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Virtual Analog Modeling Research at Aalto University

Prof. Vesa Välimäki
Department of Signal Processing and Acoustics
Aalto University
(Espoo, FINLAND)

Edinburgh, UK

Feb. 27, 2013

Aalto University

- Formed in 2010 as a merger of 3 universities, including the Helsinki University of Technology (HUT/TKK)
- Otaniemi campus located in the city of Espoo
  - About 10 km from the Helsinki city center

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2

Otaniemi Campus, Espoo, Finland

I work here

Helsinki →

Edinburgh 1700 km ↙

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3

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4

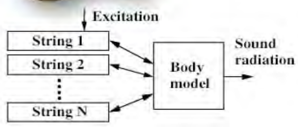
Audio Signal Processing Research Group

- Professor: Dr. Vesa Välimäki
- Senior researchers:
  - Dr. Henri Penttinen
  - Dr. Ole Kirkeby
- Postdoc researchers:
  - Dr. Heidi-Maria Lehtonen
  - Dr. Rémi Mignot (IRCAM)
- 6 researchers (PhD students):
  - S. D'Angelo, S. Oksanen, R. de Paiva, J. Parker, J. Rämö, H. Tuominen
- Visitors
  - From Italy, Estonia, Denmark, …

- Main funding sources
  - Academy of Finland
  - EU
  - GETA, CIMO
  - Companies (Nokia, Sandvik)

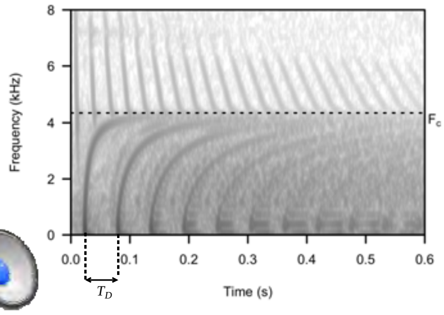
Current Research Topics

- Physical modeling of sound sources
  - Musical instruments and noise sources
- Modeling of analog music technology
  - 'Virtual analog' models
- Sound synthesis and effects processing algorithms
- Headphone audio
- Digital filters for audio processing



Spring Reverberation

- Spring reverberators are an early form of artificial reverberation



- Reminiscent of room reverberation, but with distinctly different qualities
- Our team has characterized the special sound of the spring reverberator, and modeled it digitally

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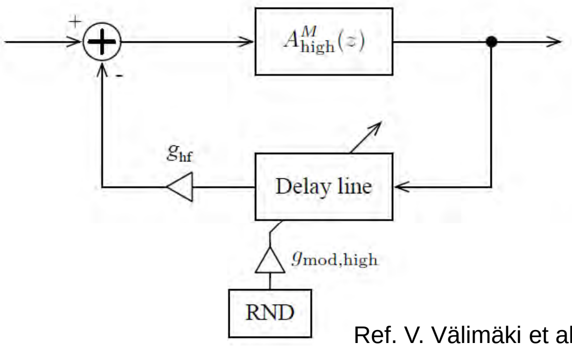
7

Parametric Spring Reverberation Model

- Many (e.g. 100) allpass filters produce a chirp-like response
- A feedback delay loop produces a sequence of chirps
- Random modulation of delay-line length introduces smearing



Ref. V. Välimäki et al., JAES, 2010.

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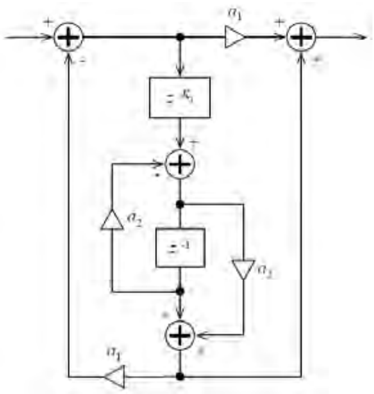
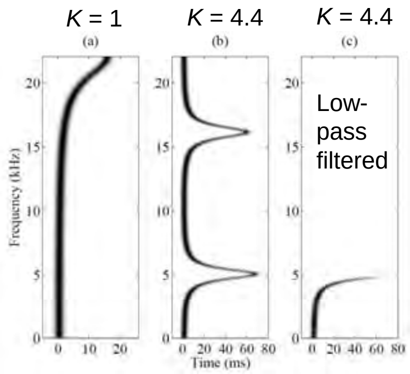
8

