Interactive Signals and Systems Laboratories Using Notebooks

Maurice F. Aburdene, Richard J. Kozick, Jaskeerat S. Baweja
Bucknell University

Abstract

This paper presents three interactive signal processing laboratories that use Matlab programs linked to a Microsoft Word document (a "notebook"). The active filter analysis and design, convolution and concert halls, and spectral analysis labs are designed for third-year students in a signals and systems course. These labs engage the students in the learning process by providing them with the opportunity to experiment and ask "what if" questions with a minimum of additional computational and documentation effort.

1. Introduction

We describe a set of interactive laboratories for a junior-level signals and systems course that uses Matlab linked to a Microsoft Word document (notebook or m-book). Notebooks facilitate the creation of interactive documents that combine text, executable Matlab code, spreadsheets for recording experimental data, and plots of simulated and experimental results. Students can use notebooks as a tool to document their laboratory activities and to prepare laboratory reports. A more detailed list of the advantages as well as evaluation of using notebooks in class are described in Shiavi[1,2].

Here we present notebooks for signals and systems laboratory experiments for:

> (a) Active filter analysis and design
> (b) Convolution: computation and application to concert halls
> (c) Spectral analysis with the discrete Fourier transform (DFT)and fast Fourier transform (FFT)

Advances in signal processing methods are fueling an explosion in many areas of electrical engineering, including multimedia, the internet, communications, and consumer electronics. These notebooks motivate the students to experiment with various cases in more detail to gain a better understanding of the fundamental ideas with immediate feedback.

2. Active filter analysis and design

The lab assignment itself is distributed to students as a notebook. It contains frequency response specifications for three active filters that the students are to design, build, and test. The notebook includes a sample Matlab program to plot the analytical frequency response of a circuit, which the students use to verify that their circuit design meets the specifications. In addition, this

notebook contains a spreadsheet that students can use to record frequency response measurements when they test their circuits. A Matlab script is provided that plots the analytical and measured frequency response of the circuit, with the resulting plots automatically included in the document. In order to produce the laboratory report, the student only needs to add appropriate text to describe the circuit design and evaluate the results. All of the Matlab code, experimental data, and frequency response plots are automatically included in the notebook.

Now we present the notebook materials for the first filter design project, which is a low-pass filter with the specifications of –5 volt/volt pass-band gain and 500 Hz cutoff frequency. Students are asked to identify a circuit that is able to meet the specifications, and to derive the analytical frequency response formula for the circuit as a function of the resistor, capacitor, and inductor values. This exercise provides an effective link from the students' prior course on circuit analysis to the present course on signals and systems.

Students select the appropriate circuit and then choose component values and amplifier to achieve the filter specifications. Then they construct the circuit and measure its frequency response.

The Matlab program in Figure 1 is included in the notebook to produce a Bode plot of the analytical and measured frequency responses. Students need only change the Matlab program to conform to their design and measurements, and then pressing CNTRL+ENTER will produce a Bode plot. The Bode plot corresponding to the given Matlab program is included in Figure 1.

The notebook is very convenient, since the Matlab coding and execution are all performed inside the notebook. Further, the resulting plot is automatically included in the notebook. For the lab report, the student adds a discussion about how well the filter design meets the given specifications.

3. Convolution: computation and application to concert halls

The objective in this lab is to practice computing the convolution sum for discrete-time systems and the convolution integral for continuous-time systems. Students begin by working in groups of two or three to solve a number of standard convolution questions. All of the convolution questions are provided in the notebook, but the students work out their solutions on paper. The students learn by explaining their work to each other and to the instructor.

