History of Virtual Musical Instruments and Effects Based on Physical Modeling Principles

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Digital Audio Effects (DAFx-17) Conference
Keynote 1

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Overview

Physical Models
Finite Differences
Early History
Voice Models
String Models
Bowed Strings
Distortion Guitar
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Outline

- Virtual Instruments and Effects
- Physical Modeling Overview
- History of Virtualization
- Virtual Voice
- Virtual Strings
- Selected Recent Developments
Virtualization

- Merriam-Webster defines *virtual* as

  ... being on or simulated on a computer or computer network — print or *virtual* books — of, relating to, or existing within a *virtual* reality ... 

- According to Elon Musk:
  “There’s a billion to one chance we’re living in base reality”
- Therefore, it could be “virtual all the way down”

- Let’s say *virtualization* involves one level of simulation
Example: Virtual Duck Call

- A duck call is a virtual quacking device
- A duck-call synthesizer is technically a virtual virtual ($V^2$) duck

Duck Call (Virtual Quacker)

More typical unit
Physical Models

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Physical Models
Physical Models

We generally follow Isaac Newton’s **System of the World**:

- No relativistic effects (yet)
- No quantum effects (almost)
- \( \Rightarrow \) Newtonian mechanics sufficient

Newton’s three laws of motion (1686) can be summarized by one classic equation:

\[
f = ma
\]

(Force = Mass times Acceleration)

- Expresses *conservation of momentum* (\( f = \dot{p}, \ p \triangleq mv \))
- Models based on Newton’s laws can quickly become complex
- Need many simplifications that preserve both **sound quality** and **expressivity** of control
Physical Modeling Formulations

Our **physical modeling tool box:**

- Ordinary Differential Equations (ODE) \[ f(t) = \dot{p}(t) = m \dot{v}(t) = ma(t) \]
- Partial Differential Equations (PDE) \[ K y''(x, t) = \epsilon \ddot{y}(x, t) \]
- Difference Equations (DE) \[ p(n + 1) = p(n) + T f(n) \]
- Finite Difference Schemes (FDS) \[ p(n + 1) = p(n) + T f(n + 1/2) \]
- (Physical) State Space Models (Vector First-Order ODE) \[ \dot{p} = Ap + Bu \]
- Transfer Functions (between physical signals) \[ H(s) = \frac{P(s)}{F(s)} \]
- Modal Representations (Parallel Biquads) \[ H(s) = \sum_k H_k(s) \]
- Equivalent Circuits and their various Solvers (Node Analysis, . . .)
- Impedance Networks [→ Lumped Models]
- Wave Digital Filters (WDF) [Masses/Inductors, Springs/Capacitors, . . .]
- Digital Waveguide (DW) Networks [Strings, Acoustic Tubes, . . .]
Recent History

2 SOUND SYNTHESIS AND PHYSICAL MODELING

Numerical Sound Synthesis, Stefan Bilbao, Wiley 2009
Finite Differences

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- Wave Digital Filters (WDF), Recent Results
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Stefan Bilbao

NUMERICAL SOUND SYNTHESIS

Finite Difference Schemes and Simulation in Musical Acoustics

WILEY
Wave Digital Filters (WDF), Recent Results

See 2015 Keynote talk (and the papers mentioned) for details:

- WDFs can now model arbitrary circuit topologies (not just parallel/series connections)
- Any number of nonlinear elements can be included
- See recent PhD thesis by Kurt Werner (and recent DAFx papers)
- Nonlinear Newton solvers remain an active area of research
"The Fender Bassman 5F6-A Family of Preamplifier Circuits—A Wave Digital Filter Case Study,"

Ross Dunkel, Maximilian Rest, Kurt James Werner, Michael Jørgen Olsen and Julius O. Smith

Ross Dunkel’s Fender Bassman WDF (Note the 25-port R-Node)
Back to History

2 SOUND SYNTHESIS AND PHYSICAL MODELING

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Early Virtualization of Strings

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Early Virtualization of Strings

The *vibrating string* was a critically important object of study in the middle-18th century, leading to