Interpolated Stretched Allpass Filter

- A low-frequency chirp is produced by a cascade of ~100 ISAFs

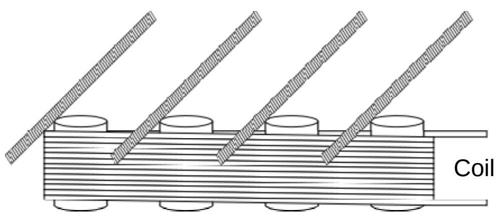




Ref. V. Välimäki et al., JAES, 2010.

Guitar Pickup Modeling

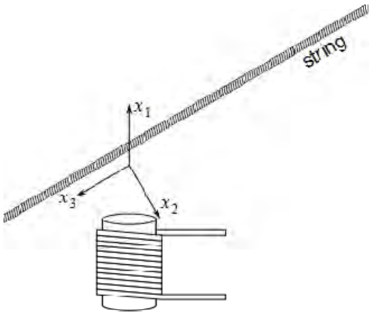
- The pickup is a magnetic device used for capturing string motion
  - Useful in steel-stringed instruments: guitars, bass, the Clavinet

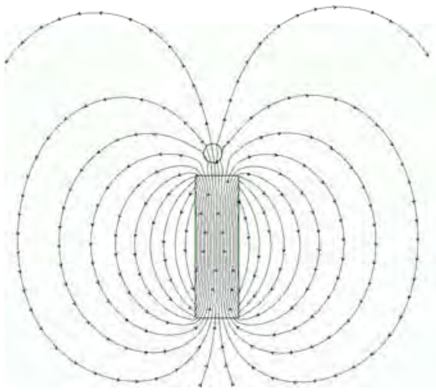


Ref. Paiva et al., JAES, 2012.

Magnetic Induction in Guitar Pickup

- String proximity increases the magnetic flux
- The change causes an alternating current in the winding



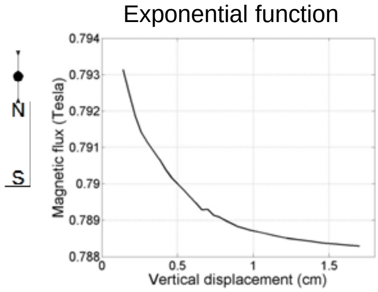


Ref. Paiva et al., JAES, 2012.

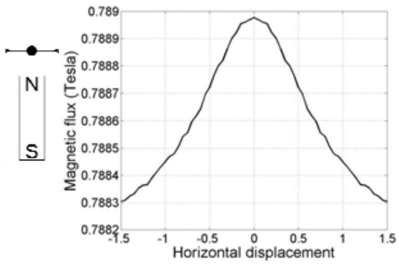
Pickup Nonlinearity

- Sensitivity is different for the vertical and horizontal polarizations
- 2-D FEM simulations using Vizimag

Exponential function



Symmetric bell-shaped

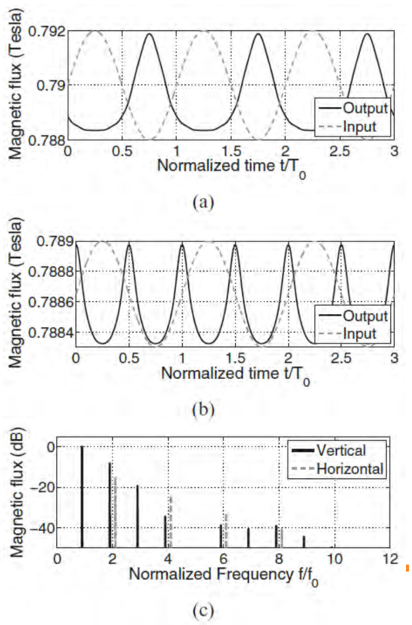


Ref. Paiva et al., JAES, 2012.

