

ECE Teaching and Learning: Challenges in Teaching Digital Signal Processing

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ABSTRACT. Teaching of some Electrical/Computer Engineering courses, as well as those in closely related fields which have high mathematical content, has always been a challenge for engineering educators. With the help of information technology and availability of software packages such as Matlab, Mathcad and WFilter, we discuss our experience in teaching of Digital Signal Processing (DSP) with the use of modern software tools. It is concluded that to help student learning and understanding of important concepts and principles, these modern computer tools should be carefully used at the right time, right place.

I. INTRODUCTION. Teaching and learning of engineering topics, especially in engineering science courses which include a considerable amount of mathematical detail, has been a difficult job for educators as well as students taking these classes. ECE Courses that have significant theoretical and mathematical content, such as electromagnetics, signals & systems, and digital signal processing, are considered by students to be difficult and abstract. Software packages can provide examples and demonstrations to help students understand this challenging content. Several textbooks (e.g., [1], [2], [3]) incorporate modern software tools such as Matlab, Mathcad and WFilter (WFilter is a filter design tool included with textbook in Reference [3]). These texts are used in junior/senior level courses as well as first year graduate courses. Examples using simulations can aid student visualization of the abstract concepts, but they also need to have an understanding of underlying mathematical concepts. Of course most students start using some of these tools in their earlier introductory courses and can apply them for solving more advanced problems encountered in upper-division classes. Instructors must be careful in using these tools when discussing the basic concepts. They should encourage students to try learning the main idea and “logic” behind the concepts before doing the number crunching and simulating the results with available software.

As an important topic we use analysis and design of electronic **filters** and illustrate the use of simulation tools in solving resulting problems in time or frequency domains. Use of filters can be interesting because many students are familiar with wireless (“smart”) cellular phones. The block diagram ([4]) in Figure 1 shows this kind of telecommunication system using many different types of filters as main components. In most Electrical/Computer Engineering curricula there are courses covering many topics of the sub-systems that are included in this wireless system including: Electrical/Electronic Circuits, Electromagnetics, Digital Signal Processing and Communication Systems. The course Signals & Systems (or Network Analysis) which usually follows the second circuits course in the junior year covers many mathematical transforms that are used in senior and advanced level courses including controls, **digital signal processing** and communication systems.

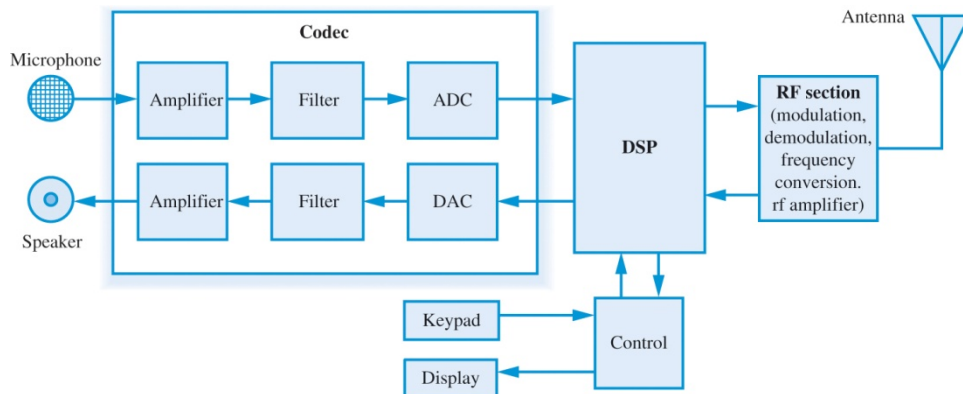


Figure 1. Cellular phone block diagram.

