Basic Filters
And
Reverberators

Filter: a frequency-dependant attenuator

It enhances some frequencies and diminishes others.
Amplitude Response

Basic Types of Amplitude Response

- **low-pass**
- **high-pass**
- **band-pass**
- **band-reject**
pass-band

stop-band

\[ f_c \text{ cutoff frequency (half power point or -3 dB point)} \]

\[ f_c \text{ center frequency} \]

Source/Filter Interaction

Source

Filter

Result

transfer function
How are they perceived?

Induced pitch

Special Signals

time

frequency

sine

dc

Nyquist

impulse

1/2 SR
Impulse Response

input
1., 0., 0., 0.,

filter

output
.1, .6, .7, .4, -.3, -.1,

time

frequency

Graphic Symbols

signal flow

multiply

add

unit delay

delay of m samples
Digital Filters
Two Types

non-recursive
feed forward
“notches”
FIR

recursive
feed back
“peaks”
IIR

first-order filters

spectral features

filter type
recursive (poles) non-recursive (zeros)

acoustic analog
stored energy resonance cancelled energy anti-resonance
\[ z^{-1} \]

**non-recursive**

\[ x(nT) \quad k \quad a \quad y(nT) \]

\[ a = 1 \quad a = -1 \]

<table>
<thead>
<tr>
<th>( n )</th>
<th>( x(nT) )</th>
<th>( y(nT) )</th>
<th>( x(nT) )</th>
<th>( y(nT) )</th>
<th>( n )</th>
<th>( x(nT) )</th>
<th>( y(nT) )</th>
<th>( x(nT) )</th>
<th>( y(nT) )</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>-2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
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<td>2</td>
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<td>3</td>
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<td>-1</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>-2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

**recursive**

\[ b = .9 \]

\[ x(nT) \quad k \quad y(nT) \]

\[ b \]

<table>
<thead>
<tr>
<th>( n )</th>
<th>( x(nT) )</th>
<th>( y(nT) )</th>
<th>( x(nT) )</th>
<th>( y(nT) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1.0</td>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1.9</td>
<td>-1</td>
<td>-0.10</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2.7</td>
<td>1</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3.4</td>
<td>-1</td>
<td>-0.18</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>4.1</td>
<td>1</td>
<td>0.84</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>4.7</td>
<td>-1</td>
<td>-0.25</td>
</tr>
</tbody>
</table>
Environmental Acoustics and Computational Simulation

Also known as

REVERB

Indirect Sound

*Indirect sound exists in all environments though we may not attend to it consciously.*
Large-Space Acoustics

We are most able to attend to indirect sound in large-spaces like concert halls or cathedrals.

Reverberation time is the duration in which the indirect sound decreases to -60 dB of the direct sound.

Large-Space Acoustics

Typical reverberation times:

