AUDIO LABS

Reverberation Enhancement Systems with Time-Varying Mixing Matrices

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Content

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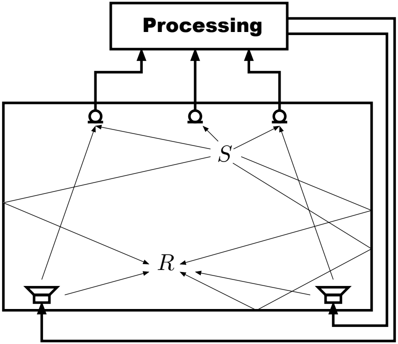
Introduction

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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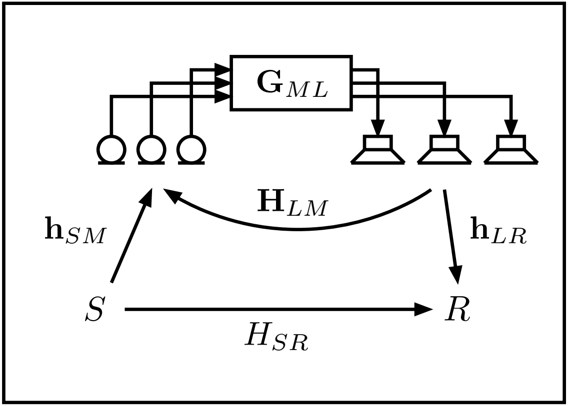
Recap: Reverberation Enhancement Systems

General Structure



Recap: Reverberation Enhancement Systems

Stability of RES

The stability of an RES depends on $\mathbf{G}_{ML}\mathbf{H}_{LM}$.

Nyquist stability for single channel feedback:

- $\mathbf{G}_{ML}(\omega)\mathbf{H}_{LM}(\omega)$ does not encircle the point $1 + \imath 0$

Nyquist stability for multi channel feedback [MacFarlane and Postlethwaite (1977)]:

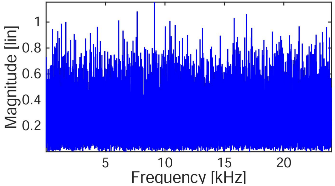
- Given the eigenvalue decomposition per frequency:

$$\mathbf{G}_{ML}(\omega)\mathbf{H}_{LM}(\omega) = \mathbf{V}\,\mathbf{\Gamma}(\omega)\mathbf{V}^{-1},$$

- Characteristic functions $\gamma_i(\omega)$ do not encircle the point $1 + \imath 0$.

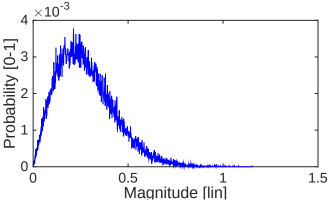
Recap: Reverberation Enhancement Systems

Gain-Before-Instability



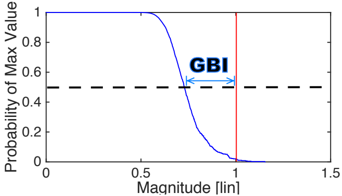
Magnitude Response $|\gamma_i(\omega)|$

$\Rightarrow$



Probability Density f

$\Rightarrow$



Cumulative Density $1 - f^K$

The gain-before-instability (GBI) is the gain μ where $\mu \mathbf{G}_{ML}\mathbf{H}_{LM}$ has a 50% risk of instability.

K is the number of independent frequency bins.

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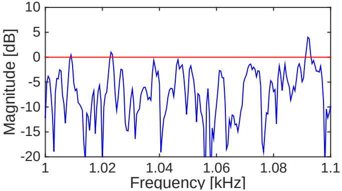
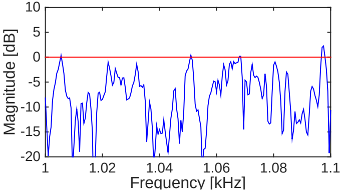
Time-varying Processing

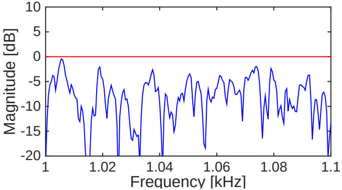
Why does time-variation help?