When dealing with signals as input (excitation) through a given system this notation is useful: $x \rightarrow y$, where y is the output (response) to the given excitation or input x . Mathematically the input/output (I/O) relation of the system depends on the nature of signals and the system we are dealing with. For continuous-time problems the relationship between input and output is a differential equation which is familiar to all junior-level engineering students. For continuous-time systems the notations used are $x(t)$, $y(t)$ as well as $h(t)$ representing the system impulse response. Of

course it is then mentioned that by digitizing the signals (the Sampling Theorem) we can study discrete-time systems resulting in I/O difference equations and signals $x[n]$, $y[n]$ and $h[n]$. It is important for students to understand that many signals in practice (e.g., speech) are continuous-time (analog) in nature and digitizing a physical signal will result in some amount of error (e.g., quantization, round-off). Another concept that will confuse students is transforming back and forth between different domains: time & frequency. As the smartphone block diagram shows, for wireless communications one needs to employ antennas as part of the over-all communication system. Antenna dimension is proportional to wavelength which in turn is proportional to inverse of the frequency of operation. Therefore we need to go from one domain (time) to another domain (frequency.) Also concepts such as spectrum, bandwidth, and power/energy spectral densities require the representation in the frequency domain. This leads to the coverage of many topics involving several forms of transforms (e.g., Fourier, Laplace, and z) in the DSP course as well as filter design methods.

Another way of distinguishing between different domains is to point out to students that both differential equations (necessary to model most physical systems) as well as difference equations are tools in the time domain. Another important tool in this domain is the **convolution** which is another topic that can be confusing to many students. When working in the frequency domain the concept of transfer (system) function (or gain) becomes important in both analysis and design of many systems. The transfer function being a function of frequency in general is a complex function requiring separate plots for magnitude and phase response.

In Section II we will discuss a few typical examples (included in the Appendix) using available software packages. More results will be presented during the Annual Conference as well as assessment of Student Outcomes (a, c, e, k) covered in the DSP course and offered during Spring 2017 semester. Finally, in Section III, we present further discussions, conclusions and future work.

II. USE of EXAMPLES, SIMULATION RESULTS. We show three examples in the Appendix, most students taking upper-division classes are familiar with differential equations and how to formulate the solutions in analytical (closed) forms. Some students may also be familiar with tools such as Mathematica or Maple. In lectures we discuss the tools of Matlab & Mathcad that can be very useful for student understanding and learning once some theoretical background is presented in the class. Most available textbooks choose to use Matlab, but Mathcad can also be very useful because of its natural and symbolic way of representing signals. WFilter ([3]) is another software tool for analysis/design of analog as well as digital filters. Another factor to consider is the cost of licensing and maintenance of these software packages. In our schools most of the tools are available in computer laboratories for student use. For some tools (e.g., Matlab) the student version is also available. Furthermore the tools can be optional especially for lecture courses where the emphasis might be on understanding and learning of basic concepts first. For details of these examples, see the Appendix.

Our digital signal processing course originally had a hardware/software-based laboratory co-requisite (with digital control) but the laboratory section was phased out recently. In Spring 2016 semester the laboratory section was conducted as a software-based section where students did simulations using mainly Matlab and Mathcad. The Spring 2017 semester is the first semester where program requires a 3-hours DSP lecture-only course. We are including as part of the course a DSP project where students are asked to work on a project, submit a “presentation” of the project and write a final report. The enrollment in the course was 31 in Spring 2016, in 2017 enrollment is 44 which will make it difficult to make in-class presentations but they are asked to submit the presentation in PowerPoint or PDF slides. There were five software exercises in 2016 as part of the software laboratory section. These “experiments” included:

- Active Filter circuit
- Input/Output Fourier Transforms, Energy Spectral Densities
- Higher-Order Filter Differential Equation Model and Simulation
- Filter Approximations (e.g., Butterworth, Chebyshev) IIR Design Problem
- FIR Digital Filter Design

These exercises were helpful when covering seemingly abstract concepts as part of the lecture. It is noted that examination questions were paper, pencil type computation/design problems using a formula page and an