- The first *wave equation* (first PDE)
- *Traveling-wave* solution of the string wave equation
- *Additive synthesis* solution for the *terminated* string
- First glimpses of Fourier-series expansions (before Fourier was born in 1768)
- The concept of *superposition* in linear systems
Main Reference

Excellent account of the period discussed here:

Olivier Darrigol
“The Acoustic Origins of Harmonic Analysis”
*Archive for History of the Exact Sciences, 2007*
"[Since the vibrating string] produces five or six tones..., it seems that it is entirely necessary that it beat the air five, four, three, and two times at the same time, which is impossible to imagine unless one says that half of the string beats the air twice, one third beats it three times, etc. while the whole strings beats it once. This picture runs against experience, which clearly shows that all parts of the string make the same number of returns in the same time, because the continuous string has a single motion, even though parts near the bridge move more slowly."

- Plucked string video: https://www.youtube.com/watch?v=Qr_rxqwc1jE
- Since there was no notion of spectrum at this time, the fundamental frequency of a sound was the periodic repetition rate of pulses in the time domain
“While meditating on the phenomena of sound, I was made to observe that especially at night one may hear from long strings not only the principal sound, but also other small sounds, a twelfth and a seventeenth above.... I concluded that the string in addition to the undulations it makes in its entire length so as to form the fundamental sound may divide itself in two, three, four, etc. undulations which form the octave, the twelfth, the fifteenth of this sound.”
Sauveur plucked a monochord having a light obstacle mounted to create “nodes”
He was surprised that the string did not move at the nodal points
• String-playing musicians surely discovered how to play harmonics by lightly damping a node
  (The Lyre dates back to perhaps 3000 BC)
• Sauveur coined the term node, inspired by nodes in the lunar orbit:
  ◦ Lunar nodes are points where the orbit of the Moon crosses the ecliptic
  ◦ The ecliptic is the apparent path of the sun around the celestial sphere
  ◦ An eclipse can only happen at one of the two lunar node points
• Sauveur also coined the term harmonic, so named because they are “harmonious” with the fundamental
Brook Taylor (1713)

- Best known for Taylor Series Expansions
- First to derive the string fundamental frequency \( f = \sqrt{K/\epsilon/2L} \), where \( K \) = string tension, \( \epsilon \) = mass density, \( L \) = string length
- Derived that the string restoring force is proportional to string curvature
- Approximated this by the distance of the string from its rest axis (oops) (but this works for a sinusoidal displacement)
- Concluded that a sinusoidal shape was the only possibility, despite Wallis having described higher-order modes previously
- Although many initial shapes were clearly possible, he assumed that the vibration would quickly assume a sinusoidal shape (only one mode of vibration supported by the string—the fundamental mode)
- In other words, he assumed the string vibrated like a mass-spring system
Jean-Philippe Rameau (1726)

- Rameau was a composer interested in studying harmonic overtones toward establishing a more scientific foundation for music theory
- His theory of harmony was based on the first three audible harmonics
- Cited Sauveur and Mersenne
- Collaborated extensively with d’Alembert
- Anticipated a kind of spectrum analyzer theory of hearing:

  “What has been said of [the separate vibrating modes of] sonorous bodies should be applied equally to the fibers which carpet the bottom of the ears cochlea [le fond de la conque de loreille]; these fibers are so many sonorous bodies, to which the air transmits its vibrations, and from which the perception of sounds and harmony is carried to the soul.”

Thus, Rameau regarded the hair cells as a bank of little sympathetic resonators.

