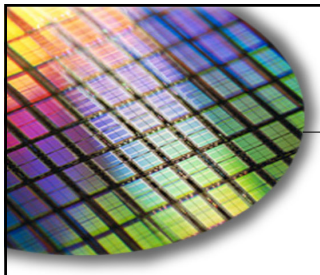


The World Leader in High-Performance Signal Processing Solutions

Switching Amplifiers;

The Gap between Theory and Practical Circuits

Bob Adams
Analog Devices Inc
Dec 4, 2003

ANALOG DEVICES

History

- Switching amplifiers have been around for many years.
- Quality and reliability of early units was very bad. They were used mostly for space-efficient high-power amplifiers.
- Recently, flat-panel TV's and multi-channel surround amplifiers have started a new wave of interest in Switching amplifiers.
- Many designers are now "re-discovering" all the challenges of switching amplifiers.

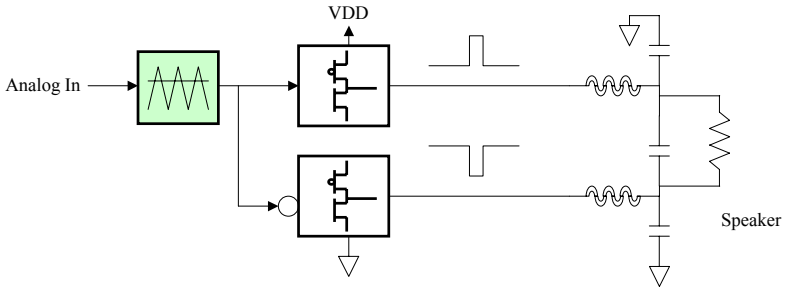
What has Changed?

- Market requirement for space-efficient amplifiers
  - 6-channel surround amplifiers
  - Flat-panel displays
- DMOS, VMOS power transistors
  - Reliable (no secondary breakdown)
  - Cheap
  - DMOS can be integrated with conventional CMOS processes
- New modulation algorithms
  - More complex switching algorithms avoid large spectral sticks at carrier frequency (good for EMI)
  - Feedback architectures reduce distortion and noise with real-world power supplies.

Design Approaches

- PWM
- Sigma-Delta
- Analog Modulators
- Digital Modulators
- Open-loop versus Closed-loop
- Power-Stage-Only Feedback

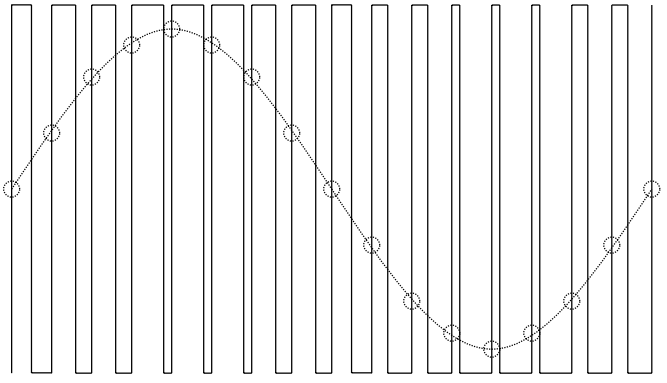
PWM



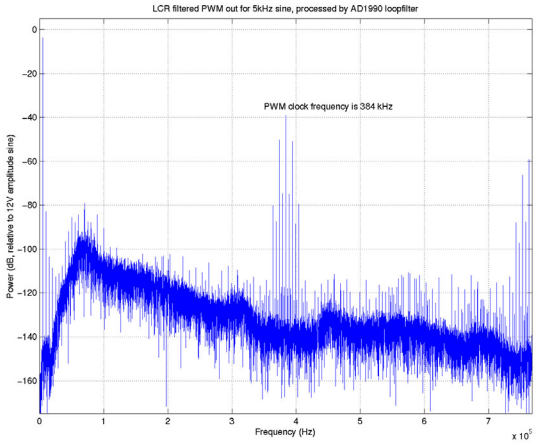
- **Drawbacks**
  - **If switching rate is too low, non-harmonic distortion is produced by carrier sidebands**
  - **Bad EMI due to strong component at the switching frequency**

PWM

The pulse sequence is the PWM representation of the output signal.



