



## **Closing the Design Cycle: Integration of Analysis, Simulation, and Measurements Results to Guide Students on Evaluation of Design**

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## Closing the Design Cycle: Integration of Analysis, Simulation, and Measurement Results to Guide Students on Evaluation of Design

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One of the relatively recent innovations in electrical engineering education has been the redesign of the laboratory experience. Where once the emphasis was on demonstration of specific theoretical concepts and the development of measurement techniques that were taught by guiding students through the experiment with step-by-step instructions, elements of engineering design are now introduced into the students' laboratory experience<sup>1</sup>. Students are challenged to determine the components to use in given circuits and, later, the circuits that will have a desired operation, which was detailed in a design specification. To minimize the time spent on design experiments, student must not only know the basics that were gained from 'cookbook' experiments, but also the value of analysis and simulation before circuit construction and measurement and how to apply the results from analysis and simulations to debug the circuit. Engineering educators have begun to modify their approach to laboratory instruction to guide students as they develop the necessary skills for design. Most open-ended design experiments follow the design cycle, integrating steps that allow students to investigate, design, plan, create, and evaluate. However, motivating students to close the design cycle during their evaluation has been difficult. A large percentage of students are able to reflect on the operation of their circuits to determine if the design criteria within constraints have been achieved. However, few take the next steps to investigate what caused deviations from expected performance and to identify where they should focus efforts to redesign the circuit to more closely match the design specifications.

Two approaches to stimulate students to complete the design cycle have been developed at Virginia Tech and used in junior-level courses. In one approach, students in an ac circuits laboratory course are asked to directly compare the results of their analyses with the measured results by physically overlaying plots of the expected and real signals. In the second approach, the students in a course on continuous and discrete signals perform two filter designs using the same circuit topology. The students characterize the performance of a cascaded bandpass filter where each bandpass filter has the same center frequency and bandwidth. They are then to redesign a cascaded bandpass filter to meet a more stringent specification for bandwidth and ripple. Students must evaluate the performance of the first cascaded filter design to determine how to approach the design of the second cascaded filter.

**Background:** The circuits laboratory courses in the Bradley Department of Electrical and Computer Engineering have undergone continuous improvement during the past decade as faculty and staff have developed experiments that have moved from a 'cookbook' approach to one in which students are presented several open-ended design projects during the semester. The motivation to alter the pedagogical approach used in the labs was to attract and retain students in the BSEE program by increasing student self-confidence, providing opportunities to instill self-reliance, developing deeper understanding of fundamental concepts through visually demonstrations, and supporting students as they strive to achieve technical goals. Other desired outcomes for all students, identified as the project evolved, were to develop better experimental

skills, to understand that there may be many paths to address a technical challenge encountered and no single solution may exist, and to stimulate greater proficiency in design. The pedagogical approach adopted was also dictated by limitations in equipment, space, and staff.

The solution chosen was nontraditional laboratories where students perform experiments outside of a lab classroom with parts supplied by the department and student-owned equipment - a digital multimeter, USB oscilloscope with function generator, and breadboard<sup>ii</sup>. The equipment along with a parts kit provided by the department is collectively known as Lab-in-a-Box. The equipment is used in two circuits laboratory courses, in which a series of experiments were designed to reinforce student learning of one-to-two fundamental concepts, or to demonstrate a complex theorem, also taught in the companion lecture course. The students are required to have the equipment available to them throughout their academic career as faculty members can assign hands-on homework assignments or in-class experiments into other courses. Hands-on activities using the electronic platform have been incorporated into courses on electromagnetic fields, signals and systems, and fiber optics<sup>iii</sup>.

As the circuits laboratory courses were refined, open-ended design projects were introduced to allow students to select and apply an appropriate set of concepts to create a circuit that met specifications. In our review of the assignments and their mapping to the design cycle, one area that was consistently weak was evaluation, specifically an objective evaluation of the final design with respect to the degree to which the circuit met the design specifications and the correlation between predicted and measured performance. The typical answer to the question at the end of a laboratory procedure “Did your circuit meet the design specifications?” is a simple “Yes”. Unfortunately, this positive answer is usually given even when the results of analysis and simulations and the actual measurements differ significantly. Students rarely made the connection between analysis and simulation of the circuits designed and the measurements and, thus, infrequently commented upon the aspects of their designs that limited the overall performance of the circuits. A similar lack of depth is encountered in the conclusions written at the end of the hands-on homework assignment or design projects. There have been two activities that were recently launched to help guide students to evaluate their design process using the results from all stages of the design process, to describe their conclusions more quantitatively, to review the design and to identify paths for improvements of their designs. The first is to attempt to close the design cycle in each open-ended design project in the two circuits laboratory courses and the second is to show students a topology that they can adapt to meet a design specification and to have the students demonstrate a design using that topography that will not meet the specifications before assigning the project.