<table>
<thead>
<tr>
<th>Concert Hall</th>
<th>Year built</th>
<th>Volume (m$^3$)</th>
<th>Area (m$^2$)</th>
<th>Number of seats</th>
<th>$t_r$ (sec)</th>
<th>Floor Balcony</th>
<th>125 Hz (sec)</th>
<th>500 Hz (sec)</th>
<th>2000 Hz (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symphony Hall, Boston</td>
<td>1801</td>
<td>18,740</td>
<td>1556</td>
<td>2630</td>
<td>15</td>
<td>7</td>
<td>2.2</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Orchestra Hall, Chicago</td>
<td>1935</td>
<td>15,170</td>
<td>1855</td>
<td>2580</td>
<td>40</td>
<td>24</td>
<td>—</td>
<td>1.3</td>
<td>—</td>
</tr>
<tr>
<td>Severance Hall, Cleveland</td>
<td>1930</td>
<td>12,700</td>
<td>1395</td>
<td>1890</td>
<td>20</td>
<td>15</td>
<td>—</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Carnegie Hall, New York</td>
<td>1891</td>
<td>24,250</td>
<td>1985</td>
<td>2760</td>
<td>23</td>
<td>16</td>
<td>1.8</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Opera House, San Francisco</td>
<td>1932</td>
<td>21,800</td>
<td>2165</td>
<td>3250</td>
<td>51</td>
<td>30</td>
<td>—</td>
<td>1.7</td>
<td>—</td>
</tr>
<tr>
<td>Arie Crown Theatre, Chicago</td>
<td>1961</td>
<td>36,500</td>
<td>3265</td>
<td>5080</td>
<td>36</td>
<td>14</td>
<td>2.2</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Royal Festival Hall, London</td>
<td>1951</td>
<td>22,000</td>
<td>2143</td>
<td>3000</td>
<td>34</td>
<td>14</td>
<td>1.4</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Royal Albert Hall, London</td>
<td>1871</td>
<td>46,600</td>
<td>3713</td>
<td>6280</td>
<td>65</td>
<td>70</td>
<td>2.4</td>
<td>2.6</td>
<td>2.2</td>
</tr>
<tr>
<td>Concertgebouw, Amsterdam</td>
<td>1887</td>
<td>18,760</td>
<td>1285</td>
<td>2200</td>
<td>21</td>
<td>9</td>
<td>2.2</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Kennedy Center, Washington</td>
<td>1971</td>
<td>19,800</td>
<td>1220</td>
<td>2760</td>
<td>—</td>
<td>—</td>
<td>2.5</td>
<td>2.2</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Source: After Béatrice (1962).
Large-Space Acoustics

Different kinds of music and sound are best presented with different reverberation times.

Indirect sound that reflects off of one wall is called a first-order reflection, off two walls a second-order reflection, etc. As the density of reflections increases, the higher-order reflections merge into the continuous sound with at least 1000 reflections/ sec we call reverberation or the late field.
Reverberation Simulation

By 1963 Manfred Schroeder has perfected the first digital reverberator. His purpose was to simulate concert hall acoustics including a multiple delay line to simulate the initial first- and second-order reflections.

Schroeder’s basic building blocks were the delay line (a non-recursive comb filter), the recursive comb filter and the all-pass comb filter.
Delay line: Non-recursive Comb Filter

\[ K \rightarrow z^{-m} \rightarrow a \]

Impulse response:
- \( K \)
- \( K_a \)
- \( m \) samples

Amplitude response:
- \( f = SR/m \)
- (explains the name comb filter)

Recursive Comb Filter

\[ K \rightarrow z^{-m} \rightarrow a \rightarrow z^{-m} \]

Impulse response:
- \( K \)
- \( K b \)
- \( K b^2 \)
- \( K b^3 \)
- \( K b^4 \)
- \( m \) samples

Amplitude response:
- \( f = SR/m \)
All-pass Comb Filter

impulse response

-\(b\)

-\(b^2\)

-\(b^3\)

-\(b^4\)

-\(z^{-m}\)

amplitude response is constant:
(recursive and non recursive parts cancel each other)

Schroeder Reverberator

Block diagram of a single channel (monophonic) reverberator

recursive comb

Allpass

(density)

(decay)
**Schroeder Reverberator**

Four recursive comb filters in parallel determine the reverb time.

**Early Reflections**

Two all-pass filters in series insure that there are 1000 reflections/sec.
Summation of recursive comb filters should approximate a flat response

Problems

1) Response is not flat

2) Impulse response has periodicities that produce pitch percepts
Air and Wall Absorption

Air and wall absorption combine to create a reverberation time that is frequency dependent. For concert halls the low-frequency reverberation time is longer:

![Graph showing reverberation time](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood or metal seats, unoccupied</td>
<td>0.014</td>
<td>0.018</td>
<td>0.020</td>
<td>0.036</td>
<td>0.035</td>
<td>0.028</td>
<td></td>
<td>m²</td>
</tr>
<tr>
<td>Upholstered seats, unoccupied</td>
<td>0.13</td>
<td>0.26</td>
<td>0.39</td>
<td>0.46</td>
<td>0.43</td>
<td>0.41</td>
<td></td>
<td>m²</td>
</tr>
<tr>
<td>Audience in upholstered seats</td>
<td>0.27</td>
<td>0.40</td>
<td>0.56</td>
<td>0.65</td>
<td>0.64</td>
<td>0.56</td>
<td></td>
<td>m²</td>
</tr>
</tbody>
</table>

Air absorption and the absorption of walls, seats and people help to shape the reverberation.
Air and Wall Absorption

In everyday environments the building materials have a strong impact on reverberation of the acoustic environment.