time point 1



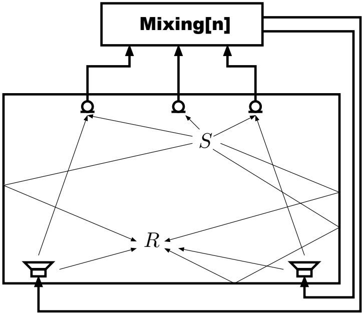
time point 2

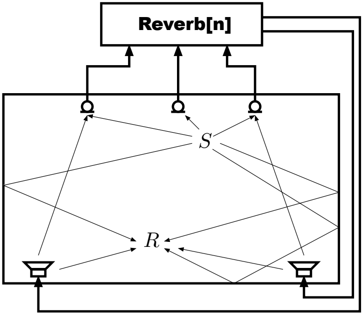


mean frequency response

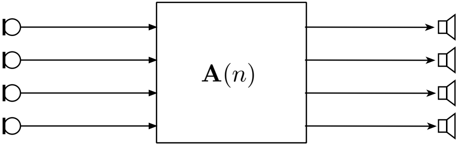
Time-varying Processing

Two Types of Processors





Time-varying Processing
Time-Varying Mixing Matrix



The eigenvalue decomposition of the feedback matrix is given by

$$\mathbf{A}(n) = \mathbf{U}^H \, \mathbf{\Lambda}(n) \, \mathbf{U},$$

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

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

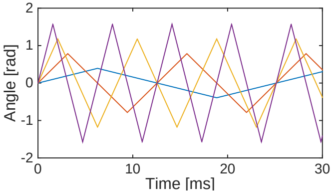
Time-varying Processing

Time-varying Matrix Eigenvalues

The angular evolution of the eigenvalues are triangular waves with

- modulation frequency,
- modulation amplitude,
- modulation spread.

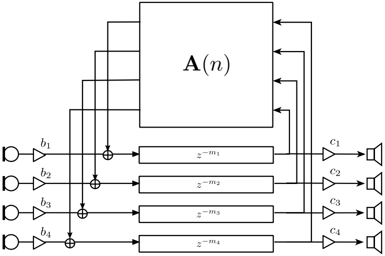
Starting values can be chosen arbitrarily, e.g. all as zeros.



$\Rightarrow N$ time-varying eigenvalues, but N^2 time-varying matrix entries.

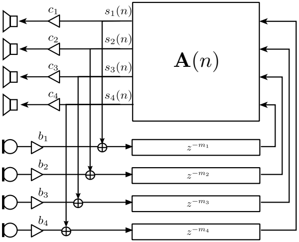
Time-varying Processing

Time-Varying Feedback Delay Network (FDN)



Standard FDN

$\Longrightarrow$



RES optimized FDN

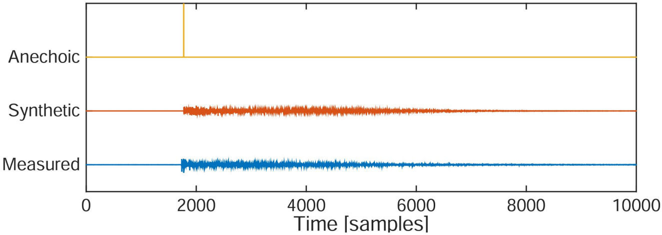
- Feedback loop creates artificial reverberation with a specified reverberation time.
- Optimized structure to maximize effect of time-variation.

Content

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

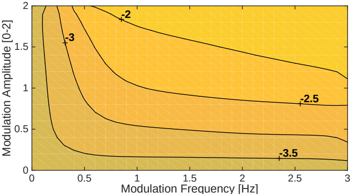
- modulation amplitude $0 - 2$,
- mean frequency up to 3 Hz,
- frequency spread of 10%.

Feedback Delay Network has

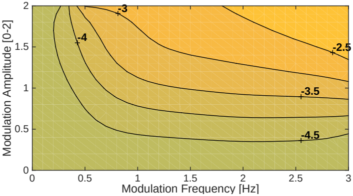
- 8 delay lines,
- reverberation time of 1.5 seconds.