Crude forms of the “place theory” of hearing (aka “resonance theory”) are said to have begun in 1605, and Helmholtz published his treatment in 1857.
Johann Bernoulli (1727)

Johann Bernoulli studied the *mass-loaded ideal massless string*, also called the *beaded string*, thereby avoiding the need for a PDE

- Made the same mistake as Taylor by assuming the restoring force was proportional to *distance* from the rest axis, instead of the force component in that direction applied by adjacent string segments
- Also overlooked higher modes of vibration, considering only the fundamental
Daniel Bernoulli extended his father’s work:

- Studied the vertically suspended chain
- Observed multiple modes of vibration (as many as there were masses), and their inharmonicity
- Found the limiting mode shapes (now called Bessel functions)
- Realized that the infinitely long chain was equivalent to a musical string
- Investigated higher-order modes experimentally
- Went on to study *elastic bands*:
Daniel Bernoulli studied vibrating elastic bands with inharmonic modes, hearing them out:

“Both sounds exist at once and are very distinctly perceived.... This is no wonder, since neither oscillation helps or hinder the other; indeed, when the band is curved by reason of one oscillation, it may always be considered as straight in respect to another oscillation, since the oscillations are virtually infinitely small. Therefore oscillations of any kind may occur, whether the band be destitute of all other oscillation or executing others at the same time. In free bands, whose oscillations we shall now examine, I have often perceived three or four sounds at the same time.”

- **Superposition** of small vibrations at different frequencies clearly conceived
- Likely suggested by the *perceptual superposition* of overtones
- Did the spectrum analyzer nature of hearing give us the concept of superposition?
String Harmonic Overtones

- "Obvious" to string-playing musicians
- Observed by Mersenne, Sauveur, Bernoulli, and others
- Not obvious to everybody! (Taylor, J. Bernoulli, d’Alembert, Euler, ...)
- Pushed as "reality" most strenuously by Daniel Bernoulli
- D’Alembert and Euler to Bernoulli:
  How can sinusoids add up to a propagating pulse?!?
Jean La Rond D’Alembert (1746)

- Invented the PDE by plugging Taylor’s restoring force $f$ into Newton’s $f = ma$ written as a *differential form* (as developed by Euler)
- Showed that any solution was a *traveling wave* to left and/or right
- Showed that Taylor’s sinusoidal fundamental mode was a special case solution
- Disagreed with Taylor that all initial conditions lead to a sinusoid
- Did not allow an initial triangular shape (not twice differentiable), and suggested using a beaded string for this case
Leonard Euler (1749)

- Euler quickly generalized d’Alembert’s results to any initial string shape.
- He showed that the solution space included Bernoulli sums of “Taylorian sines”:
  \[ y(x, t) = \sum A_k \sin\left(\frac{k\pi x}{L}\right) \cos(k\pi f_0 t) \]

- He did not consider this a general solution (one “obviously” could not make a triangular initial shape out of sines, for example).
- We of course know that it is quite general, but Joseph Fourier was not yet born (to happen 19 years later in 1768).
Daniel Bernoulli (1753)

Bernoulli was annoyed with d’Alembert and Euler:

- He had published the superposition-of-sinusoids solution long ago
- The supposedly new solutions of d’Alembert and Euler were simply a mixture of simple modes
- He didn’t like fusing the simple pure oscillations into a single formula
- He considered his “physical” analysis preferable to their abstract mathematical treatment:
Daniel Bernoulli (1753)

“I saw at once that one could admit this multitude of [Taylorian sine] curves only in a sense altogether improper. I do not less admire the calculations of Messrs. d'Alembert and Euler, which certainly include what is most profound and most advanced in all of analysis, but which show at the same time that an abstract analysis, if heeded without any synthetic [physical] examination of the question proposed, is more likely to surprise than enlighten. It seems to me that giving attention to the nature of the vibrations or strings suffices to foresee without any calculation all that these great geometers have found by the most difficult and abstract calculations that the analytic mind has yet conceived.”
The Mathematical Puzzle of the Vibrating String

- Daniel Bernoulli (1733): Physical vibrations can be understood as a superposition of “simple modes” (pure sinusoidal vibrations)

- In Euler’s formulation:

  $$y(t, x) = \sum_{k=0}^{\infty} A_k \sin\left(\frac{k\pi x}{L}\right) \cos\left(k\pi \nu t\right)$$

  (displacement of length $L$ vibrating string at time $t$, position $x$)

- D’Alembert (1747): String vibration can be understood as a pair of traveling-waves going in opposite directions at speed $c$:

  $$y(t, x) = y^+ \left(t - \frac{x}{c}\right) + y^- \left(t + \frac{x}{c}\right)$$
Mathematical Paradoxes