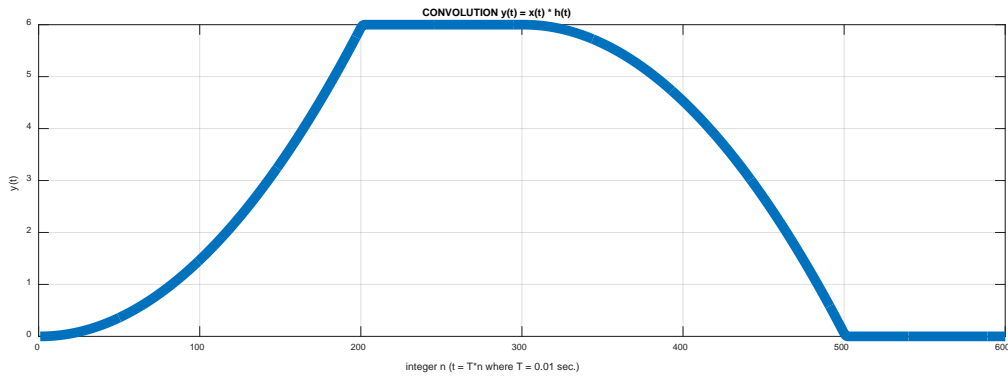
engineering calculator. Students did very well in the laboratory exercises and the report for each exercise included discussion of the use of the software tools in helping them understand their results. We have seen increased enrollment in the course, results of DSP project component introduced this year will be discussed during the Conference.

III. DISCUSSION, CONCLUSIONS. The use of modern tools in engineering topics courses (example in this paper was digital signal processing) can aid student understanding of difficult concepts. The tools also allow them to simulate their results when analyzing or designing systems in upper division classes. In Appendix we are presenting a few examples of the use of software packages in electrical/computer engineering DSP course which are also applicable to other engineering disciplines. Students should be encouraged to learn theory and basic concepts of the subject under study first and use these tools to verify their findings. In class we discuss the importance of using these tools in addition to being able to predict the expected results using “back of envelope” simple calculations (possibly using calculators too) before simulations of more complex and higher order problems using the software packages. Authors have used the software tools in their courses including digital signal processing, advanced circuits, electromagnetics and sensors. Matlab in Signals & Systems is widely used (for example see references [5] and [6].) Professor Fred W. DePiero of Cal Poly Electrical Engineering, [7], includes “Notes on Signals and Systems” where he presents IT tools examples and has a discussion of pedagogy. Our DSP senior-level course has four (4) student outcomes: (a). an ability to apply knowledge of mathematics, science, and engineering; (c). an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability; (e). an ability to identify, formulate, and solve engineering problems; and (k). an ability to use techniques, skills, and modern engineering tools necessary for engineering practice. A recommended companion text for the course includes Matlab-based problem solving approach [8]. The authors of the text use innovative approach of blending computer-based analysis/design with traditional teaching and include advanced DSP topics such as optimal and adaptive filters. Our experience has shown that the careful use of software packages and available tools can enhance student learning of engineering topics with high mathematical contents and successful achievement of these student outcomes. Students are interested in choosing this mathematically-oriented subject using IT tools as can be seen from increased course enrollment. More examples and discussion of student outcomes assessment will be presented at the Conference.

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Example 2. Difference Equation. For discrete-time analysis and design of systems, students work with difference equations. Solutions can be obtained in the time domain or in the frequency domain. Consider a discrete-time system (e.g., a digital filter) described by the following linear constant-coefficient difference equation:

$y[n] + y[n - 1] + 0.5y[n - 2] = x[n]$. We want to find the total response to the given input $x[n] = 2 \cos(n\pi/2) u[n]$, $y[-1] = 0, y[-2]=0$.

Working in the time domain the solution is obtained by finding roots of the characteristic equation (complex in this case), evaluating the forced response and then applying initial conditions:

$$y[n] = 0.8 \cos(n\pi/2) - 1.6 \sin(n\pi/2) + (0.707)^n [1.2 \cos(3n\pi/4) + 0.4 \sin(3n\pi/4)] ; n \geq 0.$$

The total response includes transient response as well as steady-state response. The solution can also be found in the frequency domain using z-transform then applying inverse transform. Here we show the response plot (Figure 3) as obtained in MATHCAD:

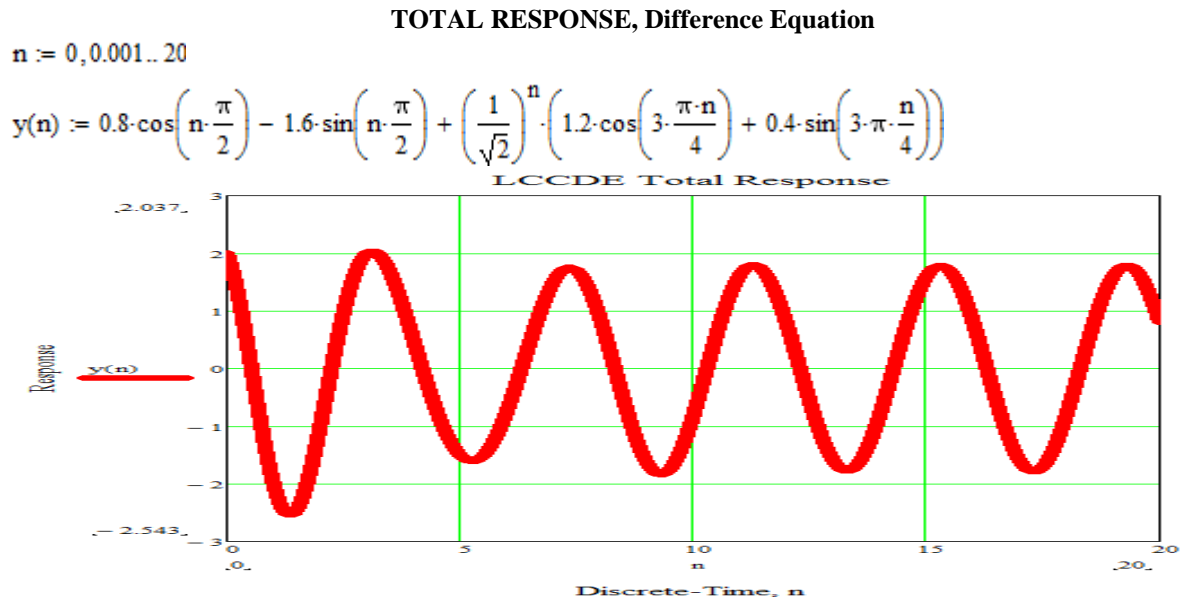


Figure 3. Total Response of difference equation using Mathcad.

Example 3. Filter Design. Filters related courses are ideal places for using the modern tools in analysis and design. The tool WFilter [3] is very useful for design of analog and digital filters. Several textbooks are available with examples of filter design using mainly MATLAB and associated toolboxes. Authors have used these tools in upper-division classes showing examples and demonstrations. Students also use them for homework, projects and presentations.

The following is an example of a student designing an analog bandpass filter. When discussing IIR digital filters the starting point is to first design an analog prototype then use transformation (e.g., bilinear) to design the digital filter equivalent.

The following specifications are provided for the design problem using Butterworth filter approximation:

Passband 3-dB cutoff frequencies: $1 \text{ kHz} \leq f \leq 2 \text{ kHz}$

Stopbands: $0 \leq f \leq 800 \text{ Hz}$ & $f \geq 2.5 \text{ kHz}$

Minimum stopband attenuation of 30 dB.

Calculations show that a minimum order of 7 will be needed for the normalized low-pass filter prototype. This filter is then transformed by using frequency transformation to find the transfer function of the bandpass filter.

$$H_{\text{LPF}}(S) = 1/[(S + 1)(S^2 + 2 \zeta_1 S + 1)(S^2 + 2 \zeta_2 S + 1)(S^2 + 2 \zeta_3 S + 1)],$$

where $\zeta_1 = \cos(\pi/7)$, $\zeta_2 = \cos(2\pi/7)$, $\zeta_3 = \cos(3\pi/7)$. Note that S is used for the normalized filter.

Finally the transformation $S \rightarrow (s^2 + \omega_{\text{pass1}}\omega_{\text{pass2}})/[(s)(\omega_{\text{pass2}} - \omega_{\text{pass1}})]$, with $\omega = 2\pi f$ is used to obtain transfer function of the 14-th order BPF.

