Signals and Systems: Theory and Practice

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Abstract

Many topics in any of the engineering curricula can be taught effectively if the teaching accompanies some form of hands-on experiments. The curriculum in Electrical Engineering is no exception. However, design and management of the hands-on projects which can be done with small and large size classes and limited human and technical resources become a major challenge for faculty. Here, the challenges and experience of incorporating hands-on experiments and visual aids in assisting teaching two courses and Signals and Systems and the Communication System courses are discussed. The experience includes teaching these courses at the Electrical Engineering Department, Idaho State University. In an effort to enhance the student experience and to make the connection between the mathematics and applications more transparent, a hardware-based laboratory could be integrated into the course. The main proponents of this approach propose the idea of having low-cost equipment for student experiments.

In this paper, we will discuss how the Digilent Electronics Explorer Board (EE Board) can be specifically used for the Signal and Systems course as well as the Communications Systems. We will also discuss students' responses and experiences in working with the EE Board. The authors hope this paper will provide assistance to other faculty in this area in implementing similar approaches for bringing hands-on experiments to some of these traditionally dry and theoretical courses.

Introduction

Signals and Systems course is the first course in the engineering curricula that introduces a concept of signal in time space and frequency space. In this course, they learn how to use Fourier series and Fourier transform to expresses a mathematical function of time as a function of frequency, known as frequency spectrum. I believe that many students find that this is a difficult time to understand the concept of signal represented in in frequency domain because what they have learnt so far in circuit and electronics are all in time domain, such as start time, stop time, and time delay. Many students get lost after the frequency spectrum is introduced. Some of them may be able to solve problems correctly by using Fourier transform properties, but they cannot give a clear answer when asked to explain or analyze signals and systems in frequency domain. Furthermore, what they learn thorough the course is only in mathematical functions with the deterministic signals such as unit impulse, unit step function, unit rectangular function, unit triangular function, etc. We all know that all of those basic functions have certain Fourier transform pairs. Thus, all of the homework and quizzes in this course are limited to those functions.

In our opinion, Signals and Systems course is a very important course because it is a prerequisite course for many junior-level and senior-level courses such as Control Systems, Communication Systems, Digital Signal Processing, etc. If the students do not have a strong background on the Fourier transform, they will struggle on the other transformations, i.e., Laplace transform, Z-transform, Discrete Wavelet transform, etc. We think that not only Signals and Systems course, but also many subjects in any of the engineering curricula can be taught more efficiently if the teaching accompanies some form of hands-on experiments. However, design and management of the hands-on projects which can be done with small and large size classes, and limited human and technical resources become a major challenge for faculty.

Similar to most of universities, ISU doesn't offer Signals and Systems Laboratory course which complements Signal and Systems course by providing EE students with exposure to the practical aspects of the design, implementation, and assessment of linear time-invariant (LTI) systems. In an effort to enhance the student experience and to make the connection between the mathematics and applications more transparent, a hardware-based laboratory could be integrated into the course. The main proponents of this approach propose the idea of having low-cost equipment for student experiments. In support of this, we surveyed many electronics websites and found a potential solution from Digilent. The Digilent EE Board [1] includes most of the test and measurement equipment required to design and test analog and digital circuits of many types. The EE Board comes with a large solderless breadboard and a software called WaveForms that includes various functions such as oscilloscopes, waveform generators, voltmeters, reference voltage generators, and thirty-two digital signal generators. With the EE Board, students can get a hands-on experience and also develop their system design skill by building circuits on the solderless board using simple jumper wires. The WaveForms software can be run on any PC that has USB ports, including low-cost Netbooks. A high-speed USB 2.0 connection is used to connect the solderless board to the personal computer (PC), ensuring that all EE Board instruments respond in real-time. The data files generated by WaveForms are stored using standard formats, making it easy to share data between instruments and to export data to spreadsheet for further analysis and report.