The following are some sample questions related to impulse response and convolution:
- Find the impulse response $h(t)$ of an ideal integrator, i.e. a system whose output $y(t)$ is the integral of the input $x(t)$, as in $y(t)=\int_{\infty}^{t} x(\lambda)d\lambda$.
- Convolve the unit step function with itself: $y(t)=u(t)*u(t)$, and sketch $y(t)$.

```matlab
% Matlab script to plot analytical and measured frequency response.
% This program is for the RC low-pass filter with frequency response
% H(jw) = 1 / (1 + (j*w*R*C))

% Define circuit element values
R = 1.15e3;   % Ohms
C = 0.22e-6;  % Farads

% Create a vector of frequency values in Hz to evaluate the response.
% Space them logarithmically to create a Bode plot.

f = logspace(1, 5, 500);       % Hz
w = 2*pi*f;                    % radians/sec

H = 1 ./ (1 + (j*w*R*C));      % Complex response
Mag = abs(H);                  % Magnitude
MagdB = 20*log10(Mag);         % dB

% Measured data and analytical frequency response can be plotted on one
% graph.  For example, 4 measured values can be entered as follows:

f_meas = [10, 100, 1e3, 1e4];
Mag_meas = [0.99, 0.95, 0.4, 0.09];
MagdB_meas = 20*log10(Mag_meas);

semilogx(f, MagdB, '-', f_meas, MagdB_meas, 'o');
legend('Analytical', 'Measured')
title('Frequency Response Magnitude')
xlabel('Frequency (Hz)');
ylabel('dB');
grid
```
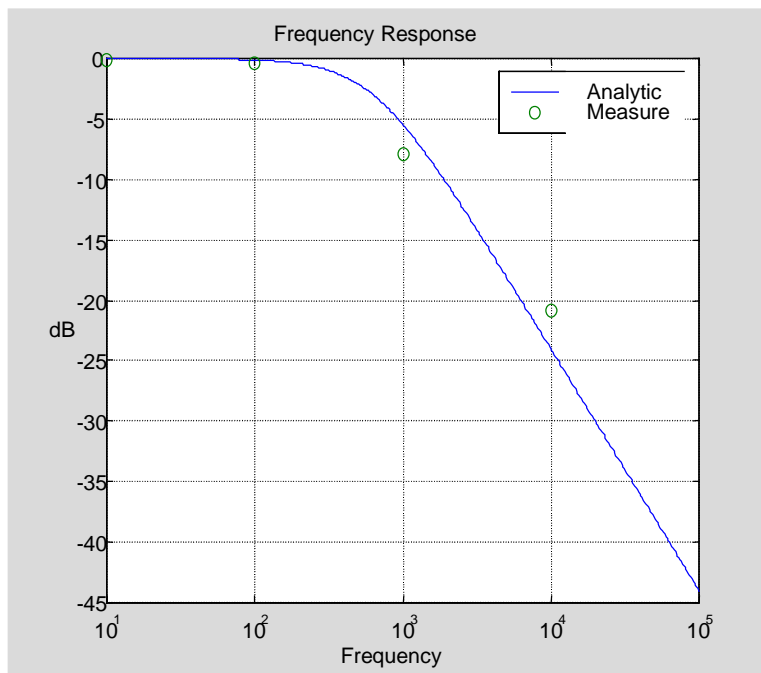

Figure 1: Matlab program and Bode plot from low-pass filter notebook.

The Matlab program in Figure 2 is included in the notebook to provide an application of convolution. The program simulates the effects of a listening room on music by processing digitized music with discrete-time systems that have various impulse responses. The filtered music is played through a speaker. The program in Figure 2 uses the impulse response g(t)=2*π*300 exp(-2*π300*t) u(t), corresponding to a low-pass filter with bandwidth 300 Hz. Another impulse response d(t) corresponding to an echo delayed by 0.4 seconds is also included in the notebook (but this is not shown in Figure 2). A plot of the impulse response is generated, in Figure 2. The notebook is very convenient as a multimedia tool, since the Matlab sound processing and playing is performed from within the notebook.

