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Introducing Spectral Analysis to Undergraduate Engineering Students

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Introducing Spectral Analysis to Undergraduate Engineering Students

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ABSTRACT

Currently, engineering students are only exposed to the theory of Fourier analysis in one of their math classes. They are not taught the relation between this transform and the frequency spectrum of the time domain data, how to find and plot its spectrum, or how to filter the data to remove unwanted noise and disturbance. Since a significant range of engineering applications require analysis of the measured data in the frequency domain, students will need to fill this gap between theory and practice without proper guidance. While MATLAB makes implementing these processes simple, only electrical engineering students who have taken a Digital Signal Processing course can understand and implement these processes.

This paper presents a module for teaching spectral analysis to second-year engineering students using an engaging and hands-on approach without the intense level of math found in Digital Signal Processing (DSP) books. The module was applied in a core engineering course at Stevens Institute of Technology, which 400 students took from nine different engineering programs. The module consisted of three steps: research in which students were asked to report an application or process that uses spectral analysis. This started with a class discussion of the shared demo examples from each engineering discipline. In the second step, the students learned to use MATLAB to analyze music signals. The authors found music to be an invaluable illustrative tool for spectral analysis. It appeals to a wide range of students and is easy to generate. The analysis included understanding the concepts of the sampling frequency, single and multi-tone signals, and finding and plotting the frequency spectrum using the MATLAB FFT command. In the third step, students learned how to use MATLAB to design low pass, high pass, band pass, and band stop filters; then filtered the music signals to remove certain frequency bands. Finally, the students observed the effect of increasing the filter order on its performance.

1. INTRODUCTION

Spectral analysis involves decomposing a signal into its constituent frequencies using the Fourier series or transform. It is a powerful tool used in various engineering disciplines to analyze and interpret signals in the frequency domain and gain insights into dynamic systems' behavior from the frequency content of signals produced or transmitted by those systems [1-39]. It has even become indispensable with the rapid increase in Artificial Intelligence (AI) applications, where engineers need to design efficient data acquisition systems whose design needs insight into the frequency characteristics of the measured data. Furthermore, creating labeled data to train the

AI algorithms often requires information about the frequency characteristics of these data. These concepts are usually learned in the DSP course offered in the Electrical and Computer Engineering curriculum. That course usually involves complex mathematical concepts, which can be challenging for students from other engineering disciplines. Also, those students are not motivated to enroll in a DSP course as they struggle to see the practical applications of spectral analysis in real-world engineering problems.

This paper presents a learning module to fill these gaps. It can be added to any of the engineering core, engineering design, or frontiers of technology courses present in most engineering programs. The module needs two lectures if the students have some knowledge about filtering and sampling continuous data. If they don't, then one lecture about these concepts is necessary. In addition to this section, the paper consists of five sections: Section 2 presents an overview of the current design IV course and its contents, section three introduces the spectral analysis module, section 4 shades light on the tool used to assess the students' learning of the new material and section five wrap the paper with the most important conclusions.

2. DESIGN IV COURSE OVERVIEW

This is the fourth course in the engineering design sequence that all engineering students at the School of Engineering and Science (SES) take. The course introduces instrumentation systems. It provides students with the ability to design basic amplifier and filter circuits (using op-amps), reviews the sampling theorem and the role of the antialiasing filters, and examines the roles and functions of analog-to-digital ADC and digital-to-analog DAC converters. These topics have broad applicability in many engineering disciplines. The Fourier series and Fourier transform are briefly touched on to explain the filter's operation and the amplifier's phase and amplitude distortions. The course is structured as one 110-minute lecture and one 170-minute lab. Table 1 lists the topics covered in the lecture part of the course and the lab experiments before spring 2022.

Table 1: Course topics and lab experiments before spring 22.

Lecture part topics	Lab experiments
• Basic components of data acquisition systems • Passive filters • Op-Amp Amplifiers. • Active filters. • Sampling theorem. • Analog to Digital converters. • Digital to Analog converters.	• Introduction to MATLAB. • Introduction to Simulink. • Introduction to Simscape. • Passive Filters. • EKG Experiment & Notch Filter. • Op-Amp . • Analog to Digital converters.

Engineering students typically learn the Fourier series and Fourier transform in their first- or second-year math courses. These courses usually have high enrolments of engineering and science students in high-capacity classrooms, and there is less focus on the application side of math. When using the Fourier series to explain the effect of filtering in the frequency domain or when explaining the causes of frequency and phase distortions, I have noticed that the students lack the understanding of what are the results of the Fourier analysis and how to relate those results to the amplitudes and frequencies of the harmonics constituting the time-domain signal analyzed by the Fourier series/transform. As such, I have spent time explaining these concepts, and by now, the students understand the term "frequency spectrum" or "spectrum." However, the students still do not know how to practically generate the frequency spectrum of real data or use the straightforward spectral analysis tools in MATLAB.

