Reverberation Enhancement Systems with Time-Varying Mixing Matrices

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1. Introduction

2. Recap: Reverberation Enhancement Systems

3. Time-varying Processing

4. Evaluation

5. Conclusion
Introduction

What is a reverberation enhancement system?

Reverberation is added by controlled feedback between microphones and loudspeakers.
Introduction

Why use a reverberation enhancement system?

Music venues may need
- improvement of poor acoustical design,
- flexible acoustics for different genres of music.

Reverberation enhancement systems (RESs) can
- increase the level of reverberation,
- extend the reverberation time,
- increase the sense of envelopment.
Introduction

Electro-Acoustic Feedback: Isn’t this dangerous?

The requirements for RESs are
- stability,
- absence of coloration.

The stability of RESs can be improved by
- de-coupling of loudspeakers and microphones,
- equalization,
- active feedback cancellation,
- time-variation.
Introduction

Types of Time-Variation

Existing techniques are
- frequency shifting (FS) [Schroeder (1962)],
- delay line modulation (DL) [Griesinger (1991)],
- allpass modulation (AP) [Lokki and Hiipakka (2001)].

But
- frequency of musical signals can be altered considerably (FS),
- inaccurate frequency response and reverberation time (DL),
- time-variation itself can be unstable (AP),
- number of time-varying coefficients is small (AP, FS, DL).

The proposed technique is feedback matrix modulation, which is guaranteed to be stable and has a quadratic number of time-varying coefficients.
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Recap: Reverberation Enhancement Systems

General Structure
Recap: Reverberation Enhancement Systems

Stability of RES

The stability of an RES depends on $G_{ML}H_{LM}$.

Nyquist stability for single channel feedback:
- $G_{ML}(\omega)H_{LM}(\omega)$ does not encircle the point $1 + j0$

Nyquist stability for multi channel feedback [MacFarlane and Postlethwaite (1977)]:
- Given the eigenvalue decomposition per frequency:
  $$G_{ML}(\omega)H_{LM}(\omega) = V \Gamma(\omega)V^{-1},$$
  - Characteristic functions $\gamma_i(\omega)$ do not encircle the point $1 + j0$. 

Recap: Reverberation Enhancement Systems

Gain-Before-Instability

The gain-before-instability (GBI) is the gain \( \mu \) where \( \mu G_{ML} H_{LM} \) has a 50% risk of instability. \( K \) is the number of independent frequency bins.

\[ f = \frac{1}{1 - f^K} \]
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Time-varying Processing

Why does time-variation help?

time point 1

time point 2

mean frequency response
Time-varying Processing
Two Types of Processors
The eigenvalue decomposition of the feedback matrix is given by

\[ A(n) = U^H \Lambda(n) U, \]

where \( \Lambda(n) = \text{diag}(\lambda_1(n), \ldots, \lambda_N(n)) \) with the eigenvalues \( \lambda_i(n) \). Matrix \( A(n) \) is real, but \( U \) and \( \Lambda(n) \) are typically complex.

For energy conservation, all \( |\lambda_i(n)| = 1 \), i.e. all eigenvalues lie on the unit circle.
Time-varying Processing

Time-varying Matrix Eigenvalues

The angular evolution of the eigenvalues are triangular waves with
- modulation frequency,
- modulation amplitude,
- modulation spread.

Starting values can be chosen arbitrarily, e.g. all as zeros.

⇒ $N$ time-varying eigenvalues, but $N^2$ time-varying matrix entries.
Time-varying Processing

Time-Varying Feedback Delay Network (FDN)

Feedback loop creates artificial reverberation with a specified reverberation time.

Optimized structure to maximize effect of time-variation.
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Evaluation

Choice of Simulation Room

- Small office space with size 5.8 x 3.9 x 3.1 m
- Mean reverberation time of 0.5 s
- 4 loudspeakers and 4 microphones
- Three types of room acoustics
Evaluation
Choice of Processor

Matrix Modulation has
- modulation amplitude $0 - 2$,
- mean frequency up to 3 Hz,
- frequency spread of 10%.

Feedback Delay Network has
- 8 delay lines,
- reverberation time of 1.5 seconds.
Evaluation

GBI with Time-Varying Mixing

anechoic $H_{LM}$

synthetic $H_{LM}$

measured $H_{LM}$
Evaluation

GBI with Time-Varying FDN

anechoic $H_{LM}$

synthetic $H_{LM}$

measured $H_{LM}$
Evaluation
Comparison between Mixing and FDN

measured $H_{LM}$, Mixing

measured $H_{LM}$, FDN
## Evaluation

### GBI Improvement via Time-Variation

For the measured room impulse responses:

<table>
<thead>
<tr>
<th>GBI [dB]</th>
<th>FDN</th>
<th>Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Time-Variation</td>
<td>-13.1</td>
<td>-9.7</td>
</tr>
<tr>
<td>Max Time-Variation</td>
<td>-5.8</td>
<td>-6.6</td>
</tr>
<tr>
<td>Improvement</td>
<td>7.3</td>
<td>3.1</td>
</tr>
</tbody>
</table>

The enhancement of 7.3 dB is an *improvement of 30%* compared to the 5.6 dB found for time-varying allpass FDNs.
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Conclusion

Take home messages

Time-varying mixing matrices in RESs have been proposed:
- Two types of processor: mixing and FDN.
- RES optimized FDN structure has been proposed.
- Quadratic number of time-varying coefficients.

Simulation results show
- GBI increases up to 7.4 dB for FDN based RES.
- GBI improvements of 30% compared to allpass FDNs.
Conclusion

Open Questions

- What is the perceptually preferable time-variation technique?
- What is the perceptually preferable amount of modulation?
Conclusion

Thank you very much for your attention.
Conclusion

Two Types of Processors

Mixing Matrix
- Relies on microphone - loudspeaker coupling
- Computationally cheap
- Reverberation time is dependent on feedback gain
- RES extends the physical reverberation

Feedback Delay Network
- Independent from microphone - loudspeaker coupling
- Computationally expensive
- Reverberation time is specified by FDN
- RES superposes artificial reverberation
Conclusion

Risk of Instability without Time-Variation

Single Channel RES

Four Channel RES
Conclusion

Comparison to Time-Varying Allpass FDN

Time-varying Allpass FDNs [Lokki and Hiipakka (2001)]
- can be unstable under strong variation
- introduce a frequency dependent delay which decreases the accuracy of the reverberation time specification
- with comb-based allpass filters have ringing tails, which depend on the feedforward-feedback gain
- there are only two time-varying coefficients per delay line
- provide experimental GBI improvement up to 5.6 dB.
### Extrema of the mean GBI

<table>
<thead>
<tr>
<th>Mixing Type</th>
<th>Min[dB]</th>
<th>Max[dB]</th>
<th>Enhancement [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anechoic</td>
<td>-3.8</td>
<td>-1.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Measured</td>
<td>-9.7</td>
<td>-6.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Synthetic</td>
<td>-4.9</td>
<td>-2.0</td>
<td>2.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Anechoic</td>
<td>-7.6</td>
<td>-1.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Measured</td>
<td>-13.1</td>
<td>-5.8</td>
<td>7.3</td>
</tr>
<tr>
<td>Synthetic</td>
<td>-8.5</td>
<td>-1.1</td>
<td>7.4</td>
</tr>
</tbody>
</table>

=> Improvement of 30% compared to time-varying allpass FDN.