Students can receive many benefits from having EE Boards in the classes. They are expected to become very good at engineering sketching, report writing, problem solving, and critical thinking during the courses. With the academic support from Digilent, the cost of an EE board is close to a price of a textbook. With the versatility of the EE board, students can also use it for other engineering classes to broaden their understanding.

Mathematical Concepts in Signal Processing

Signals and systems courses as well as those dealing with digital signal processing (DSP) are considered by students to be fairly mathematically oriented subject matters. One example of DSP analysis and design work by students involves working with various types of digital filters. Here we present one example of digital filters namely finite impulse response (FIR) digital filters. Here students are required to study, as example, windowing method of FIR filter design. In designing FIR filters one approach is to use truncation (windowing) and finite delay of the ideal (desired) impulse response function. For the ideal digital low-pass filter given as

$$H_d(\omega) = 1 \text{ for } -\omega_c \leq \omega \leq \omega_c,$$

the desired impulse response is obtained as:

$$h_d(n) = \left(\frac{\omega_c}{\pi}\right) \mathrm{Sa}(\omega_c n) \text{ for } -\infty < n < \infty$$

where sampling function is defined as:

$$\mathrm{Sa}(x) = \frac{\sin x}{x}.$$

Obviously, this filter has ∞ duration (it is also non-causal). The solution will be to use windowing and finite delay. We will illustrate this design method by designing a digital FIR differentiator (not an easy analog design using IIR, infinite impulse response, technology).
For ideal digital differentiator, the desired impulse response (IR) is given by inverse discrete-time Fourier transform as

$$h_d(n) = \frac{\cos(\pi n)}{n} \text{ for } -\infty < n < \infty \text{ with } h_d(0) = 0.$$

We use MATLAB simulation below to show a couple of typical designs using Hamming and Kaiser windows. For Kaiser window with shape parameter $\beta = 5$, we use the paper by Blachman and Mousavinezhad [2] to evaluate the zero-th order modified Bessel function of the first kind:

$$I_0(x) \approx \frac{1}{6} + \frac{1}{3}\cosh\left(\frac{x}{2}\right) + \frac{1}{3}\cosh\left(\frac{\sqrt{3}x}{2}\right) + \frac{1}{6}\cosh(x)$$

Hamming window function:

$$w(n) = 0.5 + 0.5\cos\left(\frac{\pi n}{100}\right)$$
$$H(\omega) = -2j\sum_{n} h_d(n)\cdot w(n)\cdot \sin(n\omega)$$

Kaiser window function with shape parameter $\beta = 5$:

$$w_k(n) = \frac{I_0\left(\beta\cdot\sqrt{1-\frac{n^2}{10000}}\right)}{I_0(\beta)}$$
$$H_k(\omega) = -2j\sum_{n} h_d(n)\cdot w_k(n)\cdot \sin(n\omega)$$