3. THE SPECTRAL ANALYSIS MODULE

This module is added after the ADC lecture. The discussion starts by explaining the relevance of spectral analysis in real-world engineering applications. Examples from different engineering fields, such as telecommunications, signal processing, audio processing, nondestructive testing, medical imaging, and vibration analysis, were shared with the students. The module consists of two parts, each of which takes one lecture.

Lecture one: The fast Fourier transform FFT.

This lecture starts by asking the following question:

"The data or the waveform is now discretized and acquired by the computer or microcontroller. How does one find the spectrum of this discrete data?"

Figure 1 illustrates that $x(t)$ is the discrete-time date with a time domain spacing of $T=1/F_S$, where F_S is the sampling frequency in hertz, Hz. Part b of Figure 1 shows the amplitude spectrum $|X(f)|$ of $x(t)$, which can be obtained using the following MATLAB command:

$$\mathrm{abs}(\mathrm{fft}(x))$$

The result is a vector of discrete samples in the frequency domain with a frequency spacing $\Delta F=F_S/N$, where N is the number of time domain samples. The use of the MATLAB command

$$\mathrm{angle}(\mathrm{fft}(x))$$

is also discussed, as the students have already been introduced to the concept of phase when talking about phase distortions of amplifiers. Then, the plotting of the amplitude spectrum is explained using the following two steps:

1- Generate the frequency domain vector, x-axis, with N samples from $f=0$ to $f=F_S-1$ using the MATLAB command $\mathrm{f}=\mathrm{linspace}(0, F_S-1, N)$

2- Then the spectrum is generated using the following command: plot (f, y). where y is the amplitude spectrum obtained from y= abs(fft(x))

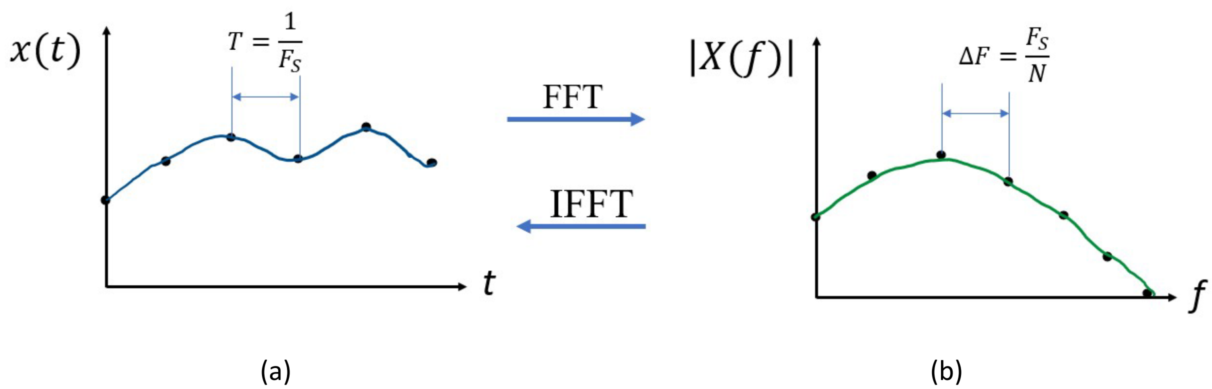

Figure 1 Amplitude spectrum of discrete-time data, a-time domain signal and b- Amplitude spectrum of $x(t)$.

Example

The MATLAB code shown in Figure 2 was shared with the students.

The students were requested to download audio signals from the following free access website: (https://www.mediacollege.com/downloads/), and then they used the code of Fig.2 to playback and draw the spectra of these signals. They started with single-tone signals and then downloaded multitone music clips. Figures 3 and 4 show the spectra of a single-tone 440 Hz audio signal and a multitone music clip. The students were encouraged to download more audio clips and apply different zooming in the frequency domain to observe where the most energy of the signal is concentrated. The students could even observe the spectra of audio clips of different musical instruments they created using apps like "Garageband," available for PCs and iPhones.

```
clear
clf
[y,Fs] = audioread('sound4.wav');
% 440Hz_44100Hz_16bit_05sec
% Fs is 44100
sound(y,Fs);
amplitude_spectrum=abs(fft(y));
% Linearly spaced vector
f=linspace(0,44100,length(y));
figure (1)
plot(f(1:20000),amplitude_spectrum(1:20000),'linewidth',2);
xlabel('Frequency [Hz]','fontsize',14,'fontweight','bold');
ylabel('Amplitude [a.u.]','fontsize',14,'fontweight','bold');
```

Figure 2 MATLAB code to playback an audio signal, determine and plot its amplitude spectrum.

