Spectral Delay Filters with Feedback and Time-Varying Coefficients

DAFx-09 presentation

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Introduction

Spectral Delay Filtering?

- Frequency-dependent delay — **Demo:** Original
- Earlier with STFT — Filtered
  - D. Kim-Boyle, "Spectral Delays with Frequency Domain Processing," in *Proc. DAFx-04*, pp. 42–45, Naples, Italy, Oct. 2004.
  - X. Amatriain, *An Object Oriented Metamodel for Digital Signal Processing with a Focus on Audio and Music*, PhD. thesis, Universitat Pompeu Fabra, Barcelona, Spain, 2004.

Alternative Approach to STFT?

- Inherently better resolution & large delays with less memory?

⇒ Solution: Cascaded allpass filters
  - V. Välimäki, J. S. Abel and J. O. Smith, "Spectral Delay Filters," *J. Audio Eng. Soc.*, vol. 57, no. 7/8, pp. 521–531, July/Aug. 2009.

Cascaded First-Order Allpass Filters

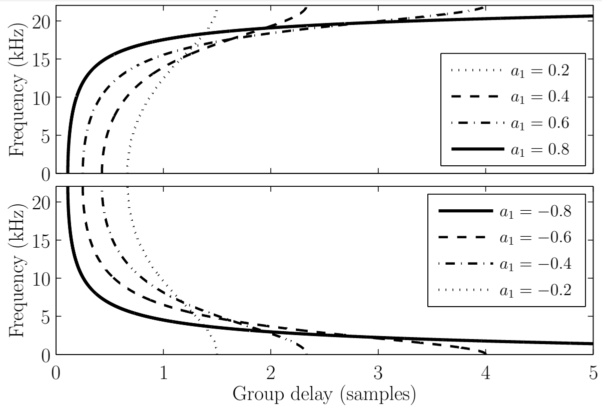
Frequency-Dependent Delay Produced by a Filter

- Described by the group delay
- Cascading of filters sums the individual group delays!

Positive coefficient

First-order allpass filter
$\left(\frac{a_1 + z^{-1}}{1 + a_1 z^{-1}}\right)$

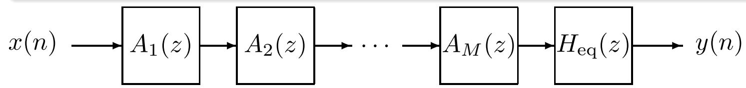
Negative coefficient



Cascaded First-Order Allpass Filters

Spectral Delay Filter (SDF)

- Cascade of several first-order allpass filters ($A_i(z)$)
- Includes also an optional equalization filter ($H_{eq}(z)$)

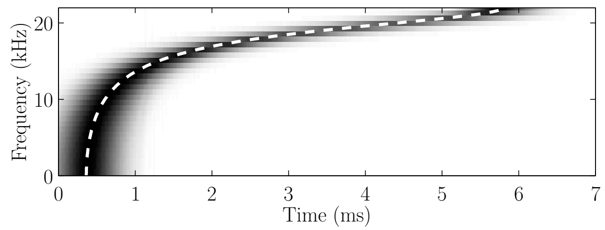


Impulse response, $a_1 = -0.9$, no EQ:

$M = 256$

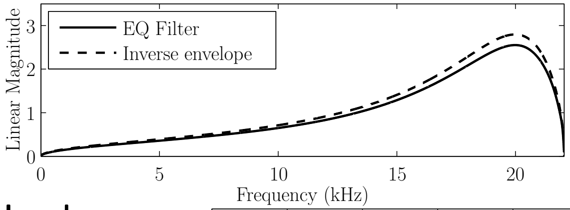
$M = 512$

$M = 1024$



(plot with $M = 64$ and $a_1 = 0.6$)

Equalization Filter Design



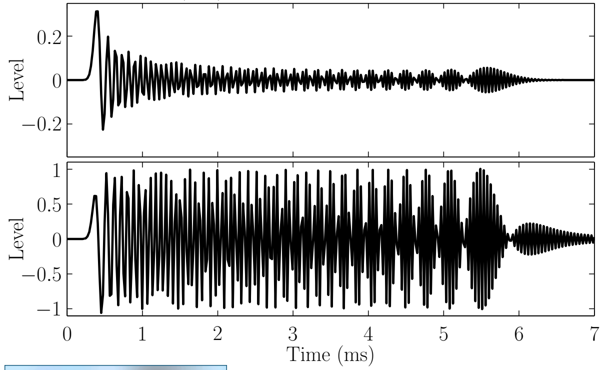
Design Example:

- $M = 1$
- $a_1 = 0.6$
- Without scaling

Impulse response, $M = 1024$, $a_1 = -0.9$:

Without EQ

With EQ



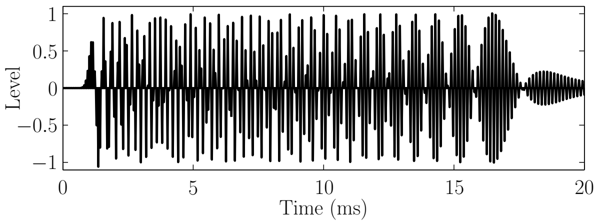
(plots with $M = 64$ and $a_1 = 0.6$)

Stretched Spectral Delay Filters

Multirate Version of the Basic SDF

- Every unit delay replaced with K unit delays (in EQ filter, too!)