***Closing the Design Cycle: Circuits Experiments:*** The University is a partner institution with MathWorks in a program that has enabled regular communications between the faculty members and the engineering staff at MathWorks, Analog Devices and Digilent. One outcome is the development of a MATLAB Data Acquisition Toolbox Support Package for Analog Discovery Hardware<sup>iv</sup> and for the Velleman PCSGU250 Oscilloscope + Function Generator<sup>v</sup>. Using the appropriate package for their oscilloscope, students are able to generate vectors in MATLAB that can be easily exported to the oscilloscope as the source code for the arbitrary function generator. Furthermore, data from the oscilloscope can be read directly into MATLAB. Students can then overlay the plots of the expected output signals, which they calculated as part of the prelab

assignment using nominal value components with ideal characteristics, with the measured outputs from the actual circuits that they have constructed. Or, they can analyze the measured data using the built-in functions in MATLAB, canned programs supplied by the instructor, or students can write their own scripts. Students readily observe points of operation where the expected and measured results deviate and they develop a deeper understanding of the concepts that determine the operation of the physical circuit.

With some additional effort, the students can tailor their original calculations, such as change component values from the nominal to the measured values, to determine the contribution of component tolerance on the circuit performance. When prompted to perform a more in-depth evaluation of their design, students may consider the effect of parasitics, such as resistance and capacitance in an inductor and other non-ideal models for the components used in the circuit. Once students have gained an appreciation of these effects, they can understand how to read a datasheet for example to select an appropriate operational amplifier based upon the input and output resistances and other device parameters rather than selecting the first one that they see in their parts kit. It is this merger of theory and practice that stimulates students to develop a deeper understanding of circuit design and enables them to create more innovative and robust designs.

The arbitrary function generators have facilitated the design of experiments that merge material from courses on signals and systems and A.C. circuits. For example, students can write an algorithm to sum a discrete number of Fourier components to form a square wave using MATLAB. In the analysis section of the experiment, they can vary the number of components that are summed to obtain a 'square' wave that has a desired set of characteristics – a rise/fall time for the edges of the square wave and a maximum percent deviation in the amplitude from the expected value. The students can plot the signal with an overlay of an ideal square wave. Figure 1 shows a plot of an ideal square wave and the summation of Fourier components from  $n = 1$  to 4. A text file containing the calculated data points as a function of time for one period of the square wave is then exported from MATLAB. This file is imported into the oscilloscope software package and is used as the source code for the output of the arbitrary function generator.