Reasonable question of the day:

*How can a superposition of **standing waves** give you a **propagating pulse**?*

\[ y(t, x) = \sum_{k=0}^{\infty} A_k \sin\left(\frac{k\pi x}{L}\right) \cos(k\pi \nu t) \]

\[ = y^+ \left( t - \frac{x}{c} \right) + y^- \left( t + \frac{x}{c} \right) \]

Another reasonable question of the day:

*How can a sum of sinusoids give an arbitrary (e.g., non-smooth) function?*

Life without Fourier theory was difficult indeed
Paradox Resolved

- Thanks to Fourier theory, we now know that the sum-of-standing-waves and traveling-waves are interchangeable and essentially complete descriptions:
  - **Standing-wave** = sum of opposite-going traveling waves
  - **Any initial state can be projected** onto standing-wave “basis functions” and reconstructed
  - For the ideal vibrating string, the basis functions are the sinusoidal harmonics
  - For more general systems, the basis functions are eigenfunctions of Hermitian linear operators beyond the basic wave equation (Lagrange, Sturm-Liouville)
Fourier Expansion

First 4 Sinusoidal Components of a Leaning-Triangle String Shape

First four modes of plucked string, showing both right-going and left-going string images (two string copies).
Animations by Dan Russel

From http://www.acs.psu.edu/drussell/demos.html

1. [Modes of a hanging chain]
2. [Standing waves on a string]
3. [Standing wave as two traveling waves]
Composers and scientists have frequently banded together to pursue joint goals and understanding. The long-time collaboration between Rameau and d’Alembert can be regarded as an early instance of “computer music:”

- 1700s - Jean-Philippe Rameau and Jean La Rond D’Alembert
- 1960s - Herb Deutsche and Bob Moog
  - ADSR envelope was suggested by Deutsche
  - It was prototyped immediately by Moog using a doorbell
  - Originally the notes were only gated (on/off)
  - Deutsche said articulation was needed—”consider the ‘ta’ of the trumpet”
  - Moog immediately thought of one-pole filtering of the gate with variable Attack and Release (Probably Decay to Sustain Level as well, but not mentioned explicitly)
Collaborations, Continued

- 1960s - Lejaren Hiller and Pierre Ruiz
- 1966 - John Lennon and Ken Townsend: Flanging effect:
  - Ken Townsend was an engineer at EMI’s Abbey Road Studio
  - John Lennon suggested there should be an automatic way to get the sound of double-tracked vocals
  - Townsend developed Artificial Double Tracking (ADT)
  - George Martin jokingly explained it to Lennon as a “double vibrocrated sploshing flange with double negative feedback”
  - Lennon later called it “flanging” and this may have been the origin of later usage

(Source: Wikipedia)
See Also “Double vibrocrated sploshing flange”
Collaborations, Continued

- 1970s - John Chowning and Dave Poole, Andy Moorer, Peter Samson, and many others:
  - PDP-1 DAC (Poole)
  - FM Bessel functions (AI Lab engineer)
  - 12-bit D/A (Moorer)
  - Samson Box (Samson and Moorer)
  - CCRMA (Moorer, Grey, et al.)

- 1970s - Prof. Barry Vercoe (MIT, CSound) and
  - Miller Puckett (FTS on Analogic AP500 array processor, score following)
  - Roger Dannenberg
  - Joe Paradiso
  - ...
Collaborations, Continued

- 1980s - Pierre Boulez and Andrew Gerzso: IRCAM, Concerts
- 1983 - David Jaffe and JOS (Music DMA & EE PhD students): Extended Karplus Strong (“make it play in tune” etc.)
- 1990 - Prof. Paul Lansky (Princeton) and Charles Sullivan: Distortion-feedback guitar
Voice Models
Early Talking Machines (Virtual Talking Heads)

Joseph Faber’s Euphonia
Early Brazen Heads (Wikipedia)