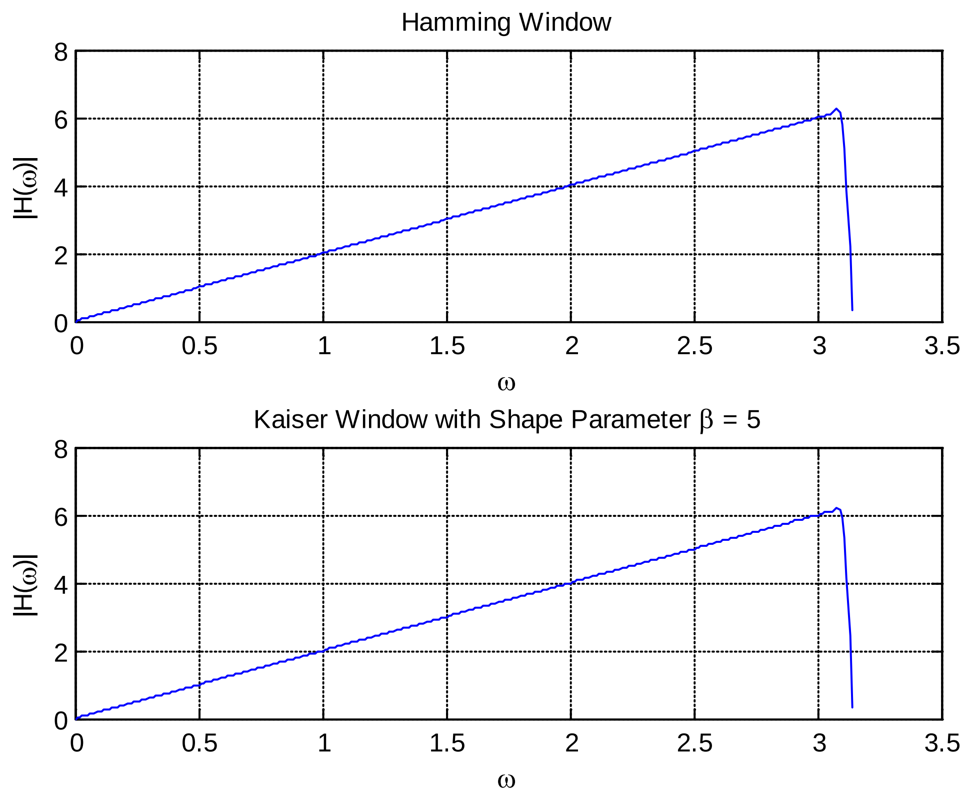

Figure 1: Frequency response of Hamming window function and Keiser window function.

The Role of EE Board in Electrical Engineering Courses

Many universities offer Communication Laboratory course, which allows students to get some experiences on both analog and digital components in the communication systems (signal generators, analog and digital filters, oscilloscopes, and spectrum analyzers). Basic analog and digital communications and theory of operation are usually covered. However, the lab course is generally a 1-credit hour course. Students have only few hours a week to experiment with the equipment.

In contrast, the EE Board is designed for daily use. It helps student to reinforce the concepts discussed in class with a hands-on approach and allows the students to gain significant experience with electrical instruments such as function generators, digital multimeters, oscilloscopes, logic analyzers and power supplies. Because the EE Board combines everything needed to design and test circuits in a single all-in-one device, it allows the students to master the use of electronic instruments and construct several circuits. With the academic/student price, the low-cost EE Board is intended for every student to own. No more once a week labs; now students can complete their designs anytime anywhere.

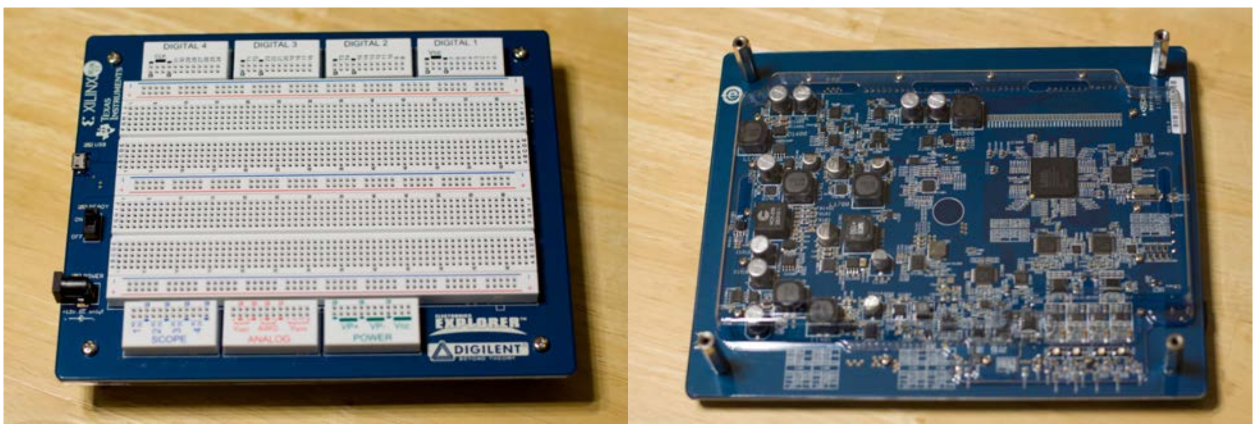

Figure 2: The EE Board: Front and Back.

