Implementation of cross-talk canceling filters with warped structures - Subjective evaluation of the loudspeaker reproduction of stereo recordings

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Outline

- Sound reproduction quality;
- Analysis and compensation of distortion and reduction of cross-talk paths;
- Software and hardware implementation;
- Experimental results;
- Demonstration;
Audio processor design

Design a filter so that \[ \text{Measured SPL} = \text{Target SPL} \]
Equalization architecture design

Standard acoustic measurements

Room measurements

Equalization filter synthesis

Filter Taps reduction

Filter implementation

DSP code (common)

Software tools (parametric)

Room measurements

Boston, September 11-13
Tools

- **Hardware:**
  - Analog Devices SHARC 21061/21065 boards;

- **Software:**
  - AURORA: measurements and acoustic characterization
  - MATLAB for filters design;
Aurora

- Plug-ins of Syntrillium CoolEdit™, http://www.sytrillium.com
- AURORA™: http://www.ramsete.com/aurora
  - TIM filter
  - Convolve with Clipboard
  - Generate MLS Signal
  - Generate IRS Signal
  - Deconvolve MLS Signal
  - Deconvolve IRS Signal
  - Acoustical Parameters
  - Inverse Filter
  - Flatten Spectrum
  - Subtract Convolved;
Aurora GUI
Design-flow

Standard acoustic measurements

Software tools (parametric)

DSP code (common)

Acoustic validation (common)

Filter Taps synthesis & reduction

Filter code synthesis

Filter implementation

Car cockpit measurements
Warped FIR

- Warped FIR algorithm. You can get more info on this specific algorithm looking at:
  
  http://www.acoustics.hut.fi/publications/papers.html
  http://www.acoustics.hut.fi/software/warp
  http://www.ludd.luth.se/~torger/filter.html
Warping: Frequency mapping

- Applying the following bilinear transformation to the $z$-plane

\[
    z = A_{\lambda}(\zeta) = \frac{\zeta + \lambda}{1 + \zeta \cdot \lambda}
\]

- Sampling-rate is not constant
- Consistent with psychoacoustics representations
Warping FIR

- Same structure as FIR, the delay unit is replaced by

\[ D_1(z) = \frac{z^{-1} - \lambda}{1 - \lambda \cdot z^{-1}} \]

- The FIR features:
  - Poor resolution at low frequencies
  - Properties well defined on a linear frequency scale
  - Linear phase
  - Short execution time (0.5 clock cycles / tap)
  - No added quantization noise
Warping FIR

\[ \text{LCNTR} = \text{Wfilter}\_\text{taps}-1, \text{DO wmac}\_\text{rr UNTIL LCE;} \]

\[ F_{12} = F_2 \times F_4, \ F_9 = \text{dm}(I5,M7), \ F_4 = \text{pm}(I9,M8); \]

\[ F_{10} = F_2 \times F_5, \ F_8 = F_8 + F_{12}, \ F_9 = \text{dm}(I5,M6); \]

\[ F_1 = F_9 - F_{10}, \ F_9 = \text{dm}(I5,0); \]

\[ F_{10} = F_1 \times F_7, \ \text{dm}(I5,M7) = F_2; \]

\[ \text{wmac}\_\text{rr}: \ F_2 = F_9 + F_{10}; \]

/* convolution */

\[ \text{LCNTR} = \text{Ff}\_\text{taps}-1, \text{DO lpf}\_\text{filter}\_\text{rr UNTIL LCE;} \]

\[ \text{lpf}\_\text{filter}\_\text{rr}: \ F_8 = F_2 \times F_4, \ F_{12} = F_8 + F_{12}, \ F_2 = \text{dm}(I5,M5), \ F_4 = \text{pm}(I9,M9); \]
Warping Frequency mapping

\[ \lambda = 0.8 \]
\[ \lambda = 0.75 \]
\[ \lambda = 0.7 \]
\[ \lambda = 0.5 \]

\( \lambda > 0 \)
\( \lambda < 0 \)
Warping Frequency mapping

- Frequency response of a car cockpit
- FIR

![Graph showing FRF and samples](image-url)
Warping Frequency mapping

- Frequency response of a car cockpit
- Frequency remapping by Warping
Warping Frequency mapping

- Frequency response of a car cockpit
- WFIR

![Graph showing frequency response of a car cockpit with FRF and samples](image)
FIR synthesis vs WFIR synthesis

- 30 taps WFIR
- 30 taps FIR
Sound harmonization

- Equalization is not sufficient to achieve a global increase of sound comfort;
- Harmonization of sound image achieves a subjective improvement of binaural sound quality;
  - *Stereo-dipole systems*
Stereo dipole system

Design $H$ so that:

Ideal condition:

$$S_L = L \cdot C_{LL}$$
$$S_R = R \cdot C_{RR}$$
Stereo dipole system

Audio source

L

R

H_{LL}

H_{LR}

H_{RL}

H_{RR}

Cross-talk paths

C_{LL}

C_{LR}

C_{RL}

C_{RR}

S_L

S_R
Stereo dipole structure

**Target:**

\[
S_L = L \cdot C_{LL} \\
S_R = R \cdot C_{RR}
\]

\[\Rightarrow\]

\[
f_{ll} = (h_{rr}) \otimes \text{InvDen} \\
f_{lr} = (-h_{lr}) \otimes \text{InvDen} \\
f_{rl} = (-h_{rl}) \otimes \text{InvDen} \\
f_{rr} = (h_{ll}) \otimes \text{InvDen} \\
\text{InvDen} = \text{InvFilter}(h_{ll} \otimes h_{rr} - h_{lr} \otimes h_{rl})
\]

**In the frequency domain:**

\[C(\omega) = \text{FT}(h_{ll}) \cdot \text{FT}(h_{rr}) - \text{FT}(h_{lr}) \cdot \text{FT}(h_{rl})\]

**Hence:**

\[\text{InvDen}(\omega) = \frac{\text{Conj}[C(\omega)]}{\text{Conj}[C(\omega)] \cdot C(\omega) + \varepsilon(\omega)}\]

\(\varepsilon(\omega)\) is a function of frequency
ASK listening room
Digital implementation

- **DSP SHARC 21061 EZ-LITE:**
  - 40 Mips, with which 880 Taps can be computed for each sample @ 44100 Hz
- **DSP SHARC 21065L**
- **AD 1847 @ 44100/48000;**
Experimental results
(Measured binaural response of the room)
Experimental results
(2048 FIR cross-talk cancelling filters)
Experimental results
(Measured response with 2048 FIR)
Experimental results
(220 FIR cross-talk cancelling filters)
Experimental results
(Measured response with 220 FIR)
Experimental results
(42 WFIR cross-talk cancelling filters)
Experimental results
(Measured response with 42 WFIR)
Subjective tests

- Subjective tests have been performed by trained people, no time-limit, several choices of music available;
- Blind Evaluation for each of the four systems (the listener can switch between them at any time):
  - WFIR
  - FIR
- 7 question with a 0-5 score.
- ANOVA statistical post-processing analysis
## Subjective tests

<table>
<thead>
<tr>
<th>Question</th>
<th>Avg. FIR</th>
<th>Avg. WFIR</th>
<th>Anova's F factor</th>
<th>Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall appreciation</td>
<td>3.57</td>
<td>4.79</td>
<td>34.47</td>
<td>0.00%</td>
</tr>
<tr>
<td>Image localization</td>
<td>3.79</td>
<td>4.36</td>
<td>4.38</td>
<td>4.63%</td>
</tr>
<tr>
<td>Stage amplitude</td>
<td>3.50</td>
<td>4.71</td>
<td>21.72</td>
<td>0.01%</td>
</tr>
<tr>
<td>Naturality</td>
<td>3.71</td>
<td>4.57</td>
<td>10.88</td>
<td>0.28%</td>
</tr>
<tr>
<td>Low frequency resp.</td>
<td>3.29</td>
<td>4.36</td>
<td>11.56</td>
<td>0.22%</td>
</tr>
<tr>
<td>Mid frequency resp.</td>
<td>3.79</td>
<td>4.07</td>
<td>1.60</td>
<td>21.71%</td>
</tr>
<tr>
<td>Hi frequency resp.</td>
<td>4.14</td>
<td>4.43</td>
<td>0.98</td>
<td>33.10%</td>
</tr>
</tbody>
</table>
Subjective tests

Averages, standard deviations and ANOVA probability results

<table>
<thead>
<tr>
<th>Question</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Overall appreciation</td>
<td>5.00%</td>
</tr>
<tr>
<td>2-Image localization</td>
<td>4.63%</td>
</tr>
<tr>
<td>3-Stage amplitude</td>
<td>0.01%</td>
</tr>
<tr>
<td>4-Naturality</td>
<td>0.28%</td>
</tr>
<tr>
<td>5-Low frequency resp.</td>
<td>0.22%</td>
</tr>
<tr>
<td>6-Mid frequency resp.</td>
<td>21.71%</td>
</tr>
<tr>
<td>7-High frequency resp.</td>
<td>33.10%</td>
</tr>
</tbody>
</table>

Question:
- WFIR
- FIR
Conclusions

- Multi-channel Warped filter equalization and harmonization;
- Automatic design of audio processors with standard acoustic measurements (AURORA);
- Implementation on DSP systems;
- Experimental results and listening tests;