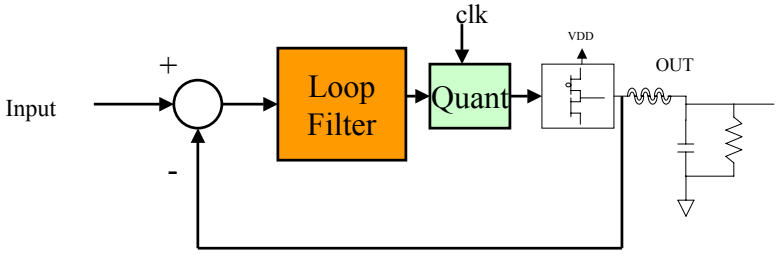
PWM EMI Performance



Design Approaches

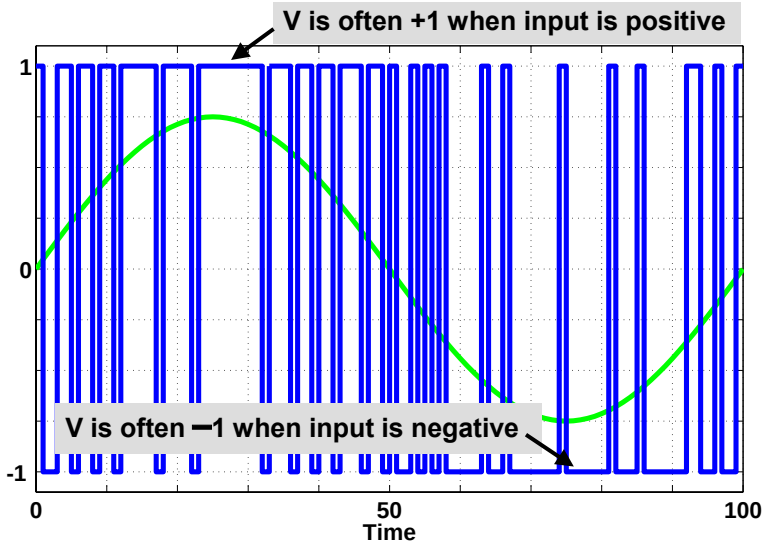
- PWM
- Sigma-Delta
- Analog Modulators
- Digital Modulators
- Open-loop versus Closed-loop
- Power-Stage-Only Feedback

Sigma-Delta

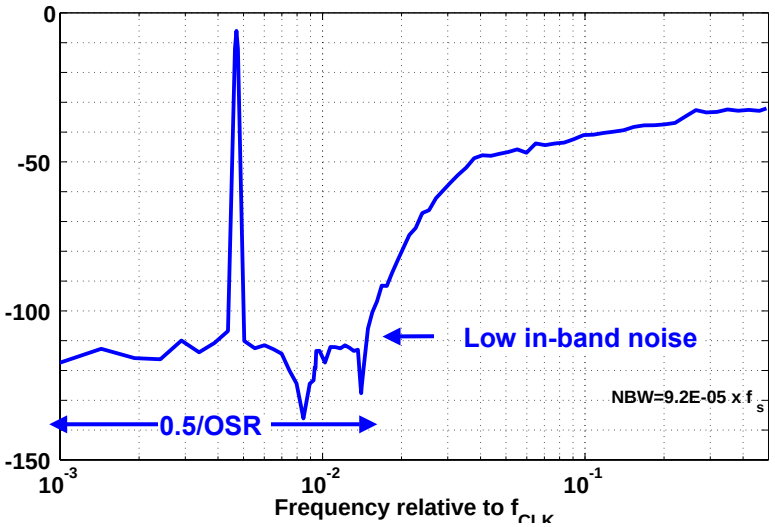


- **Advantages**
  - Very low distortion from modulation technique
  - Output stage is inside the feedback loop
  - Low EMI due to random behavior of switching
- **Disadvantages**
  - High transition rate reduces efficiency (must be specially designed to reduce transition rate)
  - Random nature of switching causes bad SNR unless the output stage is inside the feedback loop.

