Outline

- The Piano
- Commuted Piano Synthesis
- Hammer Modeling
- Piano String Modeling

The Piano

Acoustics of the Piano

- Five Lectures on the Acoustics of the Piano
- The Piano Hammer as a Nonlinear Spring

Piano Synthesis

We know how to

- simulate strings efficiently
- couple strings at the bridge

We will now discuss how to

- commute resonators and strings (for speed)
- convolve resonator impulse response with excitation (hammer)
- simulate a piano hammer in more detail
- identify the string-loop filter for stiff strings

Commuted Synthesis

Schematic diagram of a stringed musical instrument.

Equivalent diagram in the linear, time-invariant case.

Use of an aggregate excitation given by the convolution of original excitation with the resonator impulse response.

Features of Commuted Synthesis

- Enormous resonators can be implemented inexpensively (three orders of magnitude less computation for typical stringed instruments)
- Good qualitative excitation signals are easy to measure (just tap on the bridge)
- Apparent "resonator size" can be modulated by changing the playback rate of the excitation table

Drawbacks:

- Requires linearity and time invariance
Commuted Piano Synthesis

Hammer-string interaction pulses (force):

- Vertical lines = locations and amplitudes of three impulses
- Hammer-string interaction signal synthesized using one to three digital filters
- Filters depend on striking velocity

Synthesis of One Hammer-String Interaction Pulse

- Filter input = impulse
- Filter output = desired hammer-string force pulse
- As input amplitude increases, output pulse narrows $\Rightarrow$ nonlinear filter
- For each specific impulse, filter is linear time-invariant
- Piano is “linearized” separately for each hammer velocity

Synthesis of Multiple Hammer-String Interaction Pulse

Multiple hammer-string interaction pulses = superposition of several individual pulses:

- Input to each filter is a single impulse
- Sum of outputs = superposition of hammer-string force pulses
- As impulse amplitude grows, output pulses become taller and thinner, showing less overlap.

Complete Piano Model

Natural Ordering:

- Soundboard and enclosure are commuted
- Only need a stored recording of their impulse response
- An enormous digital filter is otherwise required

Commuted Ordering:
Simplified Variations of the Commuted Piano

One interaction pulse:

Up to three identical interaction pulses:

Three General Interaction Pulses

Differentially Filtered Interaction Pulses

Each new delay is equal to the travel from the hammer, to the agraffe, and back to the hammer

Striking a Digital Waveguide String

Waveguide string in “physical canonical form”:

- Delay lines contain traveling force waves
- Hammer-string force pulses are summed into both directions (by physical symmetry)

Equivalent Computational Models

- Hammer position set by feedforward comb filter
- String model independent of hammer position (more valuable for plucked strings)
- Same factoring applies to pickup locations
Use of a Tapped Delay Line

- Delay-line tap simulates hammer-strike echoes returning from the far end of the string
- Total delay line length equals twice the travel time along the entire length of the string
- Placement is not critical, so an interpolating tap is not necessary
- Tap motion gives a free built-in “flanger” effect
- Since force waves are most convenient, no sign inversion at the string endpoints

Excitation Factoring

Commuted Piano Synthesizer:

- Soundboard and enclosure
- Equalization for color variations
- Reverberation
- Flange
- Chorus
- Simulated hammer-strike echoes
- Multiple outputs

Filters are easily modified, even while a note is playing

Piano and Harpsichord Sound Examples

- [http://ccrma.stanford.edu/~jos/wav/Harpsichord.wav](http://ccrma.stanford.edu/~jos/wav/Harpsichord.wav)
- Julien Bensa’s synthetic piano

The Ideal (Lossless) Stiff String

- All $N$ allpass filters $H_a(z)$ have had a minimum sample of delay extracted, corresponding to the delay at $f_s/2$
- All have been combined at a single point
- The delay-line length $N$ is the number of samples in $K$ periods of $f_K$, where $K$ is the number of the highest partial (usually the last one before $f_s/2$)
- In stiff strings, high frequencies travel faster ⇒ allpass delay decreases with frequency
- An order 10 allpass gives high quality piano synthesis
- FFT convolution most efficient for maximum accuracy ($\text{FIR filter length } \approx N/2$ for note F1)
Nonparametric Model of Measured Piano-String Frequency Response (from Julien Bensa’s thesis)

High-quality frequency-response model based on measurements from a grand-piano string, note F1.

