NUMERICAL OPTIMIZATION OF LOUDSPEAKER CONFIGURATION FOR SOUND ZONE REPRODUCTION

15th July 2014

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Numerical optimization of loudspeaker configuration for sound zone reproduction

- Personal sound is an active research topic
• Personal sound is an active research topic

• A number of control strategies proposed [1]

• Loudspeaker arrays for personal audio:
  – Compact line array [e.g. 2,3]

**Introduction**

- **Loudspeaker arrays for personal audio:**
  - Compact line array
  - Circular array [e.g. 4,5]

Introduction

• Loudspeaker arrays for personal audio:
  – Compact line array
  – Circular array

• Both array types may have benefits
• Users may have some freedom to position loudspeakers
• We investigate optimal loudspeaker placement
**Introduction**

- Best positions for $N$ loudspeakers?
- Can optimized arrays give...
  - Improved cancellation?
  - Better control of target sound field?
  - Reduced power consumption?
  - Increased robustness?
  - Improved compensation for room?
Introduction

• Previous work
  – Crosstalk cancellation [6,7]
  – Sound zones [8]


Approach

• Sound zone source weights calculated with acoustic contrast control [9,10]

Min. $J_{ACC} = p_B^H p_B + \mu (p_A^H p_A - A) + \lambda (q^H q - Q)$

Evaluation metrics

- Generalizable set of metrics

<table>
<thead>
<tr>
<th>Evaluation metric</th>
<th>Linked characteristics</th>
</tr>
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<tbody>
<tr>
<td>Contrast</td>
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\[
C = 10 \log_{10} \left( \frac{M_B^H O_A O_A}{M_A^H O_B O_B} \right)
\]

number of observation microphones in zone B

observed sound pressures in zone A

number of observation microphones in zone A

observed sound pressures in zone B
### Evaluation metrics

- **Generalizable set of metrics**

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<tr>
<td>Control effort ( E )</td>
<td>Robustness, low electrical power</td>
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**Contrast** equation:

\[
\eta = \frac{\sum_i w_i u_i \cdot u_\alpha}{\sum_i w_i}
\]

- Energy coincident with the principal plane wave direction
- Total energy in the zone

**Numerical optimization of loudspeaker configuration for sound zone reproduction**
Evaluation metrics

- Generalizable set of metrics

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<td>$E$</td>
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$E = 10 \log_{10} \left( \frac{q^H q}{|q_r|^2} \right)$

- Sum of squared loudspeaker weights
- Reference loudspeaker weight

- Generalizable set of metrics

- Contrast
  - Minimal interference
- Planarity
  - Spatial sound distribution
- Control effort
  - Robustness, low electrical power
• Defined optimization cost function based on physical metrics

\[ Y = w_c C - w_e E + w_m M + w_\eta \eta \]

– Where

\[ M = -10 \log_{10} \left( \| \mathbf{G}_B^H \mathbf{G}_B \|_1 \| \mathbf{G}_B^H \mathbf{G}_B^{-1} \|_1 \right) \]

• Choose or optimize weighting coefficients

• Could use perceptual model [12]

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Approach

- **Sequential Forward-Backward Search** \cite{13}
  - +2, -1
- Applied each element in turn
- Focus here on contrast-only case
  - Other results included in paper
  - Selected between 6 and 30 optimal positions
  - Based on predicted performance
    (mean at 100, 200, ..., 4000 Hz for both zones)


Numerical optimization of loudspeaker configuration for sound zone reproduction
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- 60 channel circular candidate array
- Two $25 \times 35$ cm zones
- Independent performance measurement set
Results

- Array configurations
  - 10 loudspeaker example

Contrast-only

Arc

Circle
• Acoustic contrast (average over freq.)

- Circle worst over frequency
- Optimal set best for 6 loudspeakers
Results

• 10 loudspeakers over frequency

Numerical optimization of loudspeaker configuration for sound zone reproduction
Results

- Sound pressure level
  - 2650 Hz notch, simulated in free-field
Summary

• Loudspeaker array geometries not previously investigated for sound zones
• Proposed objective function based on physical metrics
• Improved min. contrast by 6 dB compared to reference arrays (10 loudspeaker example)
• Further work should investigate:
  – Weighting of cost function
  – Extended loudspeaker sets
  – Advanced numerical search methods
Did you see my last talk?

Paper #558

Stereophonic personal audio reproduction using planarity control optimization
Acknowledgements

Thanks to Alice Duque who made RIR measurements

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Results

• Optimal 10 channel arrays for other weights:

Contrast-only  Effort-only  Condition-only  Planarity-only

Numerical optimization of loudspeaker configuration
for sound zone reproduction
Results

- **Optimal 10 channel arrays:**

<table>
<thead>
<tr>
<th>Weights</th>
<th>C (dB) Mean</th>
<th>C (dB) Min.</th>
<th>E (dB) Mean</th>
<th>E (dB) Min.</th>
<th>η (%) Mean</th>
<th>η (%) Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>νc  νe  νm  νη</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>contrast-only</td>
<td>1 0 0 0</td>
<td>13.4</td>
<td>7.2</td>
<td>-4.1</td>
<td>60.3</td>
<td>4.0</td>
</tr>
<tr>
<td>effort-only</td>
<td>0 1 0 0</td>
<td>13.0</td>
<td>5.2</td>
<td>-4.9</td>
<td>74.1</td>
<td>23.9</td>
</tr>
<tr>
<td>condition-only</td>
<td>0 0 1 0</td>
<td>6.2</td>
<td>0.7</td>
<td>-9.3</td>
<td>36.4</td>
<td>-2.7</td>
</tr>
<tr>
<td>planarity-only</td>
<td>0 0 0 1</td>
<td>14.6</td>
<td>7.0</td>
<td>-4.4</td>
<td>83.5</td>
<td>23.7</td>
</tr>
</tbody>
</table>
• Measure room responses (60 × 768)
• Select optimal loudspeakers
• Calculate optimal source weights for each frequency
• Inverse FFT/shift to make FIR filters (×60)
• Independent performance measurement set