- $\approx 1125$: First talking head description:
  William of Malmesbury’s History of the English Kings:
  - Pope Sylvester II said to have traveled to al-Andalus and stolen a tome of secret knowledge
  - Only able to escape through demonic assistance
  - Cast the head of a statue using his knowledge of astrology
  - It would not speak until spoken to, but then answered any yes/no question put to it

- Early devices were deemed *heretical* by the Church and often destroyed

- 1599: Albertus Magnus had a head with a human voice and breath:
  - “A certain reasoning process” bestowed by a *cacodemon* (evil demon)
  - Thomas Aquinas destroyed it for continually interrupting his ruminations (not everyone wants a yacking cacodemon around all the time)

- By the 18th century, talking machines became acceptable as “scientific pursuit”
Wolfgang Von Kempelin’s Speaking Machine (1791)

Replica of Wolfgang Von Kempelin’s Speaking Machine
Joseph Faber’s Euphonia (1846)

17 levers, a bellows, and a telegraphic line — sang “God Save the Queen”
Joseph Faber’s Euphonia (1846)
The Voder (Homer Dudley — 1939 Worlds Fair)

http://davidszondy.com/future/robot/voder.htm
Voder Keyboard

Unvoiced source

Voiced source

Source control

Resonance control

Amplifier

Loudspeaker

Energy switch

Wrist bar

1 2 3 4 5

t-d

p-b

k-g

"stops"

10 6 7 8 9

"quiet"

VODER CONSOLE KEYBOARD

Pitch control pedal

Voder Schematic

Fig. 8—Schematic circuit of the voder.

http://ptolemy.eecs.berkeley.edu/~eal/audio/voder.html
Voder Demos

- Video
- Audio
Kelly-Lochbaum Vocal Tract Model
(Discrete-Time Transmission-Line Model)

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- Virtual Heads
- Von Kempelin
- Euphonia
- Voder Keyboard
- Voder Schematic
- Voder Demos
- KL Voice
- “Daisy”
- “Shiela”
- Linear Prediction
- Glottal Model
- Source Estimation
- LF Glottal Model
- Phonation Variation
- Lu Sounds
- Tak
- 2D Vowels
- Pink Trombone

String Models
- Bowed Strings
- Distortion Guitar

John L. Kelly and Carol Lochbaum (1962)
Sound Example

“Bicycle Built for Two”: (WAV) (MP3)

- Vocal part by Kelly and Lochbaum (1961)
- Musical accompaniment by Max Mathews
- Computed on an IBM 704
- Based on Russian speech-vowel data from Gunnar Fant’s book
- Probably the first digital physical-modeling synthesis sound example by any method
- Inspired Arthur C. Clarke to adapt it for “2001: A Space Odyssey” — the computer’s “first song”
“Shiela” Sound Examples by Perry Cook (1990)

- Diphones: (WAV) (MP3)
- Nasals: (WAV) (MP3)
- Scales: (WAV) (MP3)
- “Shiela”: (WAV) (MP3)
Linear Prediction (LP) Vocal Tract Model

- Can be interpreted as a modified Kelly-Lochbaum model
- In linear prediction, the glottal excitation must be an
  - **impulse**, or
  - **white noise**

*This prevents LP from finding a physical vocal-tract model*

- A *more realistic glottal waveform* \( e(n) \) is needed before the vocal tract filter can have the “right shape”
- How to augment LPC in this direction without going to a full-blown *articulatory synthesis model*?

**Jointly estimate glottal waveform** \( e(n) \) **so that the vocal-tract filter converges to the “right shape”**
Klatt Derivative Glottal Wave

Two periods of the basic voicing waveform

Good for estimation:

- Truncated *parabola* each period
- Coefficients easily fit to *phase-aligned* inverse-filter output
Sequential Unconstrained Minimization

(Hui Ling Lu, 2002)

Klatt glottal (parabola) parameters are estimated *jointly* with vocal tract filter coefficients

- Formulation resembles that of the *equation error method for system identification* (also used in `invfreqz` in matlab)
- For *phase alignment*, we estimate
  - pitch (time varying)
  - glottal closure instant each period
- Optimization is *convex* in all but the phase-alignment dimension
  ⇒ one potentially nonlinear line search
Liljencrantz-Fant Derivative Glottal Wave Model