Sigma-Delta in the Time Domain



Sigma-Delta in the Frequency Domain



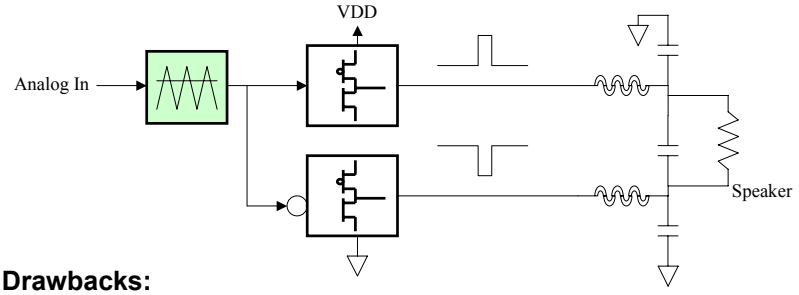
Design Approaches

- PWM
- Sigma-Delta
- Analog Modulators
- Digital Modulators
- Open-loop versus Closed-loop
- Power-Stage-Only Feedback

Analog Modulator

- **Advantages**
  - **Allows an inexpensive closed-loop system to be built, giving improved performance.**
  - **Switching can occur anywhere (not limited to a clock edge).**
- **Disadvantages**
  - **Needs a D/A converter if input signal is digital**
  - **Difficult to integrate on very small processes like 0.13u.**

Analog PWM Modulator with Open-loop Output Stage

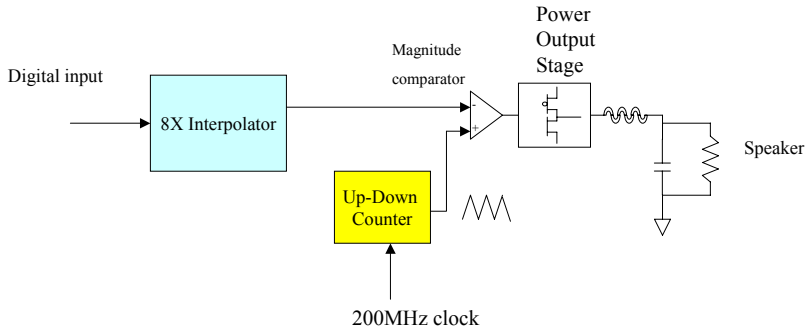


- **Drawbacks:**
  - Output stage is open-loop
  - Output stage behavior during “non-overlap” time causes noise and distortion
  - Supply must be regulated (0 dB supply rejection!)
  - Has theoretic distortion from the PWM process

Design Approaches

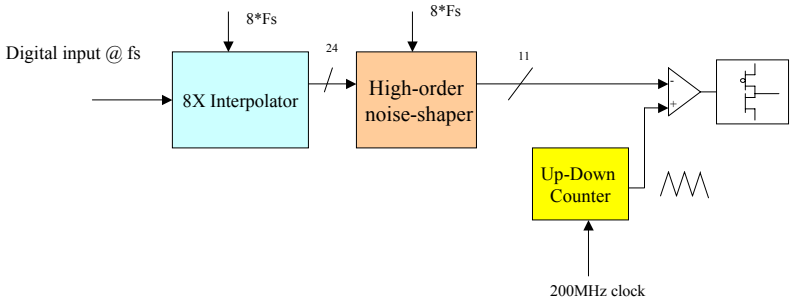
- PWM
- Sigma-Delta
- Analog Modulators
- Digital Modulators
- Open-loop versus Closed-loop
- Power-Stage-Only Feedback

Digital PWM amps with open-loop Output Stage



- **Problem**:
  - The number of possible pulse widths is quantized to about 600 widths.
  - The oversampling factor is only 8X, so with a 200MHz clock you only have an 11-bit system.

Digital PWM amp with Noise-Shaping Loops



- Using a noise-shaper improves the SNR.
- The oversampling factor is only 8, so the improvement at 20KHz is not very good.

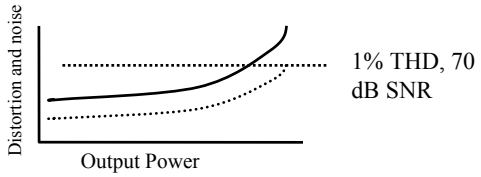
Design Approaches

- PWM
- Sigma-Delta
- Analog Modulators
- Digital Modulators
- Open-loop versus Closed-loop
- Power-Stage-Only Feedback