Students are asked to answer the following questions.
- What effect does convolution with g(t) have on the music, i.e. what is different about the music after the processing? Can you explain this effect from the shape of g(t)? (Hint: Does g(t) resemble the impulse response of an RC circuit? What type of filter does g(t) describe, and what is the cutoff frequency?)
- What effect does convolution with the echo impulse response d(t) have on the music? Can you relate this effect to the shape of d(t)? What physical mechanism might give rise to an effect like this in a concert hall?

4. Spectral analysis with the DFT and FFT

This laboratory provides an introduction to the discrete Fourier transform (DFT) and the fast Fourier transform (FFT), which are important tools that facilitated the explosion in digital signal processing (DSP) technology during the past 30 years.

The following material is distributed to students in a notebook. A file with sound samples recorded by the instructor is loaded with the Matlab commands

```
x=wavread('u:\private\elec320\lab7_1.wav');
sound(x)
X=fft(x);
```

The sampling rate for this signal is 8192 samples per second. The FFT magnitude is plotted with the Matlab commands

```
Fs=8192;
N=length(X);
f=(0:N-1)'/N*Fs;
plot(f,abs(X))
```

which produces the plot shown in Figure 3.

```
% Demonstration of music convolved with various impulse responses.

% Filter music with an impulse response (1st order)

fs = 8192;       % Sample rate
T = 1/fs;

fc = 300;        % Desired cutoff freq, in Hz
wc = 2*pi*fc;

% Make impulse response length equal to 5 time constants

t = 0:T:(5/wc);
g = wc*T*exp(-t*wc);

plot(t, g)
title('Impulse response g(t)');
xlabel('Time (sec.)');
ylabel('Amplitude');

f = wavread('u:\private\elec320\badboys.wav');  % Read digitized music file

fprintf('This is the original music . . . ');
sound(f)
fprintf('\nComputing -- please wait . . . ');
y = conv(f, g);
fprintf('\nThis is after convolution with g(t) . . . ');
pause(10);
sound(y);
```
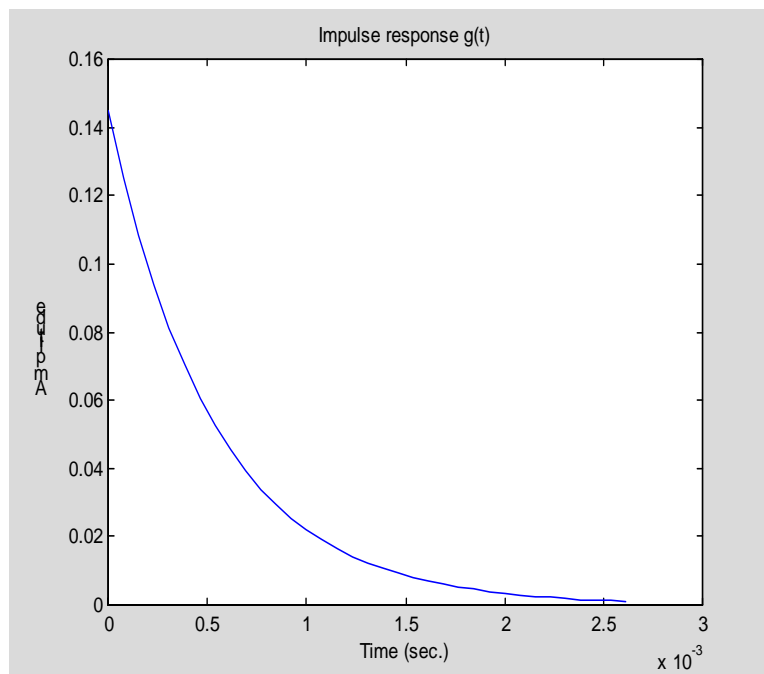