- Better for *intuitively parametrized expressive synthesis*
- LF model parameters are fit to *inverse filter* output
- Use of Klatt model in forming filter estimate yields a “more physical” filter than LP
Parametrized Phonation Types

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Julius Smith DAFx-17 – 58 / 50
Sound Examples by Hui Ling Lu

- Original: (WAV) (MP3)
- Synthesized:
  - Pressed Phonation: (WAV) (MP3)
  - Normal Phonation: (WAV) (MP3)
  - Breathy Phonation: (WAV) (MP3)
- Original: (WAV) (MP3)
- Synthesis 1: (WAV) (MP3)
- Synthesis 2: (WAV) (MP3)

where

- Synthesis 1 = Estimated Vocal Tract driven by estimated KLGLOT88 Derivative Glottal Wave (Pressed)
- Synthesis 2 = Estimated Vocal Tract driven by the fitted LF Derivative Glottal Wave (Pressed)

Google search: singing synthesis Lu
Voice Model Estimation

- Parametric source-filter model of voice + noise
- State-space framework with derivative glottal waveform as input and A model for dynamics
- Jointly estimate AR parameters and glottal source parameters using EM algorithm with Kalman smoothing
- Reconstruct a clean voice using Kelly-Lochbaum and estimated parameters
Online 2D Vowel Demo (2014)

Jan Schnupp, Eli Nelken, and Andrew King

http://auditoryneuroscience.com/topics/two-formant-artificial-vowels
Pink Trombone Voical Synthesis (March 2017)

Neil Thapen
Institute of Mathematics of the Academy of Sciences
Czech Republic

http://dood.al/pinktrombone/
Digital String Models
Karplus-Strong (KS) Algorithm (1983)

- Discovered (1978) as “self-modifying wavetable synthesis”
- Wavetable is preferably initialized with random numbers
- No physical interpretation until much later
EKS Algorithm (Jaffe-Smith 1983)

\[ N = \text{pitch period (2}\times\text{ string length) in samples} \]

\[ H_p(z) = \frac{1 - p}{1 - pz^{-1}} = \text{pick-direction lowpass filter} \]

\[ H_\beta(z) = 1 - z^{-\beta N} = \text{pick-position comb filter, } \beta \in (0, 1) \]

\[ H_d(z) = \text{string-damping filter (one/two poles/zeros typical)} \]

\[ H_s(z) = \text{string-stiffness allpass filter (several poles and zeros)} \]

\[ H_\rho(z) = \frac{\rho(N) - z^{-1}}{1 - \rho(N)z^{-1}} = \text{first-order string-tuning allpass filter} \]

\[ H_L(z) = \frac{1 - R_L}{1 - R_L z^{-1}} = \text{dynamic-level lowpass filter} \]
Karplus-Strong Sound Examples

- "Vintage" 8-bit sound examples:
  - Original Plucked String: (WAV) (MP3)
  - Drum: (WAV) (MP3)
  - Stretched Drum: (WAV) (MP3)
EKS Sound Examples

Plucked String: (WAV) (MP3)

- Plucked String 1: (WAV) (MP3)
- Plucked String 2: (WAV) (MP3)
- Plucked String 3: (WAV) (MP3)

(Computed using Plucked.cpp in the C++ Synthesis Tool Kit (STK) by Perry Cook and Gary Scavone)
EKS Sound Example (1988)

Bach A-Minor Concerto—Orchestra Part: (WAV) (MP3)

- Executed in real time on one Motorola DSP56001 (20 MHz clock, 128K SRAM)
- Developed for the NeXT Computer introduction at Davies Symphony Hall, San Francisco, 1988
- Solo violin part was played live by Dan Kobialka of the San Francisco Symphony
Several of the Karplus-Strong algorithm extensions were based on its *physical interpretation*.