Open-loop Designs

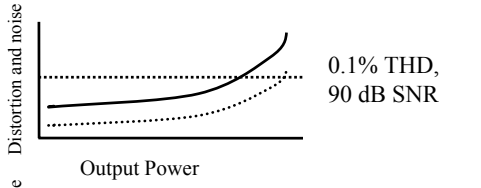
"Real-world" Experience

1) *Initial Design*



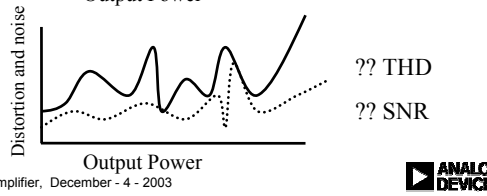
1% THD, 70 dB SNR

2) *After 2 years of re-design, under ideal laboratory conditions*



0.1% THD, 90 dB SNR

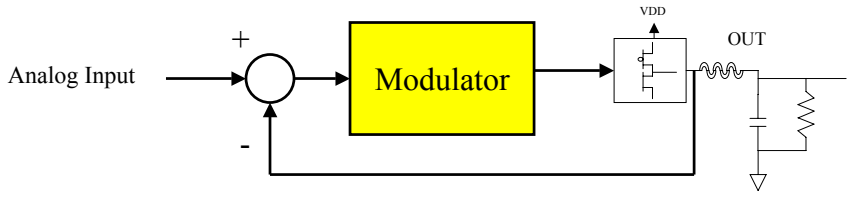
3) *In real customer system, with real power supply and over large temperature and process variations*



?? THD

?? SNR

Closed-loop designs (Analog)



- **Advantages**
  - PSRR, distortion and noise are all improved by the feedback gain.
  - Less sensitive to process shifts, changes in non-overlap time, etc.
- **Challenges**
  - Difficult to stabilize high-order designs
  - Must use special design techniques to make sure close to 100% modulation can be reached (otherwise MAX power is reduced)

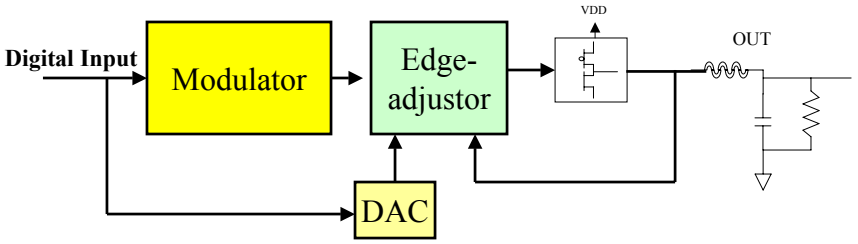
Design Approaches

- PWM
- Sigma-Delta
- Analog Modulators
- Digital Modulators
- Open-loop versus Closed-loop
- Power-Stage-Only Feedback

Power-Stage-Only Feedback

- A separate modulator, either analog or digital;
- Feedback around the POWER STAGE to shape the errors from the power stage. The shaping is done by ADJUSTING THE EDGE LOCATIONS from the modulator.

Power-stage feedback only (Digital Mod)



- **Advantages**
  - High-order modulator can be all-digital
  - Power-stage errors are shaped independently using a separate loop that adjusts only the edge positions of the main modulator.

Conclusions

- **There are a very large number of different topologies to consider**
- **Real-world problems include efficiency, EMI, PSRR, and other output-stage non-linearities.**
- **Open-loop PWM systems are not well-suited to solve real-world problems.**
- **Best topologies use some form of analog feedback.**

Additional Material

Why Switching Amplifiers did not succeed 30 years ago

- **Market Reasons**
  - Most amplifiers were only 2 channels at modest power. Switching amplifiers had only a small size/weight advantage, except at very high power.
- **Technical reasons**
  - Poor reliability. Bipolar power transistors have secondary breakdown problems.
  - Poor performance. THD+N and SNR limited by open-loop switching stage design.
  - Bad EMI. Simple PWM modulators make strong tones at the switching frequency.

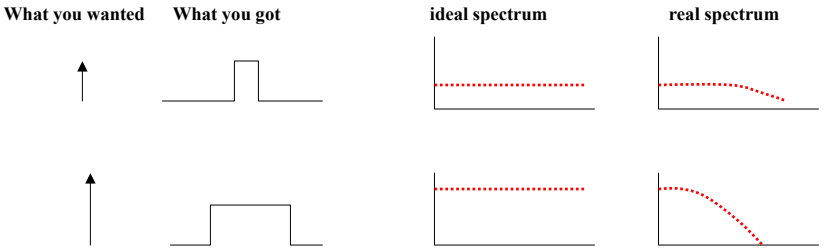
Digital Modulators

- Digital modulator is often preferred in modern systems.
- Advantages:
  - Direct digital input
  - Some DSP compensation of distortion may be possible
- Challenges
  - Hard to close the loop around the power stage (need a fast A/D)
  - Switching must occur on a clock edge (limits modulator performance).