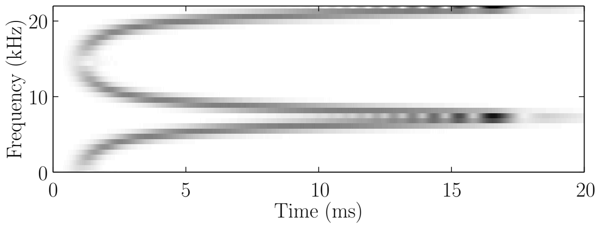
Impulse response, $M = 1024$, $K = 3$, $a_1 = -0.9$:



"Alien hiccup"

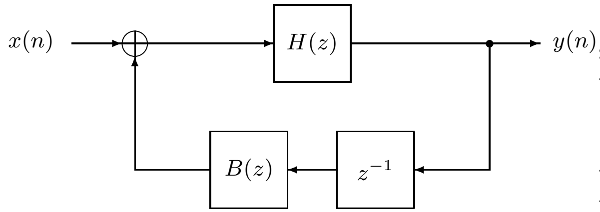
Original

Filtered



(plots with $M = 64$ and $a_1 = 0.6$)

Spectral Delay Filters with Feedback



$H(z)$: The spectral delay filter

$B(z)$: The feedback filter

Stability Conditions

- Both filters causal and stable
- The loop gain less than unity at all frequencies

Feedback Filter Design Issues

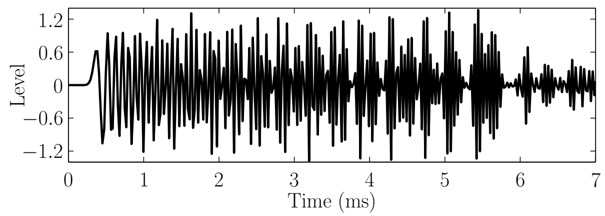
- The gain of $H(z)$ determined solely by the EQ filter
- ⇒ Sufficient attenuation must be applied by the feedback filter
- ⇒ Unsophisticated (low-order) filter designs often impractical

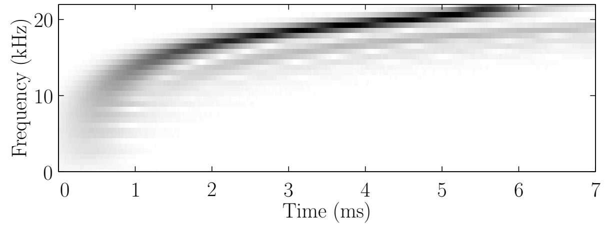
Spectral Delay Filters with Feedback

Design Example

- Feedback filter $B(z) = c(1 + z^{-1})$

Impulse response, $M = 256$, $K = 1$, $a_1 = -0.9$, $c = 1/436$





(plots with $M = 64$, $a_1 = 0.6$, $c = 1/23$)

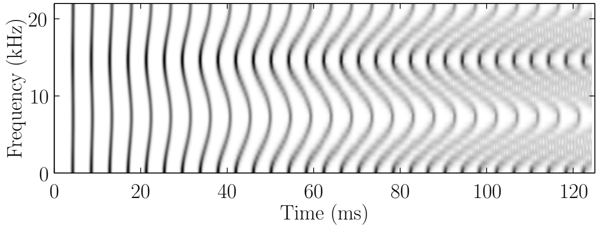
Time-Varying Spectral Delay Filters

Time-Varying Spectral Delay Filtering?

- Coefficients vary in time
- Lively, more dynamic effects obtained

Stability Conditions

- The coefficients in the range $[-1, 1]$, inclusively, for all K!
- Same condition for a time-varying EQ filter
- Gain depends on the modulation (and the input signal)



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Conclusions

Summary

- Frequency-dependent delay implemented with allpass filters
  - Inherently good resolution
  - Large delays obtainable with a low-order filter
- EQ filter to emphasize the slow (soft) part of the chirp
- Multirate structures ⇒ Simultaneous chirps
- Feedback structures ⇒ Series of chirps
- Time-varying structures ⇒ Lively, dynamic effects

Further Pointers

- The conference paper
  - Background paper: V. Välimäki, J. S. Abel and J. O. Smith, "Spectral Delay Filters," *J. Audio Eng. Soc.*, vol. 57, no. 7/8, pp. 521–531, July/Aug. 2009.
- Companion page: `http://www.acoustics.hut.fi/publications/papers/dafx09-sdf/`

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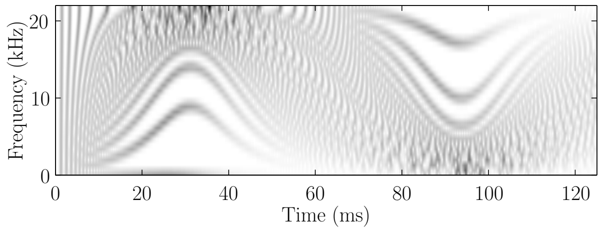
Time-Varying Spectral Delay Filters

Example: $K = 1$, with coefficients modulated with an 8 Hz sine having amplitude 0.9, without EQ filter, and with a feedback path with a constant multiplier of $B(z) = 0.99$

	$M = 256$	$M = 512$	$M = 1024$	
Impulse response	▶	▶	▶	Original
Drumming pattern	▶	▶	▶	▶

Plot: Impulse response with $M = 64$



Paper on Audio-Rate Modulated SDF

- J. Kleimola *et al.*, "Sound Synthesis Using an Allpass Filter Chain with Audio-Rate Coefficient Modulation," in *Proc. DAFx-09*...