As can be seen in Fig. 2, the EE Board has a large solderless breadboard on the top side. The solderless breadboard helps students to develop their system design skill with endless possibilities by building analog or digital circuits using simple jumper wires. On another side, the EE Board contains Spartan-3E [3] field programmable gate array (FPGA) circuit. Utilizing FPGA for high-performance computation has ensured to achieve high precision on measurements with almost zero delay.

The EE Board comes with software called WaveForms. The software offers six instruments which covers both analog and digital signals. All six instruments are as follows:

Analog Instruments

- 4-channel Oscilloscope
- 2-channel Waveform Generator
- Triple-Output Power Supplies and 4-channel Voltmeters

Digital Instruments

- 32-channel Logic Analyzer
- 32-channel Digital Signal Generator
- Static Digital Input/Output (SDIO)

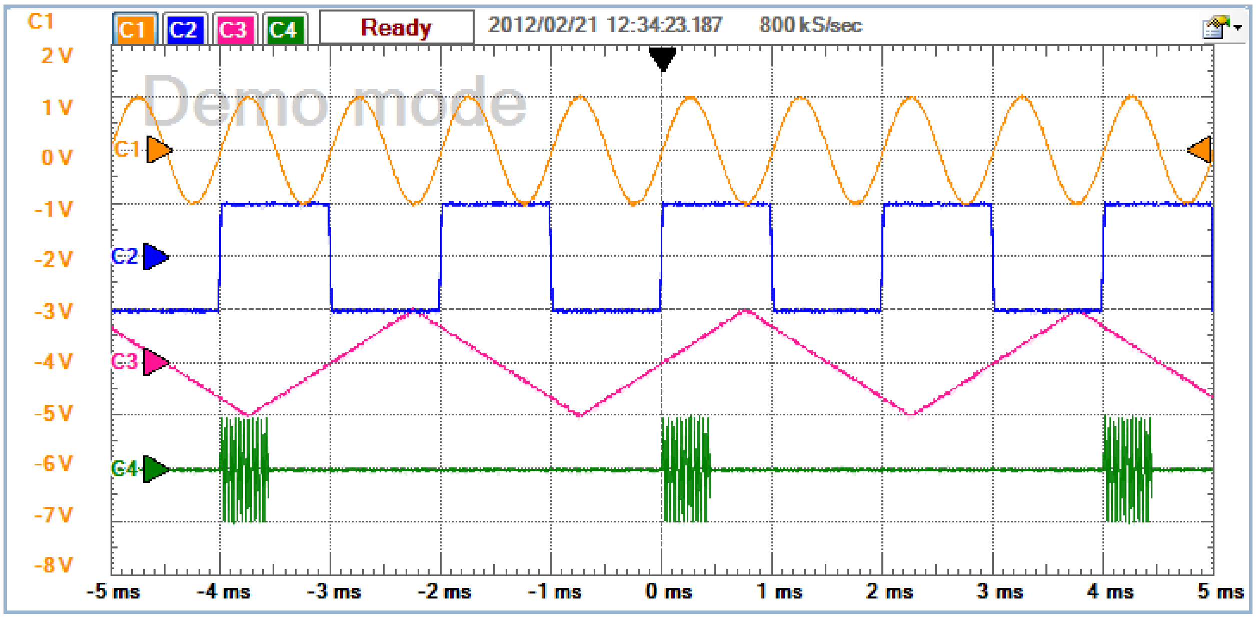

Figure 3: Oscilloscope in WaveForms Software.