Evaluation

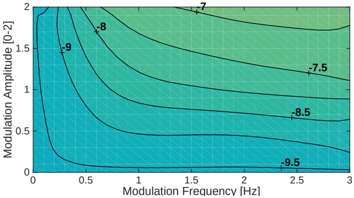
GBI with Time-Varying Mixing



anechoic $\mathbf{H}_{LM}$



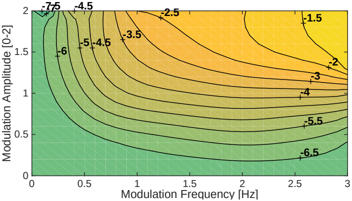
synthetic $\mathbf{H}_{LM}$



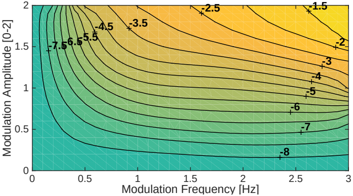
measured $\mathbf{H}_{LM}$

Evaluation

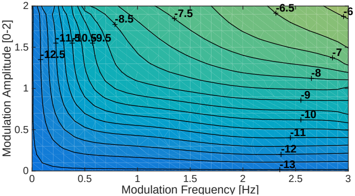
GBI with Time-Varying FDN



anechoic $\mathbf{H}_{LM}$



synthetic $\mathbf{H}_{LM}$



measured $\mathbf{H}_{LM}$

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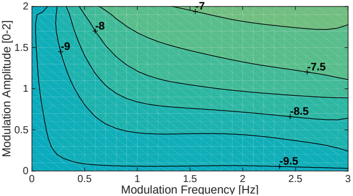
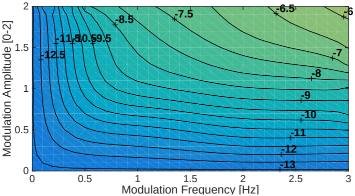
Evaluation

Comparison between Mixing and FDN



measured $\mathbf{H}_{LM}$, Mixing



measured $\mathbf{H}_{LM}$, FDN

Evaluation

GBI Improvement via Time-Variation

For the measured room impulse responses:

GBI [dB]	FDN	Mixing
No Time-Variation	-13.1	-9.7
Max Time-Variation	-5.8	-6.6
Improvement	7.3	3.1

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

Content

1. Introduction
2. Recap: Reverberation Enhancement Systems
3. Time-varying Processing
4. Evaluation
5. Conclusion

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?

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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

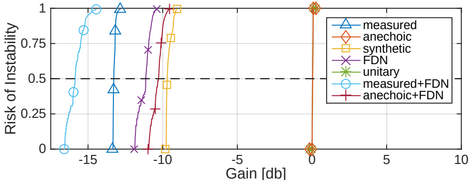
Feedback Delay Network

- Independent from mic - loudspeaker coupling
- Computationally expensive
- Reverberation time is specified by FDN
- RES superposes artificial reverberation

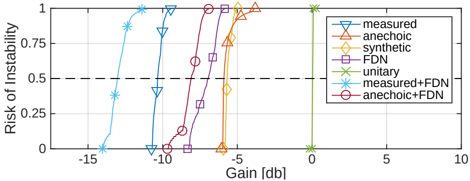
Conclusion

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.

Conclusion

Extrema of the mean GBI

Mixing	Min[dB]	Max[dB]	Enhancement [dB]
Anechoic	-3.8	-1.2	2.6
Measured	-9.7	-6.6	3.1
Synthetic	-4.9	-2.0	2.9

FDN	Min[dB]	Max[dB]	Enhancement [dB]
Anechoic	-7.6	-1.1	6.5
Measured	-13.1	-5.8	7.3
Synthetic	-8.5	-1.1	7.4

$\Longrightarrow$ Improvement of 30% compared to time-varying allpass FDN.

Bibliography

David Griesinger. Improving room acoustics through time-variant synthetic reverberation. In *Audio Engineering Society Convention 90*, pages 1–10, Paris, France, 1991.

T. Lokki and J. Hiipakka. A time-variant reverberation algorithm for reverberation enhancement systems. In *Proceedings of COST G-6 Conference on Digital Audio Effects (DAFX-01), Limerick, Ireland*, pages 28–32, 2001.

Alistair GJ MacFarlane and Ian Postlethwaite. The generalized nyquist stability criterion and multivariable root loci. *International Journal of Control*, 25(1): 81–127, 1977.

Manfred R. Schroeder. Improvement of feedback stability of public address systems by frequency shifting. *J. Audio Eng. Soc*, 10(2):108–109, 1962. URL `http://www.aes.org/e-lib/browse.cfm?elib=867`.