Integrated Active Noise Control and Noise Reduction in Hearing Aids

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Outline

■ Introduction
■ Problem description
  ◆ Standard MWF-based noise reduction scheme
  ◆ Secondary path and leakage
  ◆ ANC: general idea
■ Integrated ANC and NR
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  ◆ Integrated ANC and NR
■ Variations on the integrated ANC and NR
  ◆ Weighted approaches to integrated ANC and NR
  ◆ Zone of quiet approach to integrated ANC and NR
  ◆ Binaural approach to integrated ANC and NR
■ Conclusion and future research
Introduction
Hearing system can be decomposed in 3 parts:
Introduction: hearing

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- **Middle ear**: convert the sound vibration from the eardrum to waves in the cochlea
Hearing system can be decomposed in 3 parts:

- **Outer ear**: focus the sound energy towards the eardrum
- **Middle ear**: convert the sound vibration from the eardrum to waves in the cochlea
- **Inner ear**: convert the mechanical waves to neural signal
About 90% of losses are caused by problems in the inner-ear:
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- Reduced dynamic range
Introduction: hearing losses

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Hearing aids need to provide powerful digital signal processing (DSP) algorithms.
Introduction: Types of hearing aids:

- Canal aids: fit entirely in the ear-canal

[HealthTree. Presbycusis - understanding presbycusis hearing loss, July 2010.]
Introduction: Types of hearing aids:

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Introduction: Types of hearing aids:

- Canal aids: fit entirely in the ear-canal
- In-the-ear hearing aids: fit entirely in the outer-ear
- Behind-the-ear hearing aids (BTE): the electronics are in a small case hooked behind the ear

[HealthTree. Presbycusis - understanding presbycusis hearing loss, July 2010.]
Introduction: open fitting BTE

[Introduction]

Hearing and hearing losses

Hearing aids

Problem description

Integrated ANC and NR

Variations on the integrated ANC and NR

Conclusion and future research

[Ent and Allergy. Report-Best Type Of Hearing Aid, Consumer Reports - 7.09]

**Pros**
- Improved comfort
- Reduced occlusion effect
- Reduced risk of infection

**Cons**
- Feedback
- Noise leakage cannot be neglected
- DSP effects partly cancelled
Problem description
General listening scenario

Every day life listening scenarios can include:
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- Multiple talkers (cocktail party problem)
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- Noise sources
Every day life listening scenarios can include:

- Multiple talkers (cocktail party problem)
- Noise sources
- ...
Signal-to-noise ratio

Need to quantify “how much” noise is present compared to speech

\[
\text{SNR} = \frac{\text{Speech signal energy}}{\text{Noise signal energy}}
\]
Signal-to-noise ratio

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\[ \text{SNR} = \frac{\text{Speech signal energy}}{\text{Noise signal energy}} \]
Noise reduction in hearing aids

**Introduction**

**Problem description**

MWF-based Noise reduction

Leakage effect

Active Noise control

Integrated ANC and NR

Variations on the integrated ANC and NR

Conclusion and future research

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**Single-channel noise reduction**

*Improve SNR and comfort, not necessarily speech understanding*

**Multichannel noise reduction**

- Fixed-beamformer: steer towards speech source
- Adaptive beamformer: minimise noise contribution
- Multichannel Wiener filter (MWF): estimate speech in 1 microphone
MWF-based noise reduction

$G$ is the amplification that compensates for hearing losses.

**Multichannel Wiener Filter (MWF)**

\[
\min_w \ E\{d_{NR}[k] - w^T[k]x[k]\}^2
\]
\[
w[k] = R_{xx}^{-1}[k]r_{xd_{NR}}[k]
\]
Problem description

- Previous work on noise reduction (NR) in hearing aids focus on path from source to microphones
- Previous work on noise reduction (NR) in hearing aids focus on path from source to microphones
- What if disturbances (e.g. leakage, secondary path) are included?
Standard MWF-based Noise Reduction Scheme

Introduction

Problem description

MWF-based Noise reduction

Leakage effect

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Acoustic domain

$x_1[k]$  $x_M[k]$  $w_1[k]$  $w_M[k]$  $d_{NR}[k]$  $e_{NR}[k]$  $\bar{z}[k]$  $l[k]$  $G$

Effects of leakage and secondary path

$$\bar{z}[k] = c[k]^T (G \cdot z[k]) + l[k]$$

Leakage and secondary path may degrade SNR
Effects of leakage and secondary path

Experimental setup

- Acoustic path measurements with a manikin head and artificial ears
- Two-microphone BTE
- 1 speech source (0°), 1 noise source (270°)
- Leakage SNR \( \approx -1\, \text{dB} \)
ANC: general idea

- Passive insulation is uneasy for low frequencies
  - requires too thick/heavy walls
  - perforated panels and Helmoltz resonator
- Generate destructive interferences
- Relying on superposition principle
ANC: causality margin

\[ \delta = \Delta_{pri} - (\Delta_{ref} + \Delta_{HA} + \Delta_{sec}) \]
ANC: causality

ANC performance is highly dependent on causality
ANC: causality

ANC performance is highly dependent on causality

It would be possible to generate anti-noise by inverting and delaying the microphone signal by 10 samples.
ANC: causality

ANC usually performs poorly when non-causal

![Graph showing reference and error microphone signals over time](image)
ANC: causality

ANC usually performs poorly when non-causal

The microphone signal would have to be delayed by -10 samples and inverted to generate anti-noise.
Integrated ANC and NR
Cascaded ANC and NR

