Performance Optimization of Personal Sound Zones with Crosstalk Cancellation

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Personal Sound Zones\textsuperscript{[1]}

Rendering 3D Audio in Sound Zones

**How to realize:** controlling sound in the ear region

**Methods:** loudspeaker array beamforming\(^2\) and/or **pressure matching**\(^3\)

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\(^2\) Qiao and Choueiri, AES Conv. 151, 2021. \(^3\) Poletti, AES Conv. 125, 2008.
Performance Trade-offs

Two performance attributes
• Acoustic isolation (audio-on-audio interference)
• Crosstalk cancellation (XTC, spatial envelopment)

Subjective preference
low interference > high envelopment\(^4\)

Objective limitation
Enabling XTC degrades isolation\(^5\) due to extra cost

\[^4\] Canter and Coleman, AES Conv. 150, 2021. \[^5\] Qiao et al., JASA-EL, 2022.
How to control the trade-off between isolation and crosstalk cancellation?

(To be answered with simulations)
Designing Sound Zone Filters

Pressure matching formulation

\[ J = \|Hc - m_T\|^2 + \lambda \|c\|^2 \]

Minimize \( J \)

\[ c^* = (H^H H + \lambda I)^{-1} H^H m_T \]

Choice of target response

Monaural: \( m_T = [M, M, 0, 0]^T \)

XTC: \( m_{T,L} = [M_{A,L}, 0, 0, 0]^T \)
     \( m_{T,R} = [0, M_{A,R}, 0, 0]^T \)
Proposed Optimization

Goal: adjust the performance trade-off through filter design

“Direct” Approach (cost function)

\[ J = \|Hc - m_T\|^2 + \lambda \|c\|^2 \]

\[ |h_{A,L}^H c - M_L|^2 + 2\alpha |h_{A,R}^H c|^2 + 2(1 - \alpha) \|H_B c\|^2 \]

Reproduction Error  Crosstalk  Dark Zone Leakage

0 ≤ α ≤ 1,  α = 0.5 : original PM solution

α ↑: more envelopment  α ↓: more isolation

“Indirect” Approach (target response)

\[ m_{T,L} = [M_L,0,0,0]^T \]

\[ \tilde{m}_{T,L} = [\beta M_L, (1 - \beta) M_L, 0, 0]^T \]

0.5 ≤ β ≤ 1,  β = 1 : original PM solution

β ↑: more envelopment  β ↓: (potentially) more isolation

Example

α

β
Performance Evaluation

Two performance metrics

• Crosstalk cancellation (XTC)
  • Level difference between two ears
    \( p_{A,L} \) vs. \( p_{A,R} \)

• Inter-Program Isolation (IPI)\(^5\)
  • Level difference between target and interfering programs
    \( (p_{A,L}, p_{A,R})|_{BZ} \) vs. \( (p_{A,L}, p_{A,R})|_{DZ} \)

\[^5\] Qiao, Guadagnin, and Choueiri, JASA-EL, 2022.
Case 1: Free-Field Simulation

Simulation Setup
• reproduces a laboratory setup
• includes non-idealities (e.g., nonuniform responses, displacement) through randomness
• uses constant regularization for simplicity

Evaluation metrics (100-1000 Hz)
• IPI and XTC spectra as a function of $\alpha$ (or $\beta$)
• Spatial map of Sound Pressure Level (SPL) at a given $\alpha$ (or $\beta$)
Case 1 Results — IPI & XTC Spectra

Direct Approach (increasing $\alpha$ boosts XTC)

- Changing $\alpha$ only affects IPI @ low frequencies
- Exponential relationship between $\alpha$ and frequency for a fixed XTC

Indirect Approach (increasing $\beta$ boosts XTC)

- $\beta$ has a wider effective range on IPI compared to $\alpha$
- $\beta$ has more uniform impact on XTC across frequencies
Case 1 Results — SPL Spatial Map @ 200 Hz

(Decreasing $\alpha$ or $\beta$ boosts IPI)

Direct Approach

\[ \alpha = 5e^{-05} \]

Indirect Approach

\[ \beta = 0.5 \]

- Dark spot at contralateral ear moves towards DZ as $\alpha$ (or $\beta$) decreases
- Direct approach yields higher isolation for the mono case compared to indirect approach
Case 2: Real-World Simulation

- Simulation with measured transfer functions
- Same regularization applied
- IPI and XTC curves calculated with different $\alpha$ (or $\beta$) between 100 and 7000 Hz

Measurement Setup
Case 2 Results — IPI and XTC

Observations

- IPI & XTC levels decrease due to room reflections & non-idealities
- Previous takeaways confirmed
- Direct approach is more effective at boosting IPI than indirect approach
Conclusion

Two optimization approaches
• Direct approach (cost function) is more suitable for controlling the trade-off than the indirect one (target response)
• Indirect approach is more suitable for rendering audio with specific XTC requirements

Nature of the trade-off
• Only low frequencies are worth the compromise
• The trade-off highly depends on the system setup

Future work
• Evaluating with full measurements
• Conducting comprehensive subjective study
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