Pickup Nonlinearity

a) String displacement in the **vertical** direction leads to harmonic asymmetric distortion (*all* harmonics)

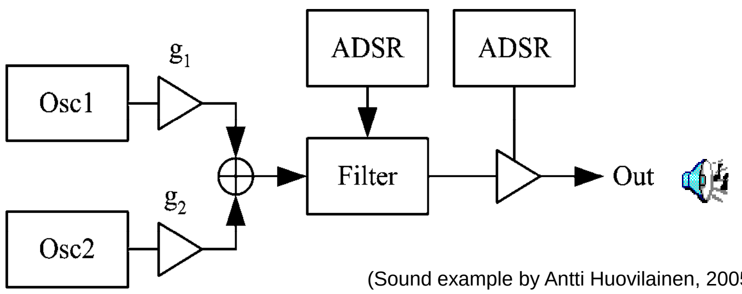
b) String displacement in the **horizontal** direction leads to harmonic symmetric distortion (*even* harmonics)



Ref. Paiva et al., JAES, 2012.

Digital Subtractive Synthesis

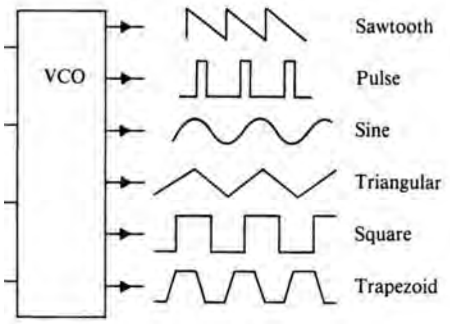
- Emulation of analog synthesizers of the 1970s
- One or more oscillators, e.g., an octave apart or detuned
- Second- or fourth-order resonant lowpass filter
- At least two envelope generators (ADSR)



(Sound example by Antti Huovilainen, 2005)

Oscillators in Subtractive Synthesis

- Usually periodic waveforms
  - All harmonics or only odd harmonics of the fundamental
- Digital implementation must suppress aliasing



(Figure from: T. D. Rossing: *The Science of Sound*. *Second Edition*. Addison-Wesley, 1990.)

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15

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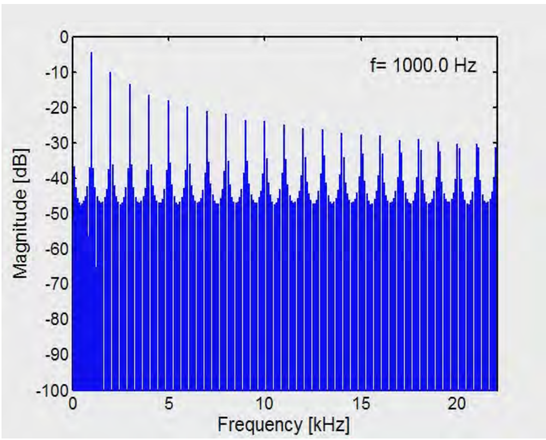
Aliasing – The Movie

- Trivial sampling of the sawtooth signal
- Harsh aliasing particularly at high fund. frequencies
  - Inharmonicity
  - Beating
  - Heterodyning



Video by Andreas Franck, 2012

16

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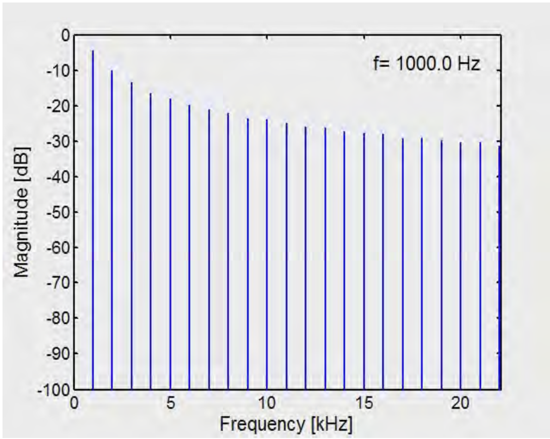
No Aliasing

- Additive synthesis of the sawtooth signal
- Contains harmonics below the Nyquist limit only



Video by Andreas Franck, 2012

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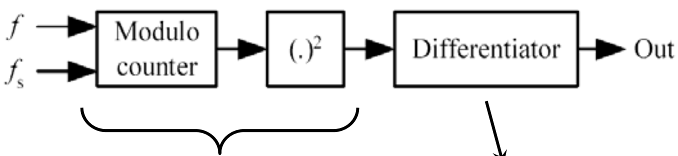
Differentiated Parabolic Wave Algorithm