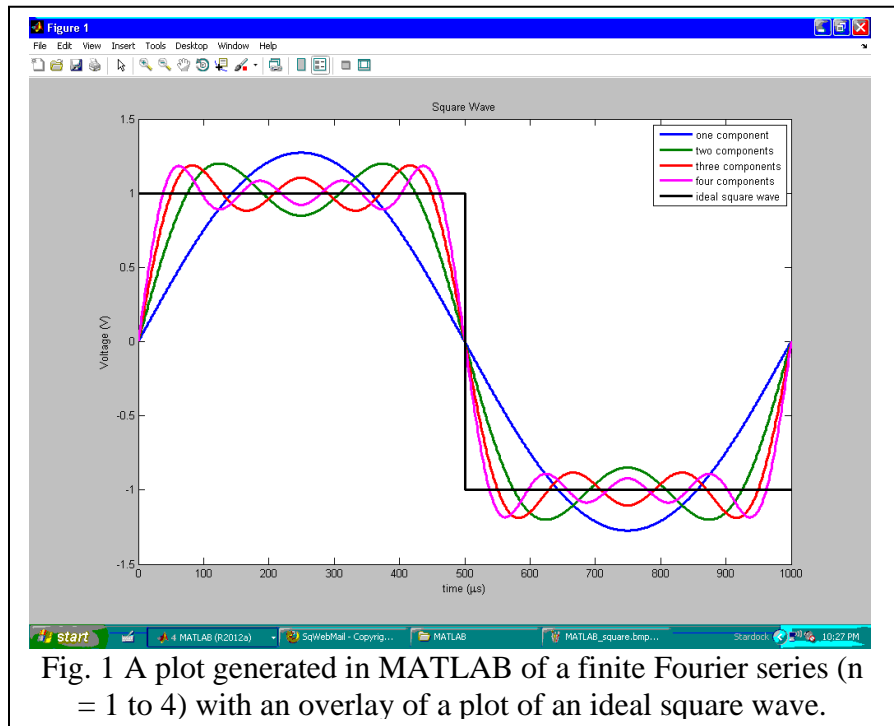


Fig. 1 A plot generated in MATLAB of a finite Fourier series ( $n = 1$  to 4) with an overlay of a plot of an ideal square wave.

The students design two bandpass filters – one designed to have a center frequency at the fundamental frequency of the square wave and a bandwidth of 175 Hz and the second bandpass

filter with a center frequency at the third harmonic and a bandwidth of 825 Hz. Both filters are first order active filters with a gain of -1. The students are not asked to predict the shape of the output signal from either of the filters in the required prelab analysis, though they are required to

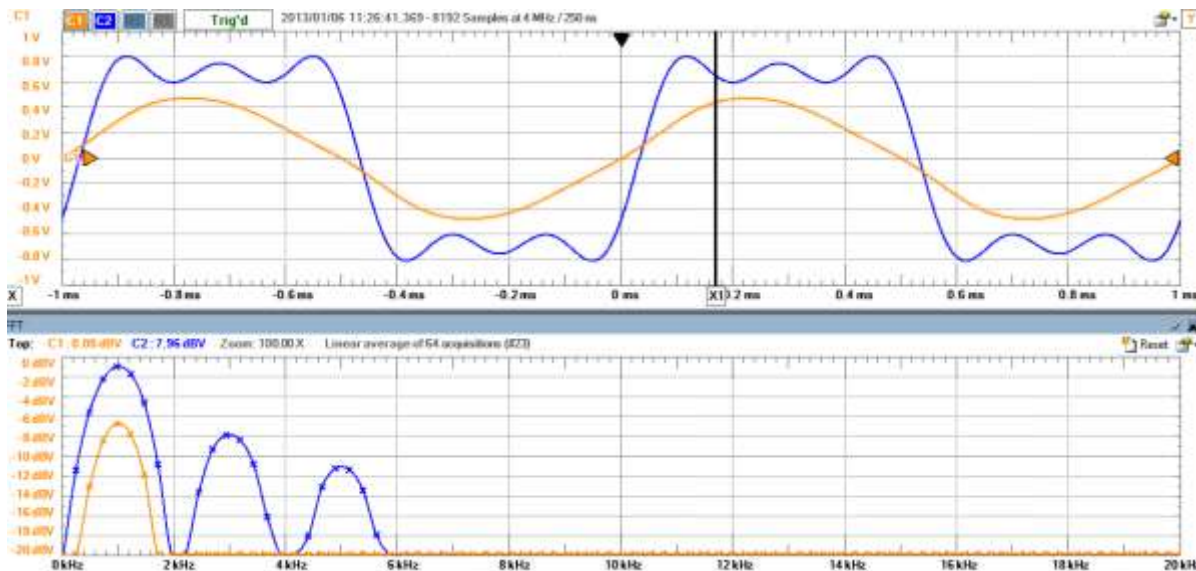


Fig. 2 Plots of the signal from the arbitrary function generator (blue) and the output of the first bandpass filter ( $f_0 = 1$  kHz and  $BW = 175$  Hz) in the time domain (upper plot) and frequency domain (lower plot).

simulate the frequency response of each filter in PSpice to demonstrate the correctness of their designs. Once the students have verified their filter designs, they then construct the filters.

With the fast Fourier transform option in the Waveforms software program, students measure the amplitudes of each frequency component in the signal that they have generated using MATLAB and compare the results with the amplitudes and frequencies of the components that are measured from the ideal square wave, which is one of the standard functions available in the library of signals on the Analog Discovery. Then, the students measure the output of the first bandpass filter using the signal that they created in MATLAB. The signal in the time domain, shown in the upper plot in Fig. 2, looks as one might expect – a reasonably good sine wave with a frequency equal to the fundamental frequency. In the frequency domain, there are still peaks associated with the higher order harmonics, but the amplitudes of these components are quite small and cannot be observed in the lower plot in Fig. 2. Next, the students measure the output from the second bandpass filter in both the time and frequency domains. The signal is not what most students expect to see (Fig. 3). As part of a series of questions in the conclusions section of the laboratory procedure, the students determine the effect of the -20 dB/decade roll-off of a first order filter on the amplitudes of the first three Fourier components and to calculate the order of the second bandpass filter that would be required to decrease the amplitudes of the fundamental and fifth harmonic by a factor of ten, at which point the output of the second filter will look like a sine wave with a frequency equal to the designed center frequency.