<table>
<thead>
<tr>
<th>Material</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete block, unpainted</td>
<td>0.36</td>
<td>0.44</td>
<td>0.31</td>
<td>0.29</td>
<td>0.39</td>
<td>0.25</td>
</tr>
<tr>
<td>Concrete block, painted</td>
<td>0.10</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>Glass, window</td>
<td>0.35</td>
<td>0.25</td>
<td>0.18</td>
<td>0.12</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>Plaster on lath</td>
<td>0.14</td>
<td>0.10</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Plywood paneling</td>
<td>0.28</td>
<td>0.22</td>
<td>0.17</td>
<td>0.09</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>Drapery, lightweight</td>
<td>0.03</td>
<td>0.04</td>
<td>0.11</td>
<td>0.17</td>
<td>0.24</td>
<td>0.35</td>
</tr>
<tr>
<td>Drapery, heavyweight</td>
<td>0.14</td>
<td>0.35</td>
<td>0.55</td>
<td>0.72</td>
<td>0.70</td>
<td>0.65</td>
</tr>
<tr>
<td>Terrazzo floor</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Wood floor</td>
<td>0.15</td>
<td>0.11</td>
<td>0.10</td>
<td>0.07</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>Carpet, on concrete</td>
<td>0.02</td>
<td>0.06</td>
<td>0.14</td>
<td>0.17</td>
<td>0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>Carpet, on wood</td>
<td>0.08</td>
<td>0.24</td>
<td>0.57</td>
<td>0.69</td>
<td>0.71</td>
<td>0.73</td>
</tr>
<tr>
<td>Acoustical tile, suspended</td>
<td>0.76</td>
<td>0.93</td>
<td>0.83</td>
<td>0.99</td>
<td>0.99</td>
<td>0.94</td>
</tr>
<tr>
<td>Acoustical tile, on concrete</td>
<td>0.14</td>
<td>0.20</td>
<td>0.76</td>
<td>0.79</td>
<td>0.58</td>
<td>0.37</td>
</tr>
<tr>
<td>Gypsum board, one-half inch</td>
<td>0.29</td>
<td>0.10</td>
<td>0.05</td>
<td>0.04</td>
<td>0.07</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Air and Wall Absorption

Moorer suggests putting low-pass filter in the feedback loop of the recursive comb filter in order to simulate air and wall absorption. This causes the high frequencies in the reverberation to die out before the low frequencies.
Air & wall absorption filter

Usually the low-pass filter inserted into the recursive comb filter is a first-order filter. Here is a second-order filter that is more accurate.

Low-frequency loss (not present in concert halls but present in other kinds of construction)

Comparison of simulated and actual rooms

simulated

real
Feedback Matrix

Strautner & Puckette 1982
Jot & Chaigne 1991

Generic Effects Processor

input

+ delay

1st order ???
tone

feedback

+/- 1

feedback phase

output

mix

output

speed

width

on/off

modulation

 delay
Control Signals/Modulators

```
+1 deviation
+ centerValue

centerValue

-.5 +1 metallic, zingy
-.5 whoosh, hollow

+/- 1 delay
5 ms 200 Hz
20 ms 50 Hz
```

“Flanging”
Chorusing

modulation controls
10-25 msec

Panning and Positioning
Panning Methods

Amplitude Panning

Intensity or Power Panning

Near-field Monitoring:
- Greatest accuracy:
- Low Frequencies: amplitude panning
- High Frequencies: power panning

Large-space Monitoring:
- power panning