- A method to produce a sawtooth wave with reduced aliasing (Välimäki, 2005)
  - 2 parameters: fundamental frequency f and sampling frequency f_s



$$p(t) = \int t \mathrm{d}t = \frac{t^2}{2}$$

$H(z) = c\,(1 - z^{-1})$
where $c = f_s/4f$

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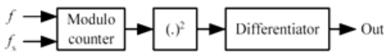
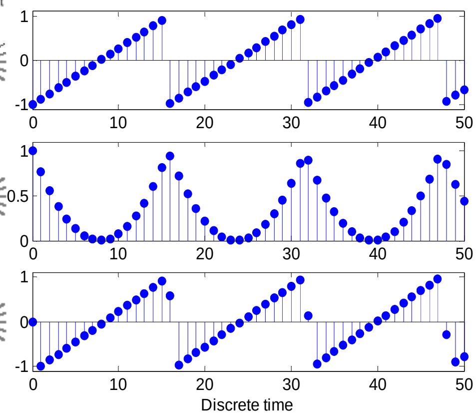
Signal Generation in DPW Algorithm

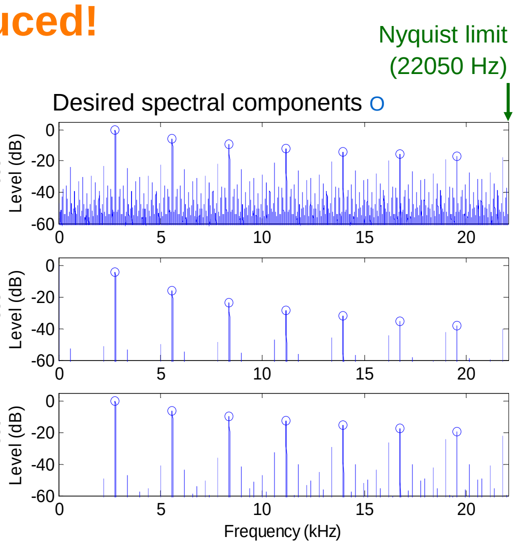


- Output of modulo counter $x(n)$
  - A 'trivial' sawtooth wave
- Squared signal $x^2(n)$
  - Piecewise parabolic wave
- Differentiated signal $c\,[x^2(n) - x^2(n-1)]$
  - Difference of neighbors



Aliasing is Reduced!

- Spectrum of modulo counter signal $x(n)$
- Spectrum of squared signal $x^2(n)$
- Spectrum of differentiated signal $c\,[x^2(n) - x^2(n-1)]$

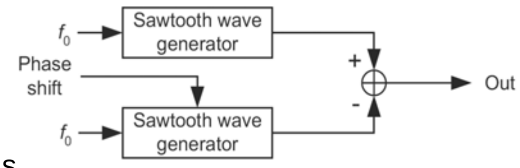


Rectangular Pulse Generation Using DPW

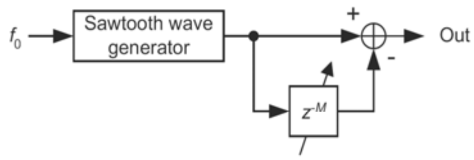
- Two alternative methods
  (Välimäki & Huovilainen 2006)

  (a) Subtract two sawtooths

  (b) Use an FIR comb filter to generate the phase shift, then subtract



(a)



(b)

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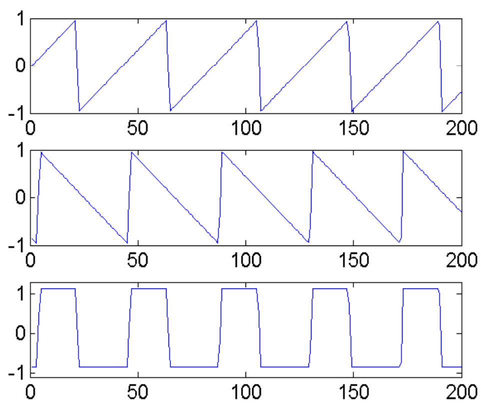
Rectangular Pulse Generation Using DPW

- Sawtooth #1
- Sawtooth #2: Delayed and inverted
- Rectangular pulse



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Higher-order DPW Oscillators

