Lab04: Digital Audio Effects

EECS20: Introduction to Real-Time Digital Systems

By K. H. Chiang, William T. Huang, Brian L. Evans.
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1 Introduction

In the last laboratory, you played music as a sequence of notes, and experimented with making the music sound more realistic. In this laboratory, you will use simple mathematical operations to add style and special effects to the computer-generated music. You will add vibrato and tremelo playing styles. For special effects, you will replicate a melody to sound as if it were coming from many similar instruments (chorusing), and incorporate echo and reverberation, which are feedback techniques employed often in rock 'n' roll.

2 Vibrato and Tremelo

Vibrato is the variation of the amplitude of a tone by a low frequency sine wave. In mathematical terms:

$$x[n] = \sin(2\pi \frac{f_m}{f_s} n) \sin(2\pi \frac{f_c}{f_s} n)$$

where f_c is the frequency of the underlying sine wave, or the *carrier frequency*; f_m is the *modulating frequency*, with $f_m \ll f_c$; and f_s is the sampling frequency, with $f_s > 2f_c$ to ensure that the Nyquist criterion is satisfied.

Tremelo is the variation of the frequency of the tone by a low frequency sine wave. In mathematical terms:

$$x[n] = \sin(2\pi \frac{f_c}{f_s} n + m \sin(2\pi \frac{f_m}{f_s} n))$$

where f_c is the frequency of the underlying sine wave, or the *carrier frequency*; f_m is the *modulating frequency*. with $f_m \ll f_c$; m is the modulation index, and f_s is the sampling frequency, with $f_s > 2f_c$ to ensure that the Nyquist criterion is satisfied. To get a feel for what these parameters actually do, graph the frequency $f_c + m \sin 2\pi f_m t$ as a function of time t; the frequency will have a nominal value of f_c, but will exhibit a sinusoidal variation at a frequency of f_m with a maximum amplitude of m. Suggested values of m will be on the order of 2.5% to 10% of f_c.

Varying the amplitude of a sine wave by some signal is commonly called *amplitude modulation*. Varying the frequency of a sine wave by some signal is commonly called *frequency modulation*. In frequency modulated (FM) radio, f_c ranges from 88.5 to 108.5 MHz, the maximum f_m is 15 kHz, and $m = 5$. In amplitude modulated (AM) radio, f_c is 530 to 1700 $\times$ 100 kHz and the maximum f_m is 5 kHz. This is one of the reasons that music on an FM radio station sounds better— more of the frequencies in the music are being transmitted. AM radio carries enough frequencies for human speech to sound good, but not enough for music because music contains frequencies over the entire audible range from 20 Hz to 20 kHz.

3 Chorusing

One way that studios use to make a few people sound like a crowd is chorusing. This is done adding to the original signal several delayed and attenuated versions of the original signal, as illustrated in Figure 1. The arrows in the figure indicate paths for the input signal. Figures such as these

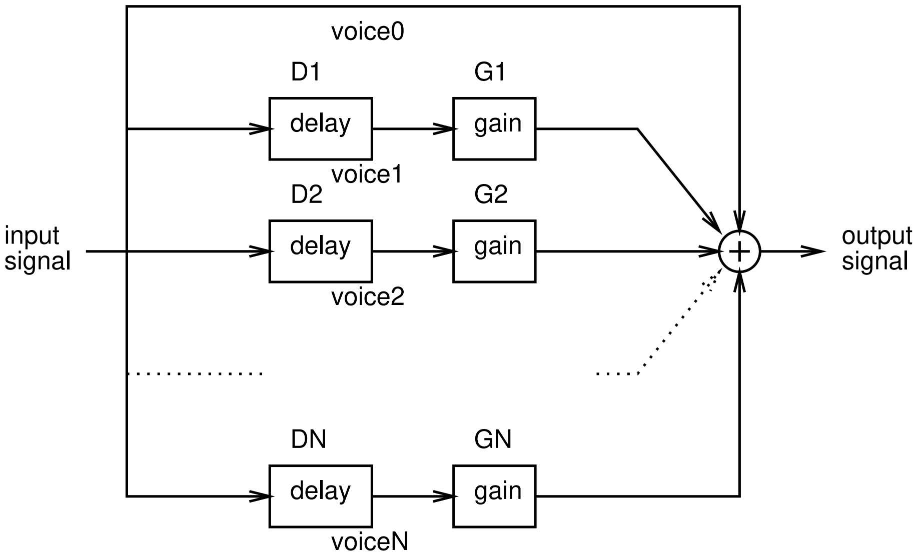

Figure 1: A system that implements chorusing.

are usually drawn with the signal flow from left to right. Blocks represent systems which operate on their inputs to produce outputs. The delay blocks will return delayed versions of their inputs; in Figure 1, the amount of delay is represented by the variables D1 through DN. The gain blocks multiply their input by a constant value; this constant value is denoted G1 through GN. The circle with the plus sign is an adder, whose output is the sum of its inputs.

4 Echo

Consider clapping your hands once in a large room. First you hear the clap, and then an attenuated version of that clap, and then an attenuated version of that attenuated version... One way to reproduce this effect in the lab is to use a feedback loop, as in Figure 2. The input to the system is the original signal and the output is the echoed signal. Note that there is a direct connection from the input to the output. However, there is also a connection feeding a delayed and attenuated [assuming the gain is less than unity] version of the output signal back into the input. This is called a feedback loop, because the output is fed back to the input.

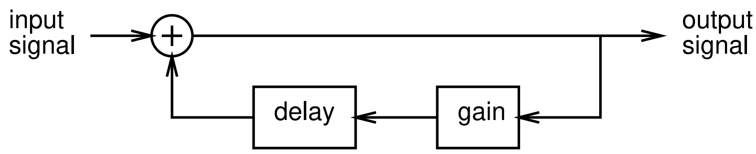

Figure 2: A system that implements echo.