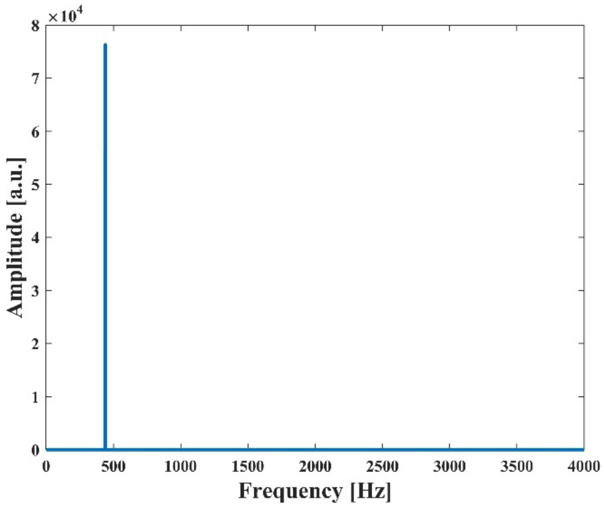

Figure 3 Amplitude spectrum of 440 Hz audio signal.

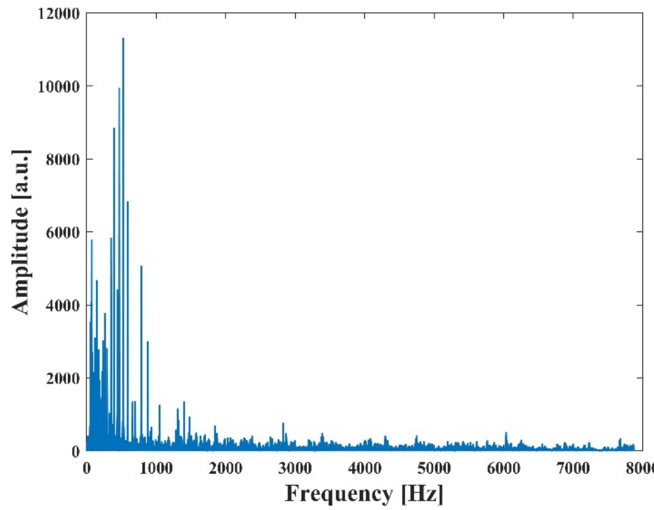

Figure 4 Amplitude spectrum of music audio clip.

Lecture two: Digital filter design using MATLAB.

MATLAB has many spectral analysis tools, and the digital filter design tool is the most basic and most used one; in this module, the students were introduced to the digital filter design commands in MATLAB. They had already been introduced to analog filter characteristics and design before, so they started with this module with a knowledge of terms like cutoff frequency, passband, stopband, frequency, and phase distortions. Also, they are familiar with differences among the different filter approximations. Table 2 summarizes the main filter design commands discussed in this module.

Table 2 Digital filter design commands in MATLAB

[B,A] = butter(N,Wn,'low'));   [B,A] = butter(N,Wn,'high');   [B,A] = butter(N,Wn,'stop')   [B,A] = butter(N,Wn,'band') Wn=   Fc/(Fs/2)   Wn: Normalized cutoff frequency.   N: is the order of the filter.   Note: for bandpass and stopband Wn is a two-element vector, Wn = [W1 W2]
[B,A] = cheby1(n,Rp,fc/(fs/2));   [B,A] = cheby2(n,As,fc/(fs/2));
x_filtered = filter(B,A,x); x: is the raw time domain data to be   filtered by the digital filter.

Fig. 5 shows a MATLAB code shared with the students to implement a Butterworth high pass filter (HPF) to filter the three tones audio signal whose amplitude spectrum is shown in Fig 6. The students were asked to determine the required cutoff frequency and filter order to remove the lowest frequency component, Fig. 7 shows the amplitude spectrum of the filtered signal. Next, the students were asked to implement a low pass filter (LPF) to remove the two higher frequencies, a band pass filter (BPF) to remove the lower and upper frequencies, and a band stop filter to remove the middle frequency. The students observed the effects of different cutoff frequencies and filter orders on the filtered signals. Furthermore, they observed how flexible the digital filter design is compared to the analog one. The students were encouraged to ask questions and provide suggestions; this fostered a deeper understanding and engagement with the material.

```
[y,Fs] =audioread('sound5.wav');
x=y(:,1); sound(x,44100);
amplitude_spectrum=abs(fft(x));
f=linspace(0,44100,length(x));
figure (1)
plot(f(1:10000),amplitude_spectrum(1:10000),'linewidth',1)
xlabel('Frequency [Hz]','fontsize',10,'fontweight','bold');
ylabel('Amplitude [a.u.]','fontsize',10,'fontweight','bold');
% wn=286/22050=0.013
[b,a]=butter(4,0.013,"high");
x_filtered=filter(b,a,x);
amplitude_spectrum_filterd=abs(fft(x_filtered));
figure(2)
plot(f(1:10000),amplitude_spectrum_filterd(1:10000),'linewidth'
,1)
xlabel('Frequency [Hz]','fontsize',10,'fontweight','bold');
ylabel('Amplitude [a.u.]','fontsize',10,'fontweight','bold');
```

Figure 5 MATLAB code to filter a multitone audio signal using MATLAB digital filter.

