Micropower Low-Voltage Digital Class D Amplifier for Hearing Aid Applications

by

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Outline

- Hearing Impairment
- Hearing Aids
- Linear Amplifiers
- Class D Amplifier
- Conclusion
Outline

● Hearing Impairment
  – Causes
  – Types
  – Levels
  – Facts
● Hearing Aids
● Linear Amplifiers
● Class D Amplifier
● Conclusion
Hearing Impairment

● Complete (deafness) or partial loss of the ability to hear from one or both ears

● Causes:
  – Blockage: earwax, foreign bodies
  – Inherited
  – Pregnancy & birth disorders: premature birth, lack of oxygen, syphilis infections, jaundice
  – Diseases & illnesses: ear infections (mumps, measles), meningitis, brain tumour, stroke
  – Ototoxic drugs: antibiotic, anti-malaria drugs
  – Excessive noise: explosion, loud music/noises
  – Injuries: head injury, ear injury
  – Age-related (presbycusis): starting from 30 years old

References: World Health Organization, NHS Direct UK
Types of Hearing Impairment

- **Conductive**
  - Outer or middle ear
  - Usually medically or surgically treatable, e.g. middle ear infections

- **Sensorineural**
  - Inner ear or hearing nerve
  - Usually permanent
  - Requires a hearing aid, e.g. excessive noise, ageing

- **Mixed**

References: World Health Organization, NHS Direct UK
Levels of Hearing Impairment

- **Mild**: unable to hear 25 - 39 dB
- **Moderate**: 40 - 69 dB
  - Need hearing aid
- **Severe**: 70 - 94 dB
  - Need lip-reading or sign language and hearing aid
- **Profound**: ≤95 dB
  - Need lip-reading or sign language
  - Hearing nerves still work → use cochlear implant

### Decibel Scale of Common Sounds

<table>
<thead>
<tr>
<th>Sound Description</th>
<th>Decibel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of Hearing</td>
<td>0 dB</td>
</tr>
<tr>
<td>Breathing</td>
<td>10 dB</td>
</tr>
<tr>
<td>Whisper, rustling leaves</td>
<td>20 dB</td>
</tr>
<tr>
<td>Library</td>
<td>40 dB</td>
</tr>
<tr>
<td>Vacuum cleaner</td>
<td>70 dB</td>
</tr>
<tr>
<td>Food blender, busy street</td>
<td>90 dB</td>
</tr>
<tr>
<td>(hearing damage after 8 hrs)</td>
<td></td>
</tr>
<tr>
<td>Jet takeoff (305 m), jackhammer</td>
<td>100 dB</td>
</tr>
<tr>
<td>(serious hearing damage after 8 hrs)</td>
<td></td>
</tr>
<tr>
<td>Thunderclap, live rock music</td>
<td>120 dB</td>
</tr>
<tr>
<td>(human pain threshold)</td>
<td></td>
</tr>
</tbody>
</table>

References: NHS Direct UK, Dangerous Decibels
Test Your Hearing Yourself!

- Do you have trouble understanding higher pitched voices such as women's and children's?
- Do you have trouble hearing conversations in a noisy background?
- Do you often ask people to repeat themselves?
- Do you hear the people that you talk to have loud enough but mumbled voices?
- Do you turn up the volume of the TV when others have no problem hearing?
- Do you have trouble localizing sounds (unilateral hearing impairment)?

Reference: Better Hearing Institute
Facts

- 278 million people worldwide have moderate to profound hearing loss (2005)
- Number rising due to a growing global population and longer life expectancies
- One quarter of cases begin during childhood
- Detecting and responding to hearing impairment in babies and young children is vital for the development of speech and language
- Properly fitted hearing aids can improve communication in at least 90% of people with hearing impairment (the other 10% may be helped medically)
- Current annual production of hearing aids meets less than 10% of global need
- Cost of hearing aids: US$1K – US$6K (expensive research, audiologist/fitter wages, custom-made, quality improvements: size, style, features)
- Increased the availability of affordable, properly fitted hearing aids and follow-up services can benefit many people with hearing impairment

Reference: World Health Organization, Better Hearing Institute
Outline

- Hearing Impairment
- **Hearing Aids**
  - Styles
  - Batteries
  - Block Diagram
  - Typical Specifications
- Linear Amplifiers
- Class D Amplifier
- Conclusion
Hearing Aids

- Primarily useful for *Sensori-Neural* hearing impairment (disease, ageing, injury)
- Magnifies sound vibrations entering the ear
- Surviving hearing nerves detect the larger vibrations and convert them into neural signals
- More nerve damage → more severe hearing loss → more amplification needed

*Practical limits*
Styles of Hearing Aids

- **Completely-in-Canal (CIC)**
  - Mild to severe
  - Small, limited power and volume

- **Behind-the-Ear (BTE)**
  - All ages
  - Mild to profound

- **In-the-Canal (ITC)**

- **In-the-Ear (ITE)**
  - Mild to severe
  - Not worn by children (as ear grows)

