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

by

Bah-Hwee Gwee
Associate Professor, Nanyang Technological University
Senior Consultant, Digital Hearing Aid Centre
Founder & Director, Advanced Electroacoustics Pte Ltd

ebhgwee@ntu.edu.sg
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</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 (hearing damage after 8 hrs)</td>
</tr>
<tr>
<td>Jet takeoff (305 m), jackhammer</td>
<td>100 dB (serious hearing damage after 8 hrs)</td>
</tr>
<tr>
<td>Thunderclap, live rock music</td>
<td>120 dB (human pain threshold)</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)?
Facts

- 278 million people worldwide have moderate to profound hearing loss in both ears (WHO’s estimates 2005).
- The number is rising mainly 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 is estimated to meet less than 10% of global need.
- Increased 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 sensorineural 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

Acoustic Output
Power Budget Allocation

- Power dissipation constraints:
  - Battery capacity: ~100 mAh
  - Expected lifespan: ≥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 Ω receiver:
  - Preamplifier and ΔΣ ADC: 70 μW
  - DSP: 600 μW
  - DAC + Class AB Amplifier + Receiver: 330 μW
Increasing the Intelligence

1. More power for the DSP
2. More algorithms
3. 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 Amplifier
(Switching Amplifiers) Basics

Maximum power efficiency = 100%
Types of Class D Amplifiers

• Analog Class D: analog modulator

• Digital Class D: digital modulator
Components of a Digital Class D Amplifier
Advantage of the Digital Class D Amplifier

- 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.
Basic Output Modulation Schemes

- Pulse Width Modulation (PWM)
- Pulse Density Modulation (PDM)
PWM Generation using an Analog Modulator

- PWM Analog Modulator

- Natural Sampling PWM: no error
  
  **zero harmonic distortion**
Total Harmonic Distortions + Noise (THD+N)

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

\[
\text{THD+N (\%)} = 100 \times \sqrt[2]{\sum_{n=2}^{\infty} \frac{f_{n}}{f_{1}} P(f_{n}) + P_{\text{noise}}} \]

\[
\sqrt{P(f_{1})}
\]
PWM Generation using a Digital Modulator

- Basic method: Uniform Sampling PWM

![Diagram showing PWM pulses, carrier signal, and input signal with sampling points labeled $S_1$ and $S_2$.]

- $S_1$ = previous sampled data
- $S_2$ = 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 \( (f_{in}) = 997 \text{ Hz} \), & carrier frequency \( (f_c) = 48 \text{ kHz} \)

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

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

\[ = \text{STF}(z)U(z) + \text{NTF}(z)E(z) \]
**ΔΣ 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
Prototype Digital Class D Amplifier IC for Hearing Aids

- Fabricated in 0.35 μm CMOS process
- Core area: 0.46 mm²
- $f_{fastclock} = 12$ 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

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$^3$: THD = -79 dB (0.01 %)

---


ΔΣ Noise-Shaper: Error-Feedback Structure

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

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

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

- Prototype IC: \(Q = 8, K = 3, L = 6\). At \(M = 0.9\) FS:
  - Theoretical SQNR = 82 dB
  - Theoretical THD+N = -77 dB
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 $f_{fast\text{clock}}$ to $2^{Q-1} \times f_L$
Frequency Doubler

PWM output from the counter

Bit 0 (LSB) of the output from the ΔΣ Noise-Shaper

(f_{	ext{fast clock}} = 2^{Q-1} \times f_i)
# PWM Pulse Generator – Simulation Results

<table>
<thead>
<tr>
<th>$Q$ (bit)</th>
<th>SQNR (dB)</th>
<th>$f_{fastclock}$ (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 \((M = 0.9 \text{ FS})\)

- **Performance:**
  - THD+N: -78 dB
  - Average THD+N \((M = 0.1 \text{ FS to } 0.9 \text{ FS})\): -75 dB

- **Power Dissipation at 1.1 V:**
  - Average: 25 µW
  - Quiescent: 18 µW

Experimental \((M = 0.9 \text{ FS})\)

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

- **Power Dissipation at 1.1 V:**
  - Average: 28 µW
  - Quiescent: 20 µW
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 $\Delta\Sigma$: high oversampling ratio and high order noise-shaper
• Hybrid Algorithmic PWM & Multi-bit $\Delta\Sigma$ Modulation: lower THD, lower fast-clock frequency, lower oversampling ratio, and lower order noise-shaper
Thank You!