As mentioned earlier, the WaveForms software can be run on any PC that has USB ports. With the advantage of using high-speed USB 2.0 connection, the solderless board and the PC can exchange information with data transfer rate up to 480 kbps. Fig. 3 illustrates the analog oscilloscope displaying four signals from four different channels simultaneously. Besides, these signals can be easily changed from time-domain signal to frequency-domain signal by turning the spectrum feature on, as shown in Fig. 4. Unlike the static graph that student learns from the textbook, the frequency spectrum in practice keeps changing in time due to the random noise. Bode transfer function is another very useful feature for the engineering courses which require students to design and analyze filters. They can play with the selection of RC to control the time constant of an RC circuit that affects rise time and fall time.

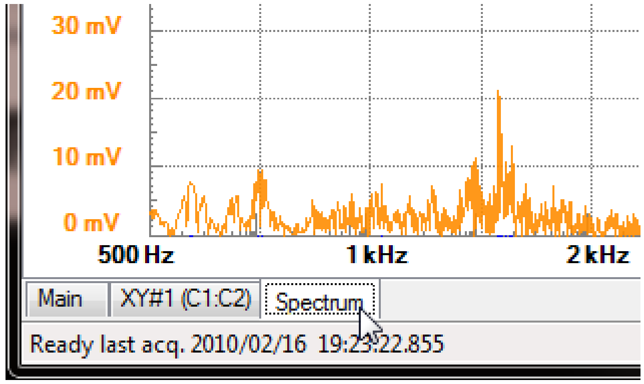

Figure 4: Frequency Spectrum.

Once students finish their works, they can easily capture all the graphs because the WaveForms software runs on the PC. Windows 7 provides snipping tool that can capture any part of the screen. Moreover, the WaveForms generates the measurement data files using standard formats, making it easy to share data between instruments and to export data to spreadsheet for further analysis and report.

Furthermore, Digilent offers a comprehensive set of educational materials designed for use in introductory analog electrical classes. The materials include video lectures, lecture notes, and assignments. The materials cover theoretical concepts as well as practical applications. These will help student to speed up their learning curve when they first get a hand-on.

Students' Response

The students' response to the approach of introducing the EE board to the lecture courses is very impressive. Naturally, students are enthusiastic to learn from equipment or some things which can response to them. The EE Board transforms the classes into an interactive and engaging learning environment. They can quickly see the response of their circuits when they make an adjustment. The output can be the graph displayed on the PC or can be some forms of circuit outputs such as light from a LED or sound from a small speaker. According to discussion with students, they said the EE Board helps them to get a better understanding about the class materials because they can perceive from what they see, unlike the abstract mathematic concepts. We found that the EE Board could response to student needs in order to enlighten them about the theoretical concepts.

Conclusion

The EE Board is designed to be the experimental companion to many of Electrical Engineering courses, including Signals and Systems and Communication Systems courses. It is intended to enhance the students' understanding of important analytical principles developed in the lecture courses by engaging them in the real-world application of these principles. Furthermore, it helps students to further develop the students' laboratory practice for experimentally testing and evaluating Electrical Engineering courses. This low-cost EE Board or similar device is modern equipment comparable to that which is used in industry. Due to the computation power of today PCs, they are powerful enough to generate complex signal waveforms with high frequency. They are also being increasingly used to acquire experimental data, to control other instruments or systems based on the data acquired, and to visualize experimental data. For most of these functions, the PC can deal with real-time or virtually real-time applications. In the long run, we are positive that this type of instruments will definitely benefit engineering students in preparing for life after graduation.

References

[1] Digilent Electronics Explorer Board. [Online] http://www.digilentinc.com.

[2] Nelson M. Blachman and S. Hossein Mousavinezhad, "Trigonometric approximations for Bessel functions," *IEEE Transactions on Aerospace and Electronics Systems*, vol. AES-22, no. 1, January 1986.

[3] Xilinx Spartan-3E. [Online] http://www.xilinx.com/support/documentation/data_sheets/ds312.pdf.