- **Open Fit BTE**
  - Behind the ear completely
  - Narrow receiver tube in ear canal
  - Eliminate occlusion effect

References: Siemens Hearing Instruments, National Institute on Deafness and Other Communication Disorders
Types of Hearing Aids

● **Analog**
  – Convert input sound waves into electrical signals and amplify them
  – Less expensive

● **Digital**
  – Convert input sound waves into numerical codes before amplifying them
  – Programmable for each individual wearer
  – Digital sound processing:
    • background noise reduction
    • acoustic feedback cancellation
    • speech enhancement
    • automatic gain
    • directional sound focus
  – Smaller, lighter
Components of a Digital Hearing Aid

- Microphone
- Preamplifier
- ADC
- Digital Signal Processor
- DAC
- Amplifier
- Receiver

Acoustic Input → Preamplifier → ADC → Digital Signal Processor → DAC → Amplifier → Receiver → Acoustic Output
Power Budget Allocation

- **Power dissipation constraints:**
  - Battery capacity: ~100 mAh
  - Expected lifespan: \( \geq 100 \) hours

- **Operating power for entire system:** 1 mA @ 1.1-1.4 V

- **Typical average power allocation @ normal ambient signal condition** (10-15 dB gain reserve below max output) and 300 \( \Omega \) receiver:
  - Preamplifier and \( \Delta \Sigma \) ADC: 200 \( \mu \)W
  - DSP: 500 \( \mu \)W
  - DAC + Class AB Amplifier + Receiver: 300 \( \mu \)W
Increasing the Intelligence

- More power for the DSP
- More algorithms
- More intelligent
How to allocate more power for the DSP?

Use a more efficient amplifier
Outline

- Hearing Impairment
- Hearing Aids
- **Linear Amplifiers**
  - Class A
  - Class B
  - Class AB
- Class D Amplifier
- Conclusion
Linear Amplifiers - Class A

Maximum power efficiency = 25 %
Linear Amplifiers - Class B

Maximum power efficiency = 78.5 %
Linear Amplifiers - Class AB

Power efficiency = 25 - 78.5 %
Outline

- Hearing Impairment
- Hearing Aids
- Linear Amplifiers
- **Class D Amplifier**
  - Digital Class D
  - Modulation Schemes:
    - Pulse Width Modulation
    - Pulse Density Modulation
    - Hybrid Algorithmic PWM & Multi-bit $\Delta \Sigma$ Modulation
  - Prototype Digital Class D Amplifier IC for Hearing Aids
- Conclusion
Class D Amp is basically Switching Amp

Maximum power efficiency = 100 %
Types of Class D Amplifiers

- Analog Class D: analog modulator
- Digital Class D: digital modulator
- Both are based on either PWM or PDM signals
Basic Output Modulation Schemes

- Pulse Width Modulation (PWM)

- Pulse Density Modulation (PDM)
Advantage of the Digital Class D Amp

- When interfaced to a DSP...
  - Analog Amplifiers (Class A, B, AB, Analog Class D) require a DAC
    - Additional IC area
    - Additional power dissipation
    - Additional noise and distortions

- Digital Class D Amplifier does not require a DAC
Components of a Digital Class D Amplifier

Diagram showing the components of a digital class D amplifier, including:
- N-bit digital signal input
- Digital modulator
- Class D output stage
- Gate driver
- LC network
- Low-pass filter
PWM Generation using an Analog Modulator

- PWM Analog Modulator

- Natural Sampling PWM: no error

  zero harmonic distortion
Total Harmonic Distortions + Noise (THD+N)

\[ \text{THD+N (dB)} = 10 \log_{10} \left( \frac{\text{Total power of harmonics + noise}}{\text{Power of fundamental}} \right) \]

\[ \text{THD+N (%) } = 100 \% \times \sqrt{\sum_{n=2}^{n_\text{max}} \frac{P(f_n)}{P(f_1)}} + P_{\text{noise}} \]
PWM Generation using a Digital Modulator

- Basic method: Uniform Sampling PWM

![Diagram showing PWM generation and uniform sampling points](image_url)

- $S_1 = \text{previous sampled data}$
- $S_2 = \text{current sampled data}$
Harmonic Distortions of Uniform Sampling PWM

- Error in the cross-over point location → harmonic distortions

- THD: -30 dB (3 %) @ input level ($M$) = 0.9 Full-Scale, input frequency ($f_{in}$) = 997 Hz, & carrier frequency ($f_c$) = 48 kHz

- Techniques to reduce harmonic distortions:
  - Interpolation of the input data samples → oversampling
  - Algorithmic PWM sampling process
Clock Freq of Uniform Sampling PWM

- Digital counter requires a fast-clock frequency of $2^N \times$ carrier frequency

- Problem:
  - For $N = 16$-bit and carrier frequency = 48 kHz, fast-clock frequency will be ~3 GHz!!!
Pulse Density Modulation