Next we show simulations using Mathcad (Figure 4) and WFilter (Figure 5).

$$\omega := 0, 1 \dots 20000$$

$$j := \sqrt{-1}$$

$$\omega_{\text{pass1}} := 2000 \cdot \pi$$

$$\omega_{\text{pass2}} := 4000 \cdot \pi$$

$$\omega_{\text{p}} := \omega_{\text{pass1}} \cdot \omega_{\text{pass2}}$$

$$d\omega := \omega_{\text{pass2}} - \omega_{\text{pass1}}$$

$$A1(\omega) := \frac{(-\omega^2 + \omega_{\text{p}})}{(j \cdot \omega \cdot d\omega)} + 1$$

$$A2(\omega) := \frac{(-\omega^2 + \omega_{\text{p}})^2}{(j \cdot \omega \cdot d\omega)^2} + 2 \cdot 0.9 \cdot \frac{(-\omega^2 + \omega_{\text{p}})}{(j \cdot \omega \cdot d\omega)} + 1$$

$$A3(\omega) := \frac{(-\omega^2 + \omega_{\text{p}})^2}{(j \cdot \omega \cdot d\omega)^2} + 2 \cdot 0.6234898 \cdot \frac{(-\omega^2 + \omega_{\text{p}})}{(j \cdot \omega \cdot d\omega)} + 1$$

$$A4(\omega) := \frac{(-\omega^2 + \omega_{\text{p}})^2}{(j \cdot \omega \cdot d\omega)^2} + 2 \cdot 0.22252 \cdot \frac{(-\omega^2 + \omega_{\text{p}})}{(j \cdot \omega \cdot d\omega)} + 1$$

$$\underline{\underline{H(\omega)}} := \frac{1}{(A1(\omega) \cdot A2(\omega) \cdot A3(\omega) \cdot A4(\omega))}$$

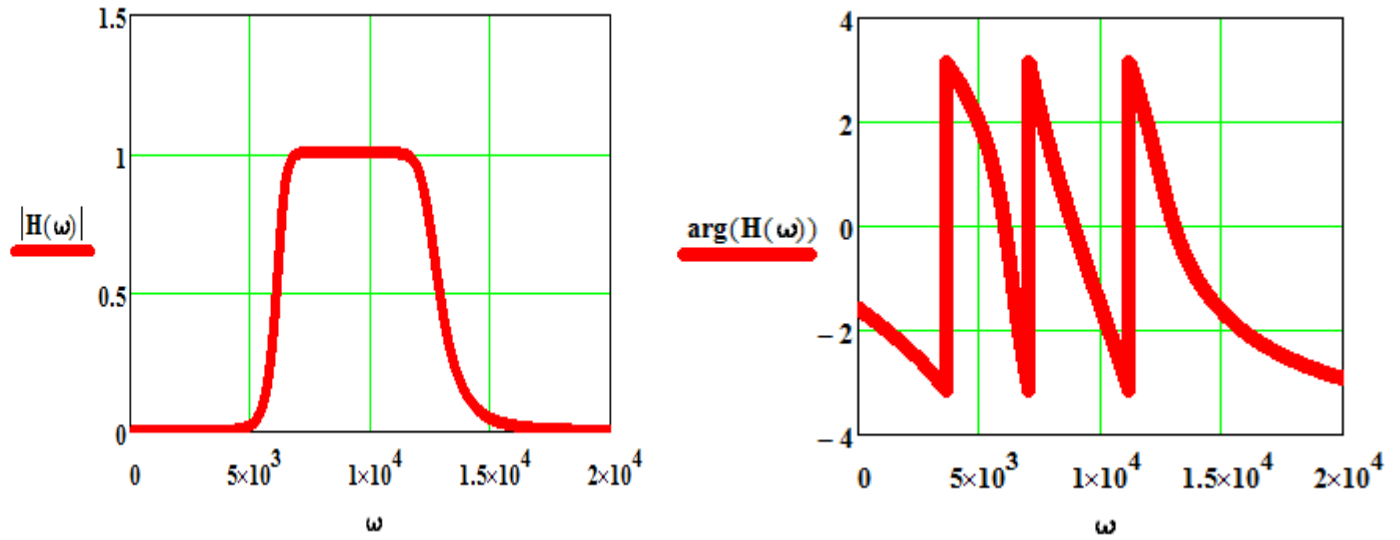


Figure 4. Frequency response plots in MATHCAD.