- Trivial sawtooth can be integrated multiple times (Välimäki *et al*., 2010)

Polynomial order	Polynomial function
$N = 1$	x
$N = 2$	x^2
$N = 3$	$x^3 - x$
$N = 4$	$x^4 - 2x^2$
$N = 5$	$x^5 - 10x^3/3 + 7x/3$
$N = 6$	$x^6 - 5x^4 + 7x^2$

The polynomial signal must be differenced $N - 1$ times and scaled to get the sawtooth wave

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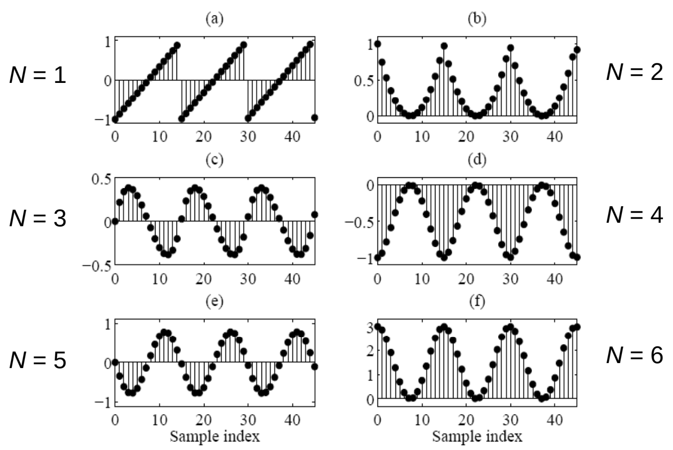
23

Integrated Polynomial Waveforms



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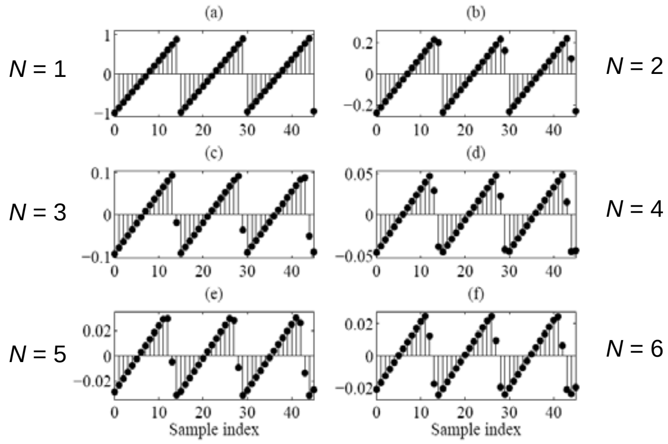
24

Differenced Polynomial Waveforms



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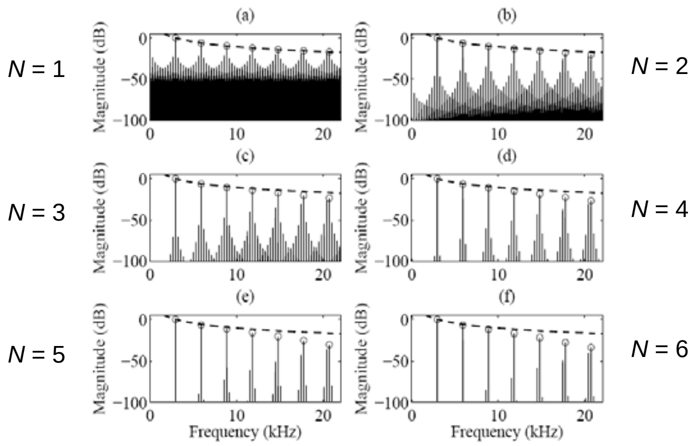
Spectra of Differenced Waveforms



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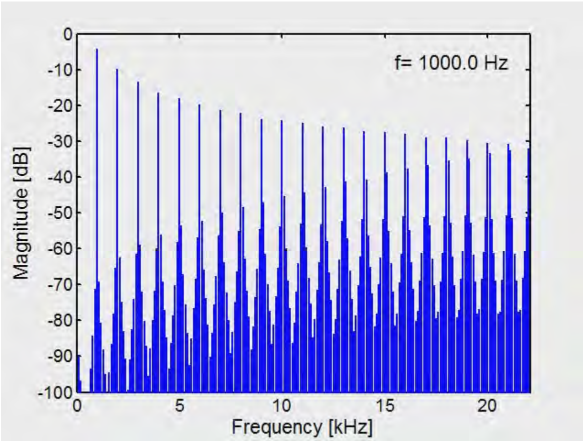
Lecture #4: Digital Sound Synthesis