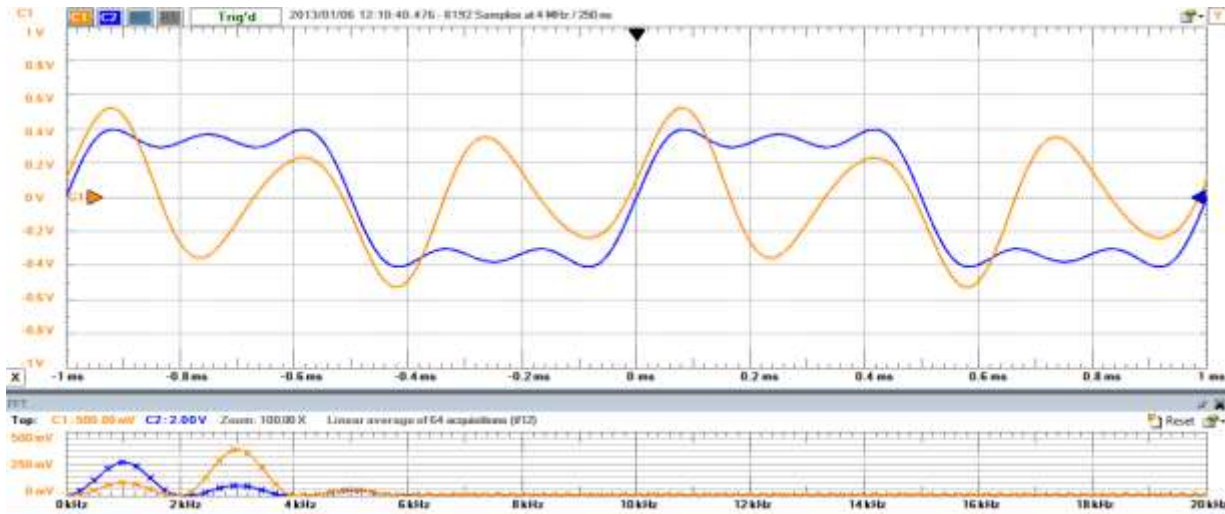


Fig. 3 Plots of the signal from the arbitrary function generator (blue) and the output of the second bandpass filter with a  $f_0 = 3$  kHz and  $BW = 825$  Hz in the time domain (upper plot) and frequency domain (lower plot).

**Closing the Design Cycle: Continuous and Discrete Signals Project:** In studying signals and systems, it is often very difficult for students to visualize the effects of filters and transfer functions, and how these concepts relate to Fourier and Laplace Transforms. For this reason, students build and test an analog filter to help connect the theory of transfer functions to practical real world applications. A Junior level design project cannot yet be completely open-ended; some scaffolding structure is therefore provided. The project was done in two parts. First, the students were to design and build a double-pole single-zero bandpass filter using the topography shown in Figure 4.

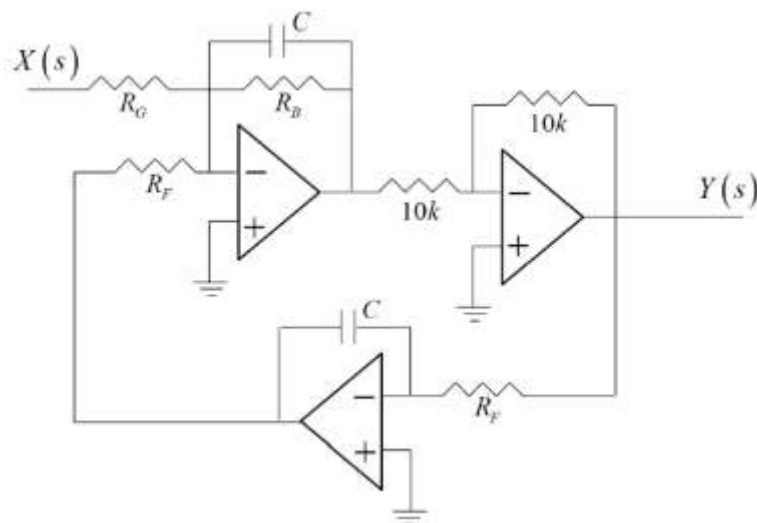


Fig. 4 Topography of the bandpass filter provided to students.

