ROSE-HULMAN INSTITUTE OF TECHNOLOGY
Department of Electrical and Computer Engineering

Audio Signals and Spectra

Lab 07

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Objectives

- To become familiar with the concept of an aperiodic signal spectrum
- To investigate typical temporal and spectral features of audio signals
- Use MATLAB to investigate audio signal processing

Equipment

Laptop Computer with MATLAB
Agilent E4402B Spectrum Analyzer
Function Generator
Oscilloscope

Background

We are learning that a signal can be represented either in the time domain or in the frequency domain. Learning some basic realities of this dual representation will be an important goal of this course. One of the cardinal rules is that events that happen quickly in time contain higher frequency content than events which occur more slowly. Sounds converted to and from electrical audio signals provide an excellent way to investigate these relationships.

The human ear can hear sounds of frequencies in the range 20 Hz to 20 kHz. However, most sounds we work with only contain frequency content in the range of about 100 Hz to 8 kHz. Lower frequency sounds, such as a tug boat whistle, have more frequency content in the low part of the audio range. Higher frequency sounds, such as bird song or dog whistles, have more content in the upper part of the range.

Plotting the signal waveform versus time is familiar from our classwork. When we plot an audio signal versus time, we become aware of events happening on different time scales. For example, we might see the amplitude of the signal go up or down on the scale of tenths of a second. This time scale determines mostly amplitude effects. The signal also oscillates on the scale of tenths of a millisecond. This time scale determines the frequency or pitch of the sounds.

We can also think of the signal as being composed of a number of sinusoids, each having a distinct frequency, amplitude, and phase (similar to a Fourier Series). The tug boat whistle can be thought of as containing sinusoids at lower frequencies, while the bird song contains sinusoids with higher frequencies. (Be sure you can differentiate between amplitude and frequency in terms of sounds.) The frequencies present and their relative amplitude and phase comprise the spectral content of the signal. The signal spectrum is simply a plot of this spectral content vs frequency, or how signal energy is distributed in frequency, just as the waveform plot displays how signal energy is distributed in time. However, this display is averaged over a period of tens or hundreds of milliseconds, thus losing information on the scale of seconds.

There are a number of tools available for examining the spectral content of the signal. The spectrum analyzer is able to display the spectral content of the signal in pseudo-real time, in the same manner as an oscilloscope (the refresh rate determines how close to real-time the display is). We can also investigate the spectral content of the signal by examining its digitized content with a digital signal processing (DSP) application called the Fast Fourier Transform, or FFT. This creates a view of the spectral content of the signal based on the entire signal sample. In this way, the FFT cannot display the spectral content in real time, but rather displays only the spectral content averaged over the entire duration of the signal sample.

Yet another DSP application is available which displays how the frequency content of the signal varies with time (sorta). This is called a spectrogram, or time-frequency plot. This combines the time and frequency dependent behavior of the signal by calculating a "Short-Time Fourier Transform" over a small time window of the signal. The center of the window (in time) is then shifted forward in time, and a new STFT is calculated. These STFTs are displayed as a function of window center time, resulting in a display of how signal spectrum evolves with time. This tool allows the evolution of the spectral content over longer time scales to be examined.

Pre-Lab

Investigate audio signal processing with MATLAB:

1. Create a directory on your laptop called "Matlab sounds". Copy all of the files from the ece 300 audio lab directory into this directory. Store all of your MATLAB programs and data files in this directory.
2. Create a MATLAB program (not a function) which will allow you to display the time waveform of an audio signal as a plot. The sound waveform samples are stored in ".mat" files, which are MATLAB format data files. In each file is stored an array "y" of signal samples and a sampling rate "Fs" (case is important). (The sample rate is equal to the reciprocal of the time between samples Ts. From the sampling rate, you will need to construct a time vector.) You can see what variables are present in a .mat file by typing "`open filename.mat`" at the MATLAB command prompt. To actually load the data into the MATLAB workspace, type "`load filename.mat`". Test your program on the sample audio files. Plot and compare the time waveforms of the train whistle file to that of the chirp, noting on the plot both short- and long-term structure in the waveform versus time and important timescales.
3. Add a line to your MATLAB main program which will play the sounds using the "`soundsc`" command. (Type "`help soundsc`" at the MATLAB prompt for details.) Make comments regarding what you hear when you listen to the train and chirp samples, and relate these features to the time waveform plotted above. Be specific.
4. Imagine a deer whistle mounted on the front of a car that emits a frequency of 5 kHz (in reality, many of those devices don't even emit sound at all, and so are ineffective). Consider the Doppler effect on your perceived frequency of the whistle. Sketch a time-frequency plot describing the effect you hear as the car drives by you at 30 mph. That is, plot the perceived signal frequency as a function of time, starting from when the car is far away and approaching you through when the car is far away and receding from you. This is a simple

spectrogram. (Hint: this is a vector velocity problem. Imagine you are standing at a point alongside the road, a distance d from the road. The car is traveling a velocity v_x down the road. This will create an effective velocity toward you. Look up the Doppler effect to finish this problem.)

5. Define chirp as it pertains to signal frequency content.
6. <optional> Obtain your favorite song, and convert it to a .wav file on your laptop. Use your MATLAB program to listen to the song using the "`wavread`" and "`wavplay`" commands. Create a second file with a few second duration clip of this song for further analysis.