- Originally, transfer-function methods were used (1982)
- Below is a digital waveguide derivation
String Excited Externally at One Point

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• Karplus Strong
• EKS Algorithm
• Physical Excitation
• Pick Position FFCF
• Digital Waveguides
• Waveguide Reverb
• Allpass Networks
• Digital Waveguide
• Signal Scattering
• Moving Termination
• Waveguide Model
• Plucked String
• Struck String

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“Waveguide Canonical Form (1986)”

Equivalent System by Delay Consolidation:

Finally, we “pull out” the comb-filter component:
EKS “Pick Position” Extension

Equivalent System: Comb Filter Factored Out

\[ H(z) = z^{-N} \frac{1 + z^{-2M}}{1 - z^{-(2M+2N)}} = \left(1 + z^{-2M}\right) \frac{z^{-N}}{1 - z^{-(2M+2N)}} \]

- **Excitation Position** controlled by left delay-line length
- **Fundamental Frequency** controlled by right delay-line length
- “Transfer function modeling” based on a physical model (1982)
Historically, it would make the most sense to say that digital waveguide synthesis arose as follows:

- D’Alembert derived the string vibration as a superposition of left- and right-going traveling-waves
- Acoustic tubes became known to obey the same form of wave equation as vibrating strings
- Signal scattering at impedance discontinuities was known from physics (elastic particle scattering theory) and was also incorporated in transmission-line theory
- Kelly and Lochbaum conceived of the piecewise cylindrical tube model of the vocal tract, and digitized it via sampling
- Digital waveguide synthesis followed as sparsification of Kelly-Lochbaum vocal synthesis, applied to strings

However, that’s not the actual story . . .
Digital Waveguide Reverberation (1985)

How it really happened:

- In a shuttle bus to ICMC-85, Gary Kendall (Northwestern U of IL) commented on how hard it was to safely modify large digital reverberators by adding feedback here and there
- Instability highly likely as a result of any “random” change
- As a filter guy, I accepted the challenge:

  How do we connect any signal in a network to any other point in the network without causing instability?
Allpass Networks

- Lossless networks were clearly a good angle to pursue
- Reverberators are typically nearly allpass from point to point
- How do we preserve the allpass property of a large network when editing it?
- The main resource I studied was Belevitch: Classical Network Theory
  - Belevitch discussed allpass networks extensively
  - Belevitch also introduced the scattering-theory formulation of circuit theory (the basis for WDFs)
  - The idea of closed waveguide networks for reverberation occurred while studying Belevitch (also using basic knowledge of transmission-line theory)
  - Waveguide synthesis was a later afterthought: Any waveguide branch could be treated as a vibrating string or woodwind bore
**Digital Waveguide Models (1985)**

\[ \text{Lossless digital waveguide} \triangleq \text{bidirectional delay line at some wave impedance } R \]

Useful for **efficient** models of
- strings
- bores
- plane waves
- conical waves

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**Outro**
Signal Scattering

Signal scattering is caused by a change in wave impedance \( R \):

\[
k_1 = \frac{R_2 - R_1}{R_2 + R_1}
\]

If the wave impedance changes every spatial sample, the Kelly-Lochbaum vocal-tract model results (also need reflecting terminations)
Moving Termination: Ideal String

Moving rigid termination for an ideal string

- Left endpoint moved at velocity $v_0$
- External force $f_0 = R v_0$
- $R = \sqrt{K \varepsilon}$ is the wave impedance (for transverse waves)
- Relevant to bowed strings (when bow pulls string)
- String moves with speed $v_0$ or 0 only
- String is always one or two straight segments
- “Helmholtz corner” (slope discontinuity) shuttles back and forth at speed $c = \sqrt{K/\varepsilon}$
Digital Waveguide “Equivalent Circuits”

a) Velocity waves.  b) Force waves.