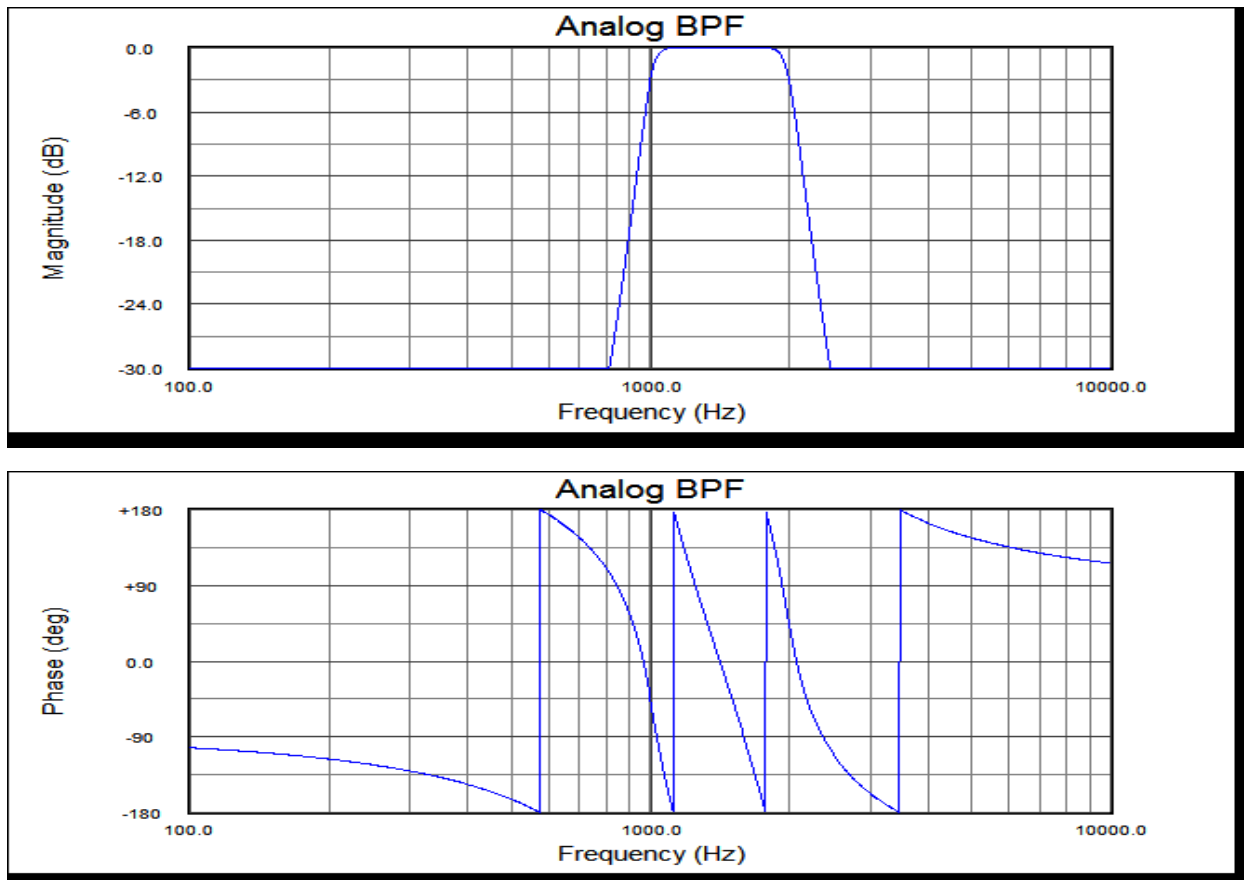


Figure 5. Filter response using WFilter.