Use NR output as ANC input

Two opposite objectives

- NR provides an output with low power noise component
- ANC requires a strong noise component to generate anti-noise
Cascaded ANC and NR

Causality problem

NR latency $\Delta \neq$ ANC need to be causal
Parallel ANC and NR

- Use BTE microphone as input for both NR and ANC
- Add NR output to ANC output

**ANC/NR opposite objectives**

ANC input now has a strong noise component to generate anti-noise
Parallel ANC and NR

Causality margin

NR latency $\Delta$ has no influence on ANC inputs
Wiener Filter (Integrated ANC and NR)

\[
\min_w \quad E\{ |c[k]^T w^T[k] x[k] + l^n[k] - d_{NR}[k]|^2 \}
\]

\[
w[k] = R_{yy}^{-1}[k] r_{yd_{Int}}[k]
\]
Integrated ANC and NR: simulations

When speech and noise are uncorrelated:
\[ w[k] = u_{NR}[k] + v_{ANC}[k] \]

The NR latency has no influence on the ANC inputs
Variations on the integrated ANC and NR
Weighted integrated ANC and NR

Integrated ANC and NR has two objectives:

**NR objective**

\[
E\{|e_{NR}|^2\} = E\{|c[k]^T w^T[k] x[k] - d_{NR}[k]|^2\}
\]

**ANC objective**

\[
E\{|e_{ANC}|^2\} = E\{|c[k]^T w^T[k] x^n[k] + l^n[k]|^2\}
\]

Fixed trade-off → not appropriate in some circumstances:

- Speech is not present
- ANC cannot cancel the type of noise efficiently (e.g., high frequency noise)
Weighted integrated ANC and NR

New optimization problem:

$$\min_{w} E\{|e_{ANC}|^2\}, \text{ subject to } E\{|e_{NR}|^2\} \leq T$$

Noise power at the eardrum

Speech distortion
MWF-based NR still introduces speech distortion:

**SD objective**

\[ E\{ |e_{SD}|^2 \} = E\{ \| \mathbf{c}[k]^T \mathbf{w}^T[k] \mathbf{x}_s[k] - d_{NR}[k] \|^2 \} \]

**ANC objective**

\[ E\{ |e_{ANC}|^2 \} = E\{ \| \mathbf{c}[k]^T \mathbf{w}^T[k] \mathbf{x}_n[k] + l_n[k] \|^2 \} \]

Similarly to previously trade-off between SD and ANC.

**New optimization problem:**

\[ \min_{\mathbf{w}} E\{ |e_{ANC}|^2 \}, \text{ subject to } E\{ |e_{SD}|^2 \} \leq T \]
Speech distortion Weighted Integrated ANC and NR

Introduction

Problem description

Integrated ANC and NR

Variations on the integrated ANC and NR

Weighted approaches

Zone of quiet approach

Binaural approach

Conclusion and future research

Noise power at the eardrum

Speech distortion

Single speech source scenario when no. sources ≤ no. microphones

The output SNR is independent of $\mu$
The error microphone cannot be located at the eardrum → The noise at the eardrum is uncontroled.
Average SNR over a desired zone

- SNR can be computed at any point of the space based on acoustic models.

- Defining a more appropriate performance measure

Average SNR over the desired zone

\[ aSNR \triangleq \frac{1}{S} \int_S SNR(r) dS \]
Zone of Quiet integrated ANC and NR

- Define a MSE at any point of the space based on acoustic models

SNR at the error microphone $\approx 10.5 dB$

<table>
<thead>
<tr>
<th>Zone 1</th>
<th>min(SNR)</th>
<th>aSNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained integrated</td>
<td>6.5</td>
<td>8</td>
</tr>
<tr>
<td>Adjusted integrated (Zone 1)</td>
<td>7.8</td>
<td>8.9</td>
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</table>

<table>
<thead>
<tr>
<th>Zone 2</th>
<th>min(SNR)</th>
<th>aSNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained integrated</td>
<td>6.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Adjusted integrated (Zone 2)</td>
<td>8.8</td>
<td>9.2</td>
</tr>
</tbody>
</table>
Binaural processing

Processing schemes presented so far are monaural:

- One ear is equipped with a BTE
- Limited number of microphones, spatial separation
Binaural processing

Bilateral schemes:

- Both ears equipped with a BTE
- BTE’s work independently
Binaural processing

Binaural schemes:

- Contra-lateral microphone → better separation
- More microphones → cancel more noise sources

\[
\begin{align*}
&x_{L,1}[k] \\
&x_{L,M}[k] \\
&w_{\text{Left}}[k] \\
&z_L[k] \\
&x_{R,1}[k] \\
&x_{R,M}[k] \\
&w_{\text{Right}}[k] \\
&z_R[k] \\
&e_L[k] \\
&e_R[k]
\end{align*}
\]
Binaural approach: causality

Experiment setup

- Noise to be controlled at the left ear
- Microphone signals from both ears

Binaural approach performance $\approx$ Best ear performance

Noise source on the left

Noise source on the right
Binaural approach (number of sources)

2-microphones approach

Constant SNR for 1 noise source

4-microphones approach

(Almost) constant SNR performance for up to 3 noise sources.
Conclusion and future research
### Conclusion/Future work

#### Conclusions
- Leakage degrades standard NR performance
- Integrated ANC and NR allows to restore the performance
- Technical problems: trade-off, microphone location...

→ The integrated ANC/NR can be modified to address some of these problems

#### Future research
- Include feedback path
- Extend binaural approach to wireless acoustic sensor network
- Investigate practical problems (*e.g.*, “latency”) before real-time tests
5 international journal articles:


5 international conference articles.

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