Figure 2: Matlab program and impulse response plot from convolution notebook.
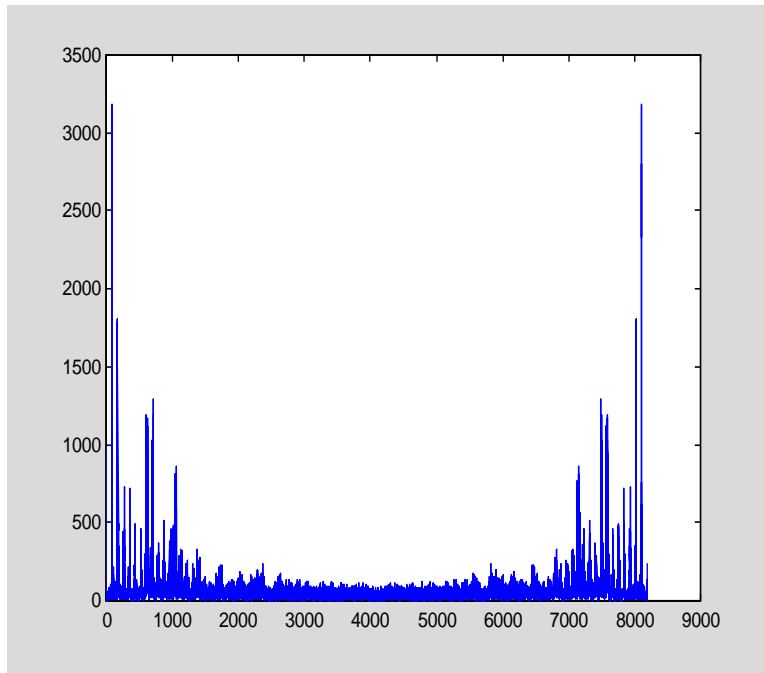
Figure 3: Plot of FFT magnitude.

Students are then asked to answer the following questions based on Figure 3 and the sound they hear when the samples are played through a speaker:

Which frequency (in hertz) appears to be dominant?
Do harmonics appear to be present? If so, at what frequencies?
Why is the spectrum symmetric? What is the folding frequency?
What is the resolution of the FFT (in hertz)?
Can you guess what produced this sound?

Students then perform spectral analysis exercises using the Matlab command `specgram` to study the time-varying frequency spectrum of a "chirp" signal.

5. Concluding remarks

We have described three signals and systems laboratories that use notebooks for a required third-year course in electrical engineering. In addition to all of the advantages of motivating the students and using widely-available software, the notebook encourages students to experiment and ask "what if" questions to gain a deeper understanding of the fundamental signal processing concepts.

Acknowledgments

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References

1. R. Shiavi," Teaching Signal Processing Using Notebooks," Session 1309, Proceedings of the 1999 ASEE Annual Conference and Exposition, Charlotte, North Carolina, June 20-23, 1999.

2. R. Shiavi, "Learning Signal Processing Using Interactive Notebooks," *IEEE Trans. On Education*, vol. 42, no. 4, p. 355, November 1999.

MAURICE F. ABURDENE
Maurice F. Aburdene is the T. Jefferson Miers Professor of Electrical Engineering and Professor of Computer Science at Bucknell University. He has also taught at Swarthmore College, State University of New York at Oswego, and the University of Connecticut. Professor Aburdene was a project engineer and project manager at the Bristol Company, a visiting research scientist at MIT's Laboratory for Information and Decision Systems, and held various summer fellowships with NASA and the Naval Research Laboratory.

RICHARD J. KOZICK
Richard J. Kozick is an Associate Professor in the Electrical Engineering Department at Bucknell University. He joined the faculty at Bucknell in 1993, and before that he was a Member of Technical Staff at AT&T Bell Laboratories for four years. He received the Ph.D. degree from the University of Pennsylvania, M.S. from Stanford University, and B.S. from Bucknell University. He is actively involved in several projects with the Army Research Laboratory in the areas of statistical signal processing and communications.

JASKEERAT S. BAWEJA
Jaskeerat S. Baweja is a graduate student in the Electrical Engineering Department at Bucknell University. Before that he worked in the Center for Development of Telematics for two years. He received his B.S. from Panjab University, India, and he is currently involved in signal processing research at Bucknell.