This system can be directly realized by summing appropriately delayed and attenuated copies of the original signal. Let the original signal be denoted $x[n]$, sampled at rate f_s. If we desire a delay of d seconds, this translates into a delay of $D = d\, f_s$ samples. In addition, if the attenuation factor is denoted α, the signal with echoes $y[n]$ is then:

$$y[n] = x[n] + \alpha x[n-D] + \alpha^2 x[n-2D] + \alpha^3 x[n-3D] + \ldots$$

5 Reverberation

If the delay in the echo system above is sufficiently small, we can no longer hear distinct echoes. With a few appropriate modifications, as described below, we instead have reverberation.

Reverberation is the combination of a direct sound, an early return, and a reverberation tail. Going back to our example of clapping in a room, the direct sound is the initial clap. The early return would be the first echo that you would hear. The reverberation tail would be all the other echoes coming back to your ears, except that they would be close enough together that they wouldn't be very distinct. A simple reverberation system is shown in Figure 3.

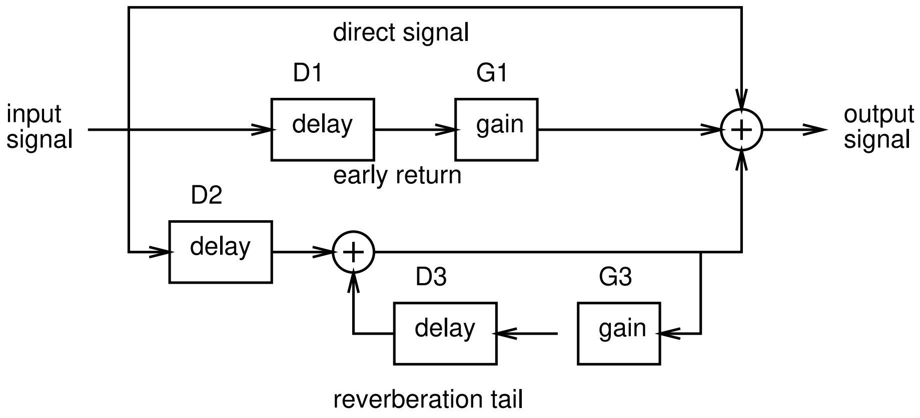

Figure 3: A system that implements reverb.

With the appropriate selection of the parameters in Figure 3, we can simulate the response of any room from a dead one [with no return at all; this would be a room with a lot of sound insulation on the walls] to an extremely lively one [like a stadium or church].

Of course, the key word here is "appropriate". From the data available on various acoustical spaces, two of the available parameters are initial time delay (ITD) and reverberation time. The ITD is the time between when you make a sound and when you hear the first echo. The reverberation time is the time it takes for a sound that you make at $t = 0$ to die away to $\frac{1}{1000}$ of its initial amplitude.

Relating the ITD and the reverberation time to the values you need to put into the system in Figure 3 is a matter of engineering discipline [translation: make a reasonable guess]. As far as i can make it out, rules of thumb for choosing the various values are as follows:

- D1: the ITD.
- G1: same as G3.
- D2: twice the ITD.
- D3: experiments say 50 ms.
- G3: $10^{-3\ D3\ /\ reverberation\ time}$.

For Symphony Hall in Boston, MA, the ITD is 15 ms and the reverberation time is 1.8 s if the hall is occupied. This translates into:

D1	15 ms
G1	0.855
D2	30 ms
D3	50 ms
G3	0.855

6 Questions

1. Vibrato and tremelo:
   (a) Implement both vibrato and tremelo on a $f_c = 440$ Hz tone. Use $f_m = 10$ Hz, and for tremelo, a modulation index of 1.
   (b) Sketch [plot by hand] waveforms for the above parameters.
   (c) Play the waveforms back using the `sound` command. Can you hear any difference between them?
   (d) What happens when you vary the modulation index?

2. Chorusing: to make yourself sound like a crowd, implement the system in Figure 1. For the various delays, choose values between 0 and 10 ms [you may wish to change this maximum value]. For the various gains, choose values between 0.9 and 1.1.

3. Echo:
   (a) Record an sound and create an echoed version of that sound by adding together appropriately attenuated and delayed copies of the original sound. For amusement value, vary the attenuation and the delay.

(b) The system in Figure 2 has the system transfer function:

$$H(z) = \frac{1}{1 - \alpha z^{-D}}$$

Read the documentation for the `filter` command. Use that command with `b=[1]`, `a=[1 zeros(1, delay-1) -alpha]`, and a sufficiently long copy of x, padded with zeros. Compare the resulting output with that directly generated. Note that the filter command could take a long time to run, especially for large values of D.

4. Reverberation:

(a) Implement the system in Figure 3 and experiment with various values of the parameters. Note that the delays are given in seconds and need to be translated into sample delays. Consider recycling some of your work from the previous section.

(b) What values make the room sound dead?

(c) Try the values in the table below.

place	ITD (ms)	reverberation time (s)
studio	20	0.40
auditorium	40	0.75
concert hall	25	1.80
church	50	3.25

5. Take the music that you generated in lab03 and run it through all your special effects above.

6. Humor value: from where did these quotes originate?[1]

(a) "What's rock 'n' roll without feedback?"

(b) "But it's louder— it goes to 11!"

(c) "Hope I die before I get old?"

[1] 1. Dave Mason, Guitarist for Pink Floyd. 2. From the movie *Spinal Tap*. 3. The Who.