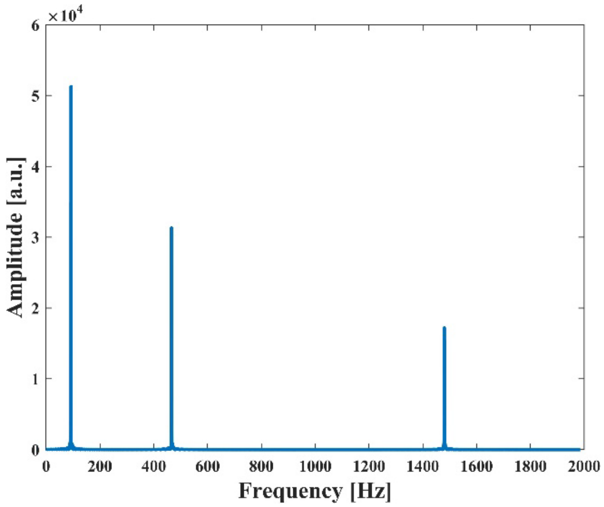

Figure 6 Amplitude spectrum of three-tone audio signal.

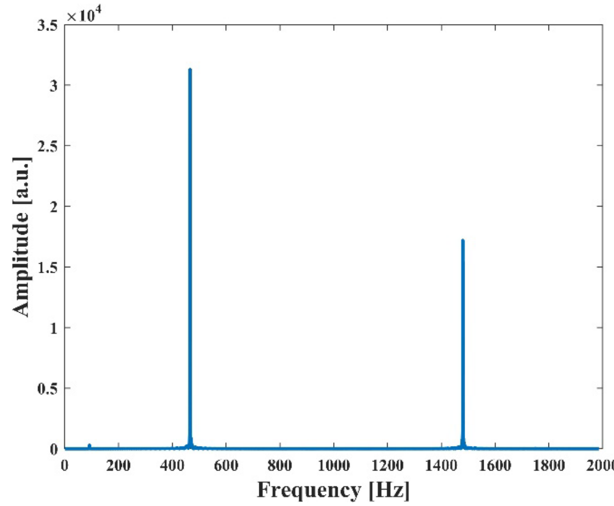

Figure 7 Amplitude spectrum of the audio signal filtered by the HPF.

At the end of this module, the students were encouraged to explore the capabilities of MATLAB further to process signals. Furthermore, this audiobook [40], which is available online, was shared with the students to continue exploring the use of MATLAB for processing audio signals in a simple way.

4. ASSESSMENT

Assessment of the module's effectiveness was based on feedback collection. The feedback form contained the following two statements where the students rated their experience on a scale of 1- strongly disagree to 5- strongly agree.

1- Digital Signal Processing (DSP) is relevant to my engineering domain.
2- I know some applications of Fourier analysis in engineering.

The number of surveyed students was 25. Table 3 shows the academic demography of the students who participated in the survey.

Tables 4 and 5 present the students' responses to these statements before and after taking the module. The sum of the percentages of students who agreed and strongly agreed to both statements has increased after learning the new material, with a noticeable increase of 47% in the positive responses to the second statement.

Table 3 Academic demography of students. Table 4 Percentage of student responses before learning the module.

Question	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Digital Signal Processing (DSP) is relevant to my engineering domain.	4%	28%	44%	20%	4%
I know some applications of Fourier analysis in engineering.	12%	48%	28%	12%	0%

Table 5 Percentage of student responses after learning the module.

Question	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Digital Signal Processing (DSP) is relevant to my engineering domain.	0%	23%	41%	18%	18%
I know some applications of Fourier analysis in engineering.	0%	5%	36%	41%	18%

5. CONCLUSIONS

This paper describes a hands-on approach to teaching spectral analysis to second-year engineering students without going through the usual complex math associated with the topic. The learning module focuses on the engineering applications of spectral analysis and how to perform the analysis using MATLAB tools. The students understood the concept of the frequency domain and how signals can be analyzed in terms of their frequency components. Furthermore, the percentage increase in students' responses after taking the module shows that it helps foster interdisciplinary connections within the engineering field, making it an excellent candidate for core engineering courses.

In future delivery of this module and to better motivate the students for the topic, they will be asked to write a literature review assignment on a specific application of spectral analysis in the student's chosen engineering discipline. The assignment should be submitted before the start of the module.

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