DPW Sawtooth Sweep

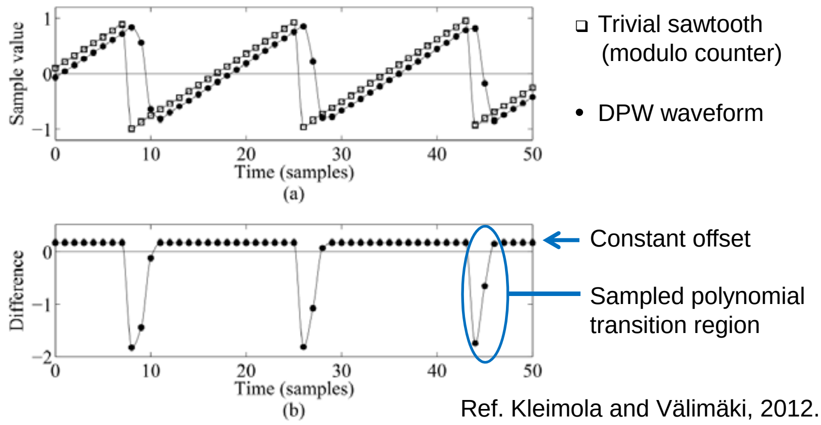
- One integration and derivation



Video by Andreas Franck, 2012

Polynomial Transition Region (PTR)

- The PTR algorithm implements DPW efficiently and extends it



Ref. Kleimola and Välimäki, 2012.

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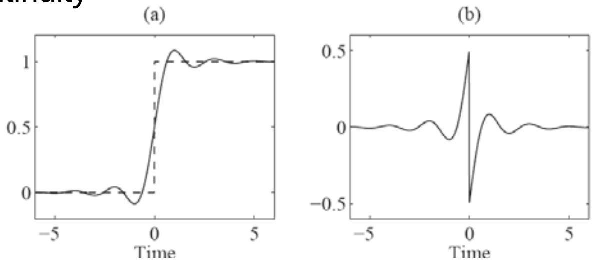
BLEP Method

- BLEP = Bandlimited step function (Brandt, ICMC'01), which is obtained by integrating a sinc function
  - Must be oversampled and stored in a table
- BLEP residual samples are added around every discontinuity



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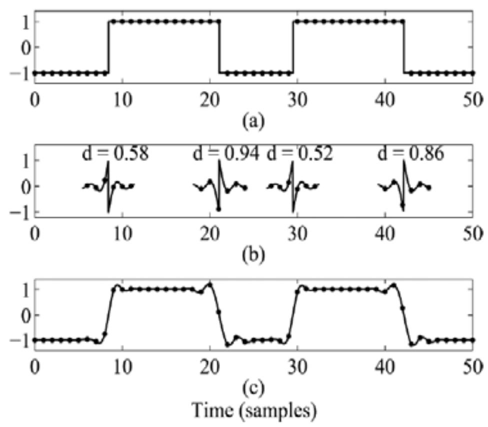
29

BLEP Method Example

- A shifted and sampled BLEP residual is added onto each discontinuity
- The shift is the same as the fractional delay of the step
- The BLEP residual is inverted for downward steps

(Välimäki *et al*., 2012)



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30

Polynomial BLEP Method

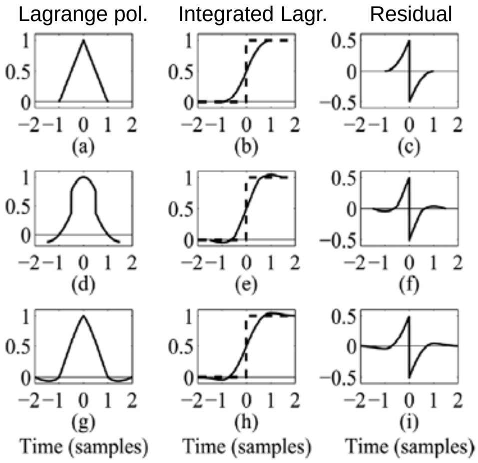
- The BLEP residual table can be replaced with a polynomial approximation

