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Homework #4: Reverberation Analysis & Synthesis
Due Date: May 10, 2011

# 1 Problem Set

In this problem set you will first analyze the space and recordings made at Memorial Church to characterize its reverberation. Then, based on this analysis, you will synthesize a Reverb to simulate the space in Memorial Church.

The files provided (`memchu 2011 recordings.zip`) contain the response of the church to different balloon pops and sine sweeps, recorded at the stereo pair of B&K reference mics in the crossing center or using an omni-figure 8 configuration using the AKG mics placed in the West Transept/Side Chapel.

The file name (`XX_YY_ZZ.wav`) specifies the configuration of a particular recording, according to the following convention:

- `XX` indicates the input signal (bp = balloon pop; ss = sine sweep)
- `YY` indicates the mic setting (sp = stereo pair; of8 = omni-figure 8)
- `ZZ` indicates the repetition, useful to match sp recordings to of8 recordings (repetition = seq corresponds to the sequence of balloon pops we did at the end, with people at different places in the church)

The recordings are not post-processed. Each channel of the stereo file contains one of the microphone recordings. For the omin-figure 8 configuration, the left channel corresponds to the omni mic recording and the right channel to the figure 8 mic recording.

**Problem 1. [20 points]**

**1(a). [10 points]** Referring to the table of Sabine coefficients in §9 of the course notes and the air absorption decay rates a few pages later, estimate $T_{60}(\omega)$ for Memorial Church at 250 Hz, 1000 Hz and 4.0 kHz. Approximate the church as a totally enclosed shoebox, 25m wide, 40m long, 10m high. Use plywood for the ceiling and half the floor, use glass for about a tenth of the walls and plywood for another tenth, and assume marble for everything else.

**1(b). [5 points]** What if the church were half its size?

**1(c). [5 points]** What if the church floor were carpeted?

**Problem 2. [40 points]**

**2(a). [5 points]** Choose a couple balloon pop recordings and plot the spectrogram of the first 2.5 seconds and of the first 300 milliseconds of one of the balloon response channels. Use 256-point long windows and a hop size of 32 points. If you use the variable `stft` for your short time Fourier transform, the following will make a nice spectrogram plot:

```
imagesc(20*log10(abs(stft)/max(max(abs(stft)))), [-80 0]); grid;
axis('xy'); colorbar; colormap(jet);
```

Type `help imagesc` to figure out how to mark the time and frequency axes. Indicate the arrival of any major reflections in the first 250 milliseconds.

**2(b). [10 points]** Use the Matlab function `butter` to create a set of octave-wide, fourth-order bandpass Butterworth filters, centered at 125 Hz, 250 Hz, ..., 8.0 kHz (to create your filter bank, we suggest you either use the diadic Butterworth low-pass/high-pass decomposition we discussed in class, with transition frequencies at the geometric means of the band center frequencies, or use Butterworth band-pass filters for each of your bands). Turn in a plot showing their transfer function magnitudes. (Hint: Use the Matlab function freqz.)

**2(c). [15 points]** Apply each of the octave band filters you made to the balloon pop. Use the Matlab function `filtfilt` which applies the filter twice, once forward in time and once backward in time, to create a zero-phase filter. Estimate the $T_{60}$ for each band by forming a running mean of the band energy, and computing the slope of the dB smoothed energy (using least-squares or visual inspection). Plot the results on a log frequency axis using `semilogx`. Compare the two chosen balloon pops in terms of their $T_{60}$ per band.

**2(d). [10 points]** Find the maximum signal energy to mean noise energy ratio (the measurement SNR) for each band. To estimate the noise level, find the average noise energy before the arrival of the balloon pop.

**Problem 3. [30 points]**

The sine sweep `ss_src.wav` is an exponential sweep from 20 Hz to the band edge. Find the impulse response of the church between the Mackie speakers and one microphones using the Matlab commands:

```
c = real(ifft(1./fft(s)));
ir = fftfilt(c, [r; zeros(length(c),1)]);
```

where `s` is the sine sweep and `r` is either the left or right sweep response, of one of the sine sweep responses recorded (choose one of the `ss_YY_ZZ.wav` files).

- Plot the spectrogram of the sweep response.
- Plot the spectrogram of the measured impulse response, and point out any plainly visible reflections in the first 250 milliseconds after the direct path arrival.
- Why is the sweep signal zero padded?
- Apply the octave band filters to the impulse response, and estimate the band $T_{60}$, initial level, and measurement SNR in each octave band. How do these compare to that from the balloon response?

# 2 Laboratory

**Problem 4. [100 Points]**

In this lab, the plugin Reverb will be modified to incorporate filters which control the decay time and output equalization.

Source code can be downloaded from the class website. All necessary materials are contained in the file `Lab2_MAC_VST.zip` or `Lab2_WIN_VST.zip`.

Solutions for each exercise should include the source files `Reverb.cpp` and `Reverb.h`, suitably modified. The files must be able to be compiled. Additional write-up is required for some sections of this problem.

**4(a). [70 Points]** The feedback delay network reverberator Reverb as implemented has first-order filters in its feedback loop. Based on user settings specifying the low-frequency and high-frequency decay times and a transition frequency, design first-order shelf filter coefficients for each delay lines filter. The shelf filters should have DC and band-edge gains designed to give the selected decay times, taking into account the associated delay line lengths. The filters should also have gains equal to the geometric mean of their DC and band-edge values at the transition frequency. Set the pole frequency equal to the transition frequency.

Remember that an analog shelf filter has the following prototype:

$$h(s) = \frac{\ell_\pi s/\rho + \ell_0}{s/\rho + 1}$$

where $\ell_0$ and $\ell_\pi$ define the DC and high-frequency gains and $\rho$ controls the transition frequency (see page 250 of the course notes for more details).

Verify that you are approximately getting the desired decay time as a function of frequency for the low-frequency decay time set to 2.0 seconds and the high-frequency decay time set to 0.5 seconds, with the transition frequency set to 1.5 kHz. Hand in a spectrogram of the sample impulse response.

**4(b). [30 points]** Consider Table 1 showing estimates of the $T_{60}(\omega)$ for a reverb impulse response `memchu_bpeq.wav`, synthesized from a Memorial Church balloon pop response. Find settings of the $T_{60}$ controls and wet/dry mix such that the impulse response of the FDN reverberator sounds like the impulse response provided. This can be done by ear or using Matlab to estimate the correct parameters.

| frequency [Hz] | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 | 16000 |
|---|---|---|---|---|---|---|---|---|
| $T_{60}$ [ms] | 3556 | 3618 | 4085 | 4386 | 3788 | 2378 | 1129 | 484 |

Table 1: Synthetic Impulse Response $T_{60}$ as a function of frequency