loops. Modulated high frequency signals that enter the amplifier can fold back into the baseband and manifest as either noise or distortion.

8 FET DRIVER

The high and low side drive signals have intrinsic delay and delay mismatch, resulting in similar distortion mechanisms to those seen in the comparator. The maximum delay mismatch specification sets the minimum dead time possible without risk of cross conduction. Dead time (DT) accuracy and repeatability have a strong influence on the distortion produced by the output stage.

High side supplies bootstrapped to the low side bias supply experience voltage drops of the bootstrap diode and Vds of the low side device at current. The result is a high side driver supply voltage lower than that of the low side driver. The H and L gates exhibit different rise and fall times, propagation delays and PD mismatch associated with supply level. H and L side FETs are driven to different levels of saturation related to gate voltage, affecting relative turn off delay times. All of these mechanisms affect PWD.

Propagation delay mismatch tends to worsen with load. Buffering the driver output helps to minimize this effect.

9 OUTPUT STAGE

At idle, switches operate in the soft switching region. The rise and fall rates are fairly linear and well matched and are a function of the inductor current at the instant the on-side switch is turned off.

When the average inductor current exceeds the peak ripple current, the system is hard switching. For the following example, assume the current is large and flowing into the inductor.

In the hard-switched mode of operation, the H→L transition will be soft switched and have edge signatures similar to those seen at idle, albeit faster due to the larger current. During the L→H transition, the high-side switch will hard switch to clear the low-side conducting diode, resulting in a linear but faster edge. Since the edges are differentially offset from each other, PWD is produced. In states between hard and soft switched, transitions may begin soft and end hard, further degrading and differentiating the edge signatures and rates. As the edge rates change, so does the effective dead time, resulting in both PWD and DT induced distortions.

Pulse amplitude distortion can result from several mechanisms including bus pumping in half bridge circuits, excessive or asymmetrical ringing in the switching waveform, or high and low frequency supply ripple.

10 CONCLUSION

The majority of the distortion mechanisms found in a switching amplifier have been presented. Some are intrinsic to the process while others can be controlled with careful component selection and attendance to design and construction details. It is hoped that the designer will have a better appreciation of these mechanisms moving forward, recognize their underlying cause and understand how to successfully combat them.

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