  (Välimäki *et al*., 2012)
- Lagrange polynomials can be integrated and used for approximating the sinc function
- Low-order cases are of interest:

  N = 1 (Välimäki and Huovilainen, 2007)

  N = 2 (Välimäki *et al*., 2012)

  N = 3 (Välimäki *et al*., 2012)



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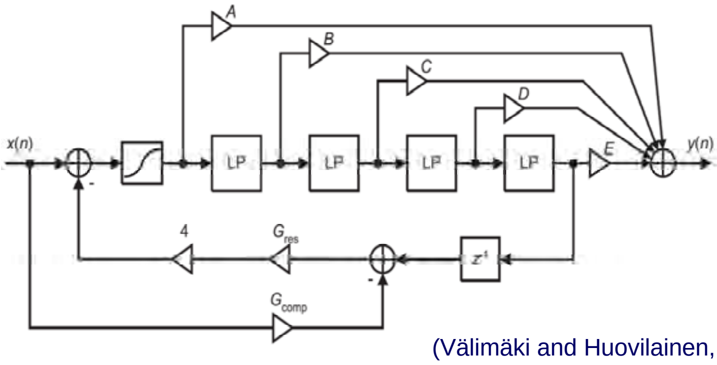
A Digital Resonant Filter

- Simplified version of the digital 4^{th}-order Moog ladder filter (Huovilainen, DAFx 2004)



(Välimäki and Huovilainen, 2006)

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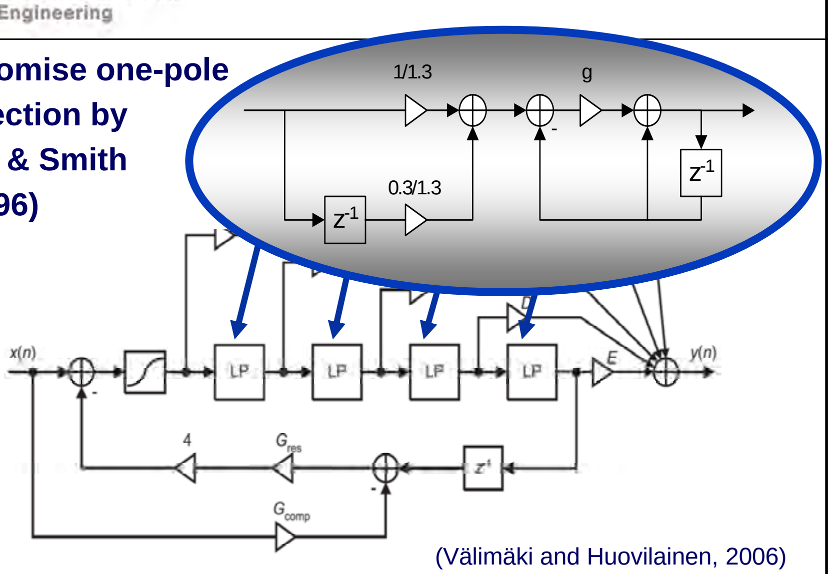
Compromise one-pole filter section by Stilson & Smith (ICMC'96)



(Välimäki and Huovilainen, 2006)

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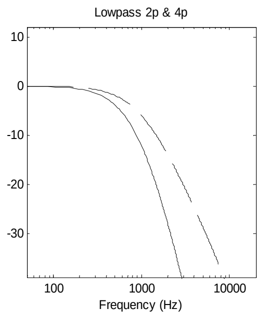
Various Magnitude Responses