- 1-bit $\Delta \Sigma$ Modulation
- $\Delta \Sigma$ Modulation: oversampling & noise-shaping
- Oversampling in digital = interpolation of data
Interpolator

- To interpolate the original sampled input data (increase the input sampling frequency)
- To attenuate the error spectral images by-product
1\textsuperscript{st}-order $\Delta \Sigma$ Noise-Shaper

\[ V(z) = U(z) + \left(1 - z^{-1}\right)^K E(z) \quad ; K = 1 \]

\[ = STF(z)U(z) + NTF(z)E(z) \]
**K-bit ΔΣ Noise-Shaper: Error-Feedback Structure**

- \( V(z) = U(z) + H_f(z)E(z) + E(z) \)
  - \( = U(z) + (1 + H_f(z))E(z) \)
  - \( = U(z) + NTF(z)E(z) \)

- \( NTF(z) = (1 - z^{-1})^K \)
- \( H_f(z) = NTF(z) - 1 \)
ΔΣ Noise-Shaper: Signal to Quantization Noise Ratio

- SQNR (dB) = \[6.02Q + 1.76\] + 20 \log(M) + 10 \log\left(\frac{2K + 1}{\pi^2K}\right) + (2K + 1)10 \log(L)

- Prototype IC: \(Q = 8, K = 3, L = 6\). At \(M = 0.9\) FS:
  - Theoretical SQNR = 82 dB
  - Theoretical THD+N = -77 dB
\[\Delta \Sigma\] Spectrum

- For PDM, \( Q = 1 \) \( \rightarrow \) requires either:
  - High \( L \) (oversampling ratio), or
  - High-order noise-shaper
Hybrid Algorithmic PWM & Multi-bit $\Delta \Sigma$ Modulation
PWM Pulse Generator

- To convert the Q-bit digital data from the $\Delta\Sigma$ Noise-Shaper into the PWM pulses

- Counter: also function as a frequency divider

- Proposed frequency doubler: halve the required $f_{fastclock}$ to $2^{Q-1} \times f_L$
Frequency Doubler

$\text{PWM output from the counter}$

$\text{Bit 0 (LSB) of the output from the } \Delta \Sigma \text{ Noise-Shaper}$

$\text{($f_{\text{fastlock}} = 2^{Q-1} \times f_i$)}$
PWM Pulse Generator – depending on $Q$

<table>
<thead>
<tr>
<th>$Q$ (bit)</th>
<th>SNR (dB)</th>
<th>$f_{\text{fastclock}}$ (MHz)</th>
<th>Average Power Dissipation ($\mu$W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>76</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>82</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>88</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>94</td>
<td>49</td>
<td>26</td>
</tr>
</tbody>
</table>

At 0.35 $\mu$m CMOS process & 1.1 V power supply
Simulation and Experimental Results

Simulation ($M = 0.9$ FS)

Experimental ($M = 0.9$ FS)

- **Performance:**
  - THD+N: -78 dB
  - Average THD+N ($M = 0.1$ FS to $0.9$ FS): -75 dB

- **Power Dissipation at 1.1 V:**
  - Average: 25 $\mu$W
  - Quiescent: 18 $\mu$W

- **Performance:**
  - THD+N: -74 dB (0.02 %)
  - Average THD+N ($M = 0.1$ FS to $0.9$ FS): -70 dB (0.03 %)

- **Power Dissipation at 1.1 V:**
  - Average: 28 $\mu$W
  - Quiescent: 20 $\mu$W
Algorithmic PWM

- To improve the linearity of the Uniform Sampling PWM (THD: -30 dB (3%)) at $M = 0.9$ FS and $f_c = 48$ kHz
- Cross-point deriver: estimate the Natural Sampling cross-over point (e.g. $\delta$C PWM$^{[1]}$, LI PWM$^{[2]}$)
- Linear Interpolation PWM (LI PWM): THD = -67 dB (0.04%)
- Combined 1st & 2nd-order Lagrange Interpolations Sampling PWM: THD = -79 dB (0.01%)


Prototype Digital Class D Amplifier IC

- Fabricated in 0.35 μm CMOS process
- Core area: 0.46 mm²
- $f_{\text{fastclock}} = 12$ MHz
- $Q = 8$
- Output frequency = 96 kHz
- Measured THD+N: -74 dB (0.02 %) at $M = 0.9$ FS (typical THD of hearing aids: -40 dB or 1 %)
- Measured average power dissipation: 28 μW at 1.1 V

Conclusions

- **Class D amplifier:**
  - Power efficient
  - More power for DSP of a hearing aid
- Advantage of digital Class D amplifier: no DAC
- US PWM: high THD and high fast-clock frequency
- PDM 1-bit ΔΣ: high oversampling ratio and high order noise-shaper
- Hybrid Algorithmic PWM & Multi-bit ΔΣ Modulation: lower THD, lower fast-clock frequency, lower oversampling ratio, and lower order noise-shaper
Some selected publications:


thank you