Digital Modulators

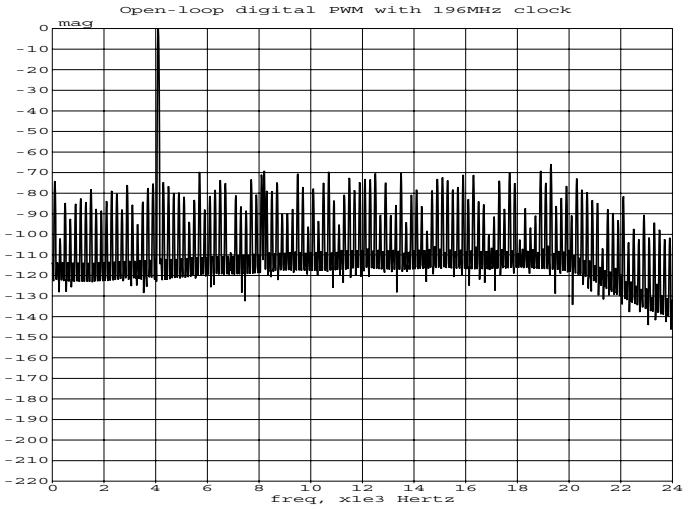
- Design Choices:
  - Digital PWM using High-frequency Clock
    - Resolution limited by clock speed (finite number of pulse widths)
  - Digital PWM with digital noise-shaping loop
    - Oversampling factor is not very high (8x)
  - Digital Sigma-Delta Modulator
    - Transition rate is too high, need some way of reducing it.

Theoretic PWM Distortion

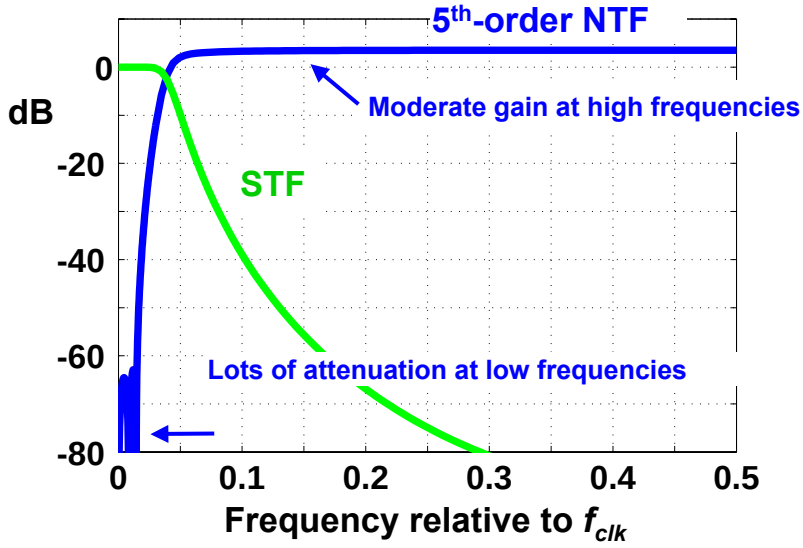


- High frequency signal components are modulated by the sinc(x) response of the variable-width pulse.
- Various compensation schemes have been proposed.

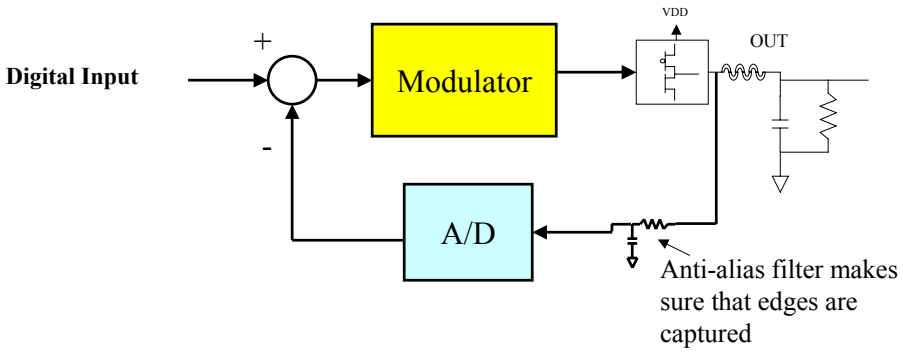
Sim for digital amp with 196MHz clock, no feedback



Example STF and NTF



Closed-loop Design (Digital)



- **Challenges**
  - A/D must have full resolution of desired SNR
  - A/D must have very low latency
  - A/D must have a filter to anti-alias the edge behavior.