Lowpass filter

2nd-order: C = 1

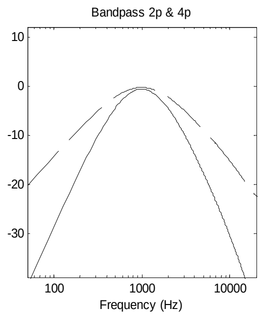
4th-order: E = 1



Bandpass filter

B = 2, C = -2

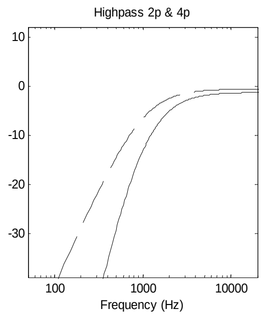
C = E = 4, D = -8



Highpass filter

A = 1, B = -2, C = 1

A = E = 1, B = D = -4, C = 6



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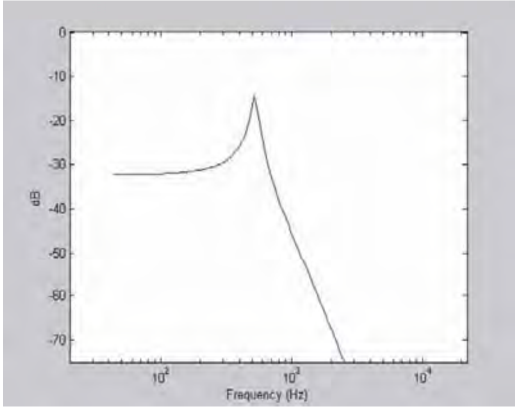
Sweeping the Resonance Frequency

- Changing the resonance frequency does not affect the Q value (much)



Video by Oskari Porkka & Jaakko Kestilä, 2007

 35

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Sweeping the Resonance Frequency

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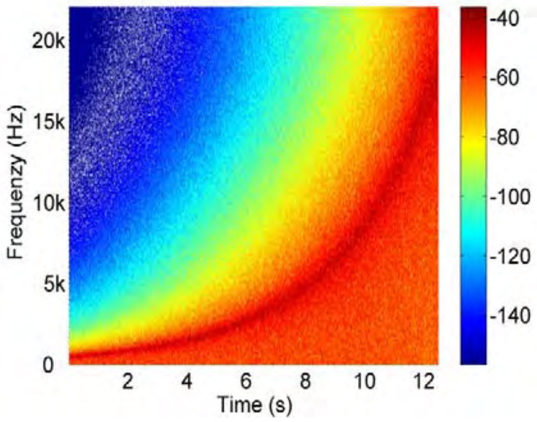

Image by Oskari Porkka & Jaakko Kestilä, 2007

 36

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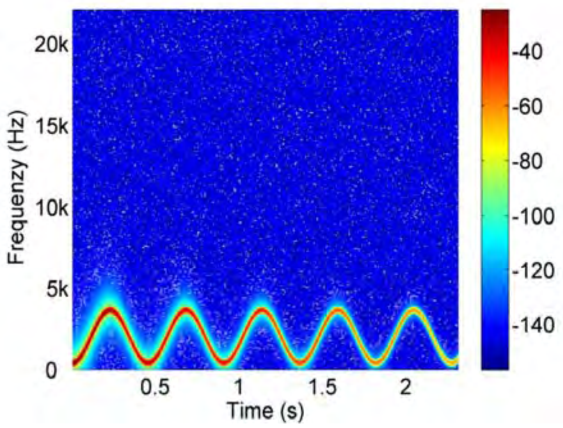
Self-Oscillation

- When C_{res} = 1, the digital Moog filter oscillates for some time
- Note that C_{res} can be made larger than 1, because the TANH nonlinearity limits the amplitude and guarantees stability



Sound & image by Oskari Porkka & Jaakko Kestilä, 2007

 37

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Moog Filter Sound Examples

Original

Lowpass with LFO,
resonance = 0.99

Original

Lowpass with sweep,
resonance = 0.8

Sounds by Oskari Porkka & Jaakko Kestilä, 2007

 38

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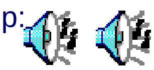
Valencia, Spain, 17.5.2012

Mobile Audio Processor

- Collaboration of TKK Acoustics Lab and VLSI Solution Oy (Tampere, Finland): SP-Mini project
- For mobile audio applications: phones, games, toys
- Uses the Scalable Polyphony MIDI (SP-MIDI) specification
  - A version of MIDI for mobile applications: reduced sound set, drop voices when necessary

- Main synthesis principle: digital subtractive synthesis
  - DPW oscillator algorithm used for most sounds
  - Virtual analog resonant filter (by Antti Huovilainen)
- Music examples from software simulation of the chip:
  - SP-MIDI files taken from the Web



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