Students were asked to derive the transfer function of the structure, assuming ideal op-amps, and to then provide values for  $R_G$ ,  $R_B$ ,  $R_F$ , and  $C$  so that the resultant bandpass filter had a center frequency of 2.5 kHz and a 3 dB bandwidth of 1.5 kHz.

The transfer function resulting from analysis, either by loop/nodal equations or op-amp configuration sub-system transfer functions - in terms of the component values - is given below.

$$H(s) = \frac{\frac{1}{R_G C} s}{s^2 + \frac{1}{R_B C} s + \frac{1}{(R_F C)^2}} \quad (1)$$

In the above equation, the center frequency corresponds to  $(R_F C)^{-1}$ , the 3 dB bandwidth corresponds to  $(R_B C)^{-1}$  and the gain at the center frequency corresponds to  $R_B (R_G)^{-1}$ . After the students had derived the transfer function and determined the values needed for  $R_G$ ,  $R_B$ ,  $R_F$ , and  $C$ , they were to build the circuit on a breadboard using the resistors, capacitors, and op-amps available to them in their personal Lab-in-a-Box (LiaB) kit. Figure 5 shows typical results – from a design with ideal components, from the same design but with measured component values, and from its measured LiaB implementation.

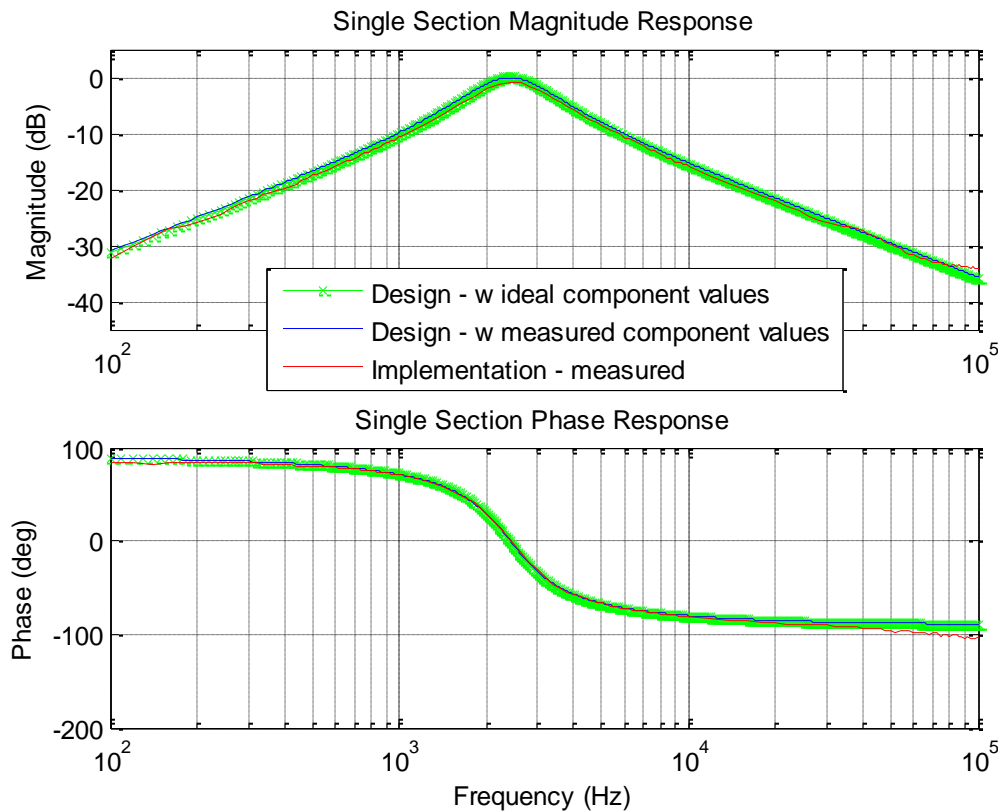


Fig. 5 Frequency responses for single bandpass section.

The students can readily ascertain – by zooming in – that center frequency, bandwidth, and roll-offs are very close to the theoretically expected values