Stiff-String Loop-Filter Identification

A basic problem in waveguide synthesis of string is identifying the loop filter $H_l(z)$ which controls

- Partial overtone decay time (due to $|H_l(e^{j\omega})|$)
- Partial overtone tuning perturbations (due to $\angle H_l(e^{j\omega})$)

Loop-Filter Design Methods

One of the earliest methods was “periodic linear prediction” — a linear combination of a small group of samples predicts a sample one period away from the midpoint of the group.

More recently, methods have been developed based on measurements of the time-constant of decay for each partial overtone, since this is what matters the most.

- Record a plucked (or struck) string.
- Measure frequency $f_k$ and decay time $\tau_k$ for each overtone.
  - Energy Decay Relief (EDR) useful for this purpose
  - Sinusoidal modeling has been used as well
  - In either case:
    * Fit a straight line to the log of the amplitude envelope (e.g., using polyfit in Matlab or Octave).
    * Decay time $\tau_k$ is simply related to the slope of this line.
  - Translate each decay-time $\tau_k$ into a desired loop-gain at each frequency $f_k$, thus determining $|H_l(e^{j\omega_k})|$ for each partial.
  - If desired, use the inharmonic spacing of the $f_k$ to compute samples of the desired phase of the loop filter, $\angle H_l(e^{j\omega_k})$.
  - Use a general purpose digital filter design routine to design the loop filter which best approximates the desired frequency-response samples $H_l(e^{j\omega_k})$.
  - Phase-matching filter design utilities:
    - Steiglitz-McBride algorithm (IIR or FIR)
      See stmbc in Matlab Signal Processing Tool Box
    - Equation-Error Minimization (IIR or FIR)
      See invfreqz in matlab
    - Hankel-Norm Minimization (IIR)
Also called a “balanced truncation model” (state space)
- Linear-phase FIR (firl, firls, remez)

- Phase-insensitive filter design:
  - Linear Prediction
    See lpc or yulewalk in the Matlab SPTB
  - Create a desired linear or minimum phase and use a phase-sensitive design method.

- The fit at low frequencies should be weighted higher.
- A simple $1/f$ weighting usually works well.
- **Bark spectral warping** is commonly used. It implicitly weights low frequencies more by “stretching out” the low-frequency frequency axis and compressing the high-frequency frequency axis.
- Piano strings are highly dispersive:
  - Recall that every LTI filter can be factored into a linear phase filter in series with an allpass filter
  - The allpass part for a low-pitched string requires on the order of 100 poles (and 100 zeros) to provide a closely matched impulse response
  - Ten poles is a typical number used in practice (can be very good perceptually)

- Most methods for allpass filter design fail numerically at this high order
- The linear-phase part, in contrast, is well approximated using only an 8-tap FIR filter, and can be designed by any good method for FIR filter design (e.g., invfreqz in Matlab/Octave)

**Order Estimation**

Given a desired frequency response, a rough digital filter order estimate can be obtained as follows:

- FIR: Look at the IFFT duration (e.g., $20 \log(|h(n)|)$)
- IIR: Start with half of the FIR order (equal degrees of freedom)
- In either case, convert desired frequency response to minimum phase whenever possible: Matlab code: [http://ccrma.stanford.edu/~jos/filters/Matlab_listing.mps_a.html](http://ccrma.stanford.edu/~jos/filters/Matlab_listing.mps_a.html)
- For piano strings, a low-order minimum-phase damping filter is fine because we’re going to need a high-order allpass dispersion filter anyway