An Effective Model of Bucket-Brigade Device-Based Audio Circuits

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Topology

- Invented by Sangster at Philips, 1968
- Sampled signal passed through capacitors at clock rate (bucket brigade analogy)
- Early implementations proved to be overly inefficient
- Improved by Sangster and Reticon Corporation in the 1970s - each capacitor is separated by a DC biased gate
- Architecture widely used (by Panasonic, Reticon, and Philips) until digital delays became cheaper
Antiphase-clock bucket brigade circuit found in most BBD integrated circuits.
Circuit Examples

- Echo circuits
  - Many-thousand-stage delay line
  - Highly variable clock frequency
  - Anti-aliasing and reconstruction filters
  - Compression, expansion
  - Feedback (repeating echo)

- Chorus, Vibrato, Flanger
  - ~1,000 stages
  - LFO varies clock frequency
  - Anti-aliasing and reconstruction filters
  - Feedback in some cases
Commonly implemented BBD echo block diagram
Moog MF-104Z Delay
Commonly implemented chorus block diagram
Arion SCH-1 Chorus circuit diagram
Filtering Requirements

\[ \text{Delay Time (s)} = \frac{N}{2f_{cp}} \]

- **Echo Circuits**
  - Common implementation: 300 ms delay time with 4096 stages
  - ~7 kHz clock frequency
  - Sometimes as low as ~4 kHz!

- **Chorus Circuits**
  - 10 ms delay with 1024 stages
  - 51.2 kHz clock frequency
  - Sometimes lower

- **Anti-aliasing and reconstruction filters needed**
Filter Implementation

- Sallen-Key lowpass filters
  - Transistor-based common
  - Op-amp-based less common

- Cutoff frequency typically chosen to be 1/3 to 1/2 of the BBD clock
- In echo circuits, third-order anti-aliasing, and series third- and second-order reconstruction
- In chorus, flanger, and vibrato, typically lower total order
- Switched-capacitor filters rare, but smart
Third-order, transistor-based Sallen-Key low-pass filter
Typical magnitude responses of anti-aliasing filter and reconstruction filters
Measured and calculated combined magnitude response
Modeling BBD Filters

● First, obtain a frequency response based on circuit values and Sallen-Key filter transfer functions (or direct measurements)

● Then, digitize using any of a number of filter design methods (for example, invfreqz)

● Highly accurate filters are possible at relatively low-orders
  ○ Third order ~5-7
  ○ Second order ~2
  ○ Total ~9

● Filter representation is often the most perceptually relevant part of the model
Digitized combined filter response, ninth-order
Companding

- BBDs have a low dynamic range
  - ~60 dB SNR common
  - THD increases dramatically when amplitude is over about 10% of the supply voltage
  - Effects are worse as the number of stages increases

- Companding
  - Compression preceding the BBD
  - Expansion following the BBD
  - Results in a low dynamic range in the BBD "channel"
  - Normally only found in echo circuits
Effect of companding on the dynamic range of a signal
570- and 571-series

- The majority of BBD systems which include a compander use the 570- or 571-series compander.
- Pair of variable gain amplifiers and level detectors.
- Gain is internally set to have a compression or expansion ratio of 2.
- Level detector controlled by external capacitor.
  - Internally, the signal is rectified and sent through a RC filter.
  - Resistor is internally set to 10kOhm.
  - Capacitor value chosen to minimize ripple.

\[ \tau = 10000C_{\text{rect}} \]
Modeling BBD Compansion

- Use the average signal level to determine the gain of the system
  - Expander (feedforward)
    \[ f(x) = \text{avg}(|x|)x \]
  - Compressor (feedback)
    \[ f(x) = \frac{x}{\text{avg}(|f(x)|)} \]
- Averaging circuitry can be modeled by a one-pole digital filter
  - Input should be rectified
  - Model easily calculated based on external capacitor value
    \[ y(n) = x(n) \frac{T}{RC + T} + y(n - 1) \frac{RC}{RC + T} \]
BBD Aliasing

- Discrete-time sampling produces large amounts of aliasing distortion
- This effect is ideally (and mostly) removed by anti-aliasing and reconstruction filters
- Modeling approaches
  - Can be ignored, but an interpolating delay line should be used
  - Downsampling/upsampling more realistic
  - Delay line of fixed length with "virtual" BBD clock source is most accurate and gives pitch shifting when changing the delay time for free
**Insertion gain**

- BBDs have a "frequency-dependent" insertion gain (filtering)
- Can be thought of as not being able to transfer charge at speeds near the Nyquist limit
- Varies with clock frequency and number of stages
- Typically between 0 to 2 dB for lower frequencies, down to -4 to -6 dB near the Nyquist limit
- Much less dramatic than anti-aliasing and reconstruction filters
- Digital filters based on measured response could model this effect
**BBD Noise**

- BBDs introduce noise, SNR typically ~60 dB
- Result of imperfect transactions between BBD stages
- Varies slightly with number of stages and clock frequency
- Can be reduced, but not removed, by compansion
- Inclusion in the model depends on application  
  - Can be omitted for an intentionally clean digital system  
  - Must be included to realize the "self-oscillation" effect common to BBD-based echos
Nonlinearities

- THD typically rated and measured to be about 1% per 1024 BBD stages
  - Hardly apparent for choruses, vibratos, and flangers
  - More apparent in echos, where the signal is recirculated
- Minimized by biasing input signal
- Does not vary dramatically with signal level (separate from BBD clipping)
- Aliasing distortion makes measurement difficult
Measured magnitude spectrum for pure sine tone input
Peaks in magnitude spectrum for pure sine wave inputs at various levels
Nonlinearity Modeling

- Modeling is difficult because it is not a "clipping" nonlinearity
- Polynomial nonlinearity provides a good estimate

\[
f(x) = \begin{cases} 
1 - a - b & \text{for } x > 1 \\
x - ax^2 - bx^3 + a & \text{for } -1 < x < 1 \\
-1 - a + b & \text{for } x < -1 
\end{cases}
\]

- Parameters can be chosen to match one particular sine wave input level
- A more accurate implementation could vary parameters based on the average signal level
- Anti-aliasing filter in BBD system conveniently reduces digital nonlinearity aliasing problems
Harmonic distortion resulting from nonlinearity model
Model Example

● Models a 4096-stage BBD echo circuit
● Includes compansion, filtering, "virtual clock", noise, and nonlinearities
● Practical difficulties
  ○ Feedback compressor creates a delay-free loop
  ○ "Virtual clock" implementation results in excessive aliasing distortion due to "clock jitter"
  ○ Compander estimate not exact
  ○ Component values also vary filter response
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Further Reading

● "Practical Modeling of Bucket Brigade Device Circuits" paper
● References therein
● Datasheets and circuit diagrams
  ○ http://experimentalistsanonymous.com/diy/