(Animation)

(Interactive Animation)
Ideal Plucked String (Displacement Waves)

- Karplus Strong
- EKS Algorithm
- Physical Excitation
- Pick Position FFCF
- Digital Waveguides
- Waveguide Reverb
- Allpass Networks
- Digital Waveguide
- Signal Scattering
- Moving Termination
- Waveguide Model
- Plucked String
- Struck String

- Load each delay line with half of initial string displacement
- Sum of upper and lower delay lines = string displacement
Ideal Struck String (Velocity Waves)

- Karplus Strong
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Hammer strike = \textit{momentum transfer} = velocity step:

\[ m_h v_h(0-) = (m_h + m_s) v_s(0+) \]
Bowed Strings (1986)
Digital Waveguide Bowed Strings (1986)

- Reflection filter summarizes all losses per period (due to bridge, bow, finger, etc.)
- Bow-string junction = \textit{memoryless} lookup table (or segmented polynomial)
Bowed and Plucked Sound Examples by Esteban Maestre

- Synthetically Bowing STK’s Bowed.cpp
- Finite-Width Thermal Friction Model for Bowed String
- Waveguide Strings Coupled to Modal-Synthesis Bridge
Electric Guitar with Overdrive and Feedback
Distortion output signal often further filtered by an *amplifier cabinet filter*, representing speaker cabinet, driver responses, etc.
Distortion Guitar Sound Examples

(Stanford Sondius Project, ca. 1995)

- Distortion Guitar: (WAV) (MP3)
- Amplifier Feedback 1: (WAV) (MP3)
- Amplifier Feedback 2: (WAV) (MP3)
Virtual Electric Guitars Now
moForte Guitar for iOS and (later) Android

Real-time on iPhone 4S and iPad 2 (and later)
Guitar and effects written in the FAUST language:

- Full physically modeled electric-guitar + effects:
  - Six vibrating strings — general excitations
  - Distortion
  - Compression
  - Phaser
  - Five-band parametric equalizer
  - Flanger
  - Reverb

- Responds to
touchscreen gestures (plucks, and stumming)

- Hard to fully utilize five points of multitouch on iPhone and ten on iPad!
- Android audio latency has gotten much better
- The Android scheduler remains an issue
  (need real-time protection for audio callbacks)
- JUCE + Faust looking good for Android version
These Effects Plus Six Feedback-Distortion Guitar Strings Together Require 115% of an iPhone 4S or iPad 2 CPU
ARM CPU Performance

Overview

Physical Models

Finite Differences

Early History

Voice Models

String Models

Bowed Strings

Distortion Guitar

iOS Guitars

- moForte Guitar
- CPU Performance
- CPU & GPU
- GeoShred
- GeoShred Demos

Recent Research

Outro

Julius Smith
Update: ARM CPU and GPU Performance as of iPhone 6s

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GeoShred: Virtual Distortion Electric Guitar (iOS)

GeoShred merges moForte Guitar with Geo Synthesizer for iOS

GeoShred for iOS

The iPad turns out to be a kick-ass virtual musical instrument!
# GeoShred Demos

- Jordan on GeoShred (YouTube):
  - GeoShred Pro 2.5 (Sep 2017)
  - NAMM 2015
- JOS Under the Moon (YouTube)
Selected Recent Research
Scattering Delay Network (SDN), Four Walls

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Scattering Delay (Digital Waveguide) Networks (SDN)

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Recent Research
- SDN
- TASLP
- 2D Bridge

Outro

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Image Method Analysis of a Two-Wall SDN

- All paths are present
- Direct and first-order reflections can be exact
- Higher-order reflections are lengthened
- Can combine with exact early reflections to obtain perceptual equivalence
“Joint Modeling of Bridge Admittance and Body Radiativity for Efficient Synthesis of String Instrument Sound by Digital Waveguides” (IEEE-TASLP, March 2017; see also IEEE-SPL, Nov. 2016)

Esteban Maestre, Gary Scavone, and Julius Smith

Violin Radiativity Model
2D Bridge Modeling for Bowed Strings

Two-dimensional Bridge Model
In Conclusion
Conclusion

It all begins and ends with

string theory!

(Physics Joke)
Summary

- Physical Modeling Approaches
- Update on Wave Digital Filters
- Recent and Early History of Virtual Strings and Voice
- Update on Voice Models
- Update on String Models and Effects
- Selected Research Updates