Procedure

Examining Sinusoidal Signals

1. Use the MATLAB program you created in the prelab to create and display the time waveform $x(t) = 0.1\cos(2\pi 3000t) + 0.1\cos(2\pi 7000t)$ and duration corresponding to a few periods of the lower frequency waveform. The *sample rate* F_s should be 20*8192 Hz. Comment on the plot obtained and explain the plot features (e.g. is there enough *resolution?* and how is the signal energy is distributed in time?).
2. Next, use the provided MATLAB function *baf_fft.m* to view the spectrum of the signal. For this to work properly, you will need to use a longer sample of the signal, i.e. a longer signal duration, say 64 periods. This FFT function will display the spectral components of the waveform. Comment on the important features of the signal spectrum. Can you see any time variations in the spectral content? Explain.

Examine the Audio Signal Waveforms

3. Connect the headphone output from your laptop to the input of the oscilloscope using the provided adaptor. Play the audio samples using your Matlab script and the `sound` or `soundsc` command, and view the waveform on the oscilloscope. Displaying the waveform correctly requires you to think about the time scales of the events in the time signal (*autoscale* will not give the results you expect!). Based on your Prelab observations, what time scale should the oscilloscope be set for?
4. Capture the time waveform for the train whistle and chirp samples on the scope over appropriate time intervals (think about this). It will be easiest to do this by loading the sample into the workspace and typing "`sound(y,Fs)`" at the command prompt without hitting return. When you are ready to capture the sample, press return in the Matlab command window while simultaneously pressing the "Single" button on the scope. (This will take some practice!) Paste the waveforms into your notebook and comment on the important features in the waveforms.
5. <optional> Choose your favorite song audio file and capture its time waveform on the scope using appropriate amplitude and time scales. Paste a copy of the scope display in your lab notebook.

Examine the Audio Signal Spectrum

6. Using the function baf_fft.m, plot the fft (time-averaged) spectrum of the audio signal samples. Relate important features in the spectrum to the time waveforms and sound of the signals.

7. Use the built-in FFT feature of the oscilloscope to obtain a plot of the audio signal spectrum, first using MATLAB generated sinusoids to learn the operation of the scope's FFT capability. The FFT feature is available through the "Math" button between the channel 1 and 2 selection buttons. Note: the time scale used above to observe the time waveform will not suffice for examining the signal spectrum due to the details of how the FFT is computed in the scope. The FFT sample rate is controlled by the horizontal scale. Set the horizontal scale such that the FFT sample rate is 10 ksamples/sec in order to see signal content up to 5 kHz. (The sample rate should always be at least twice the highest frequency in the signal, and 5x is even better.)

   Note: The time scale settings and the actual capture technique for the waveform are awkward. This is a rather crude way of studying the spectrum of the signal, but you hopefully will recognize that the MATLAB is better for calculating the FFT of the signal samples, and that the spectrum analyzer is better for viewing the signal spectrum in real time.

8. Now obtain a spectrum plot from the spectrum analyzer. You will need to think a bit about how to do this. Note that the spectrum analyzer uses a much shorter time average its display, and thus shows a more real-time version of the signal spectrum.

9. Are there any significant differences between the spectral plots obtained using the three different methods?

10. <optional> Use the audio spectrum MATLAB program to view the spectrum of the song you chose on your laptop. Verify that the spectrum matches what was displayed using the FFT on the scope.

Examine the Time-Frequency Characteristics of Audio Signals

11. Create a new MATLAB program (based on your program from above) which will display the time-frequency plot for the various audio samples using the `spectrogram` (or `specgram`) command. Start with the time and frequency plotting program for the sinusoid in part 1 (covering, say, 1028 periods). Note that simply using the command "`spectrogram(y)`" or "specgram(y)" will display the spectrogram for the vector y with the time axis actually representing the index into the y vector, and the frequency axis covering the range 0 to $F_s/2$, normalized to $F_s/2$ (so you will get misleading results if you input a frequency > $F_s/2$). A slice of the 3D spectrogram plot at a given time index is gives the spectral content vector formed from a window of y vector values centered at that index, i.e. a view similar to a spectrum analyzer display at that time. In this way, the evolution of the spectrum in time is displayed in the spectrogram. (Read this paragraph again until you understand it!) I would use the command **spectrogram(y,[1:128],[],[],Fs,'yaxis'**) (or **specgram(y,[],Fs)**), but that's just me.

12. Using the **subplot** command, create a plots of both the signal versus time and the time-frequency content of the train whistle and chirp samples. Comment on the features you see

in the time-frequency plot, and explain them in terms of what you hear. Compare the results to the fft plot and explain the differences. Paste the time frequency plots of the two signals in your notebook along with your comments.

13. Given your results from this lab exercise, what information is present in the spectrogram (spectrogram plot) relative to that present in the FFT? To the time waveform?
14. <optional> Use the time frequency plot program you have created to view the content of your favorite song. Comment on how the features present in the plot correlate to what you hear.

Putting it all Together

15. In your conclusions section, comment on the things you have learned in this laboratory investigation. Include the following two explanations specifically: 1. Comment on the difference between the short- and long-term time variations in the signals, and what those variations correspond to in the signal sounds and time frequency plots. 2. Explain the difference in the information presented in the FFT and the spectrogram plots.

Report

Present your results in your lab notebook in a neat fashion (plots, comparisons, comments, and answers to the questions posed above). Be sure that all members of your lab group sign the lab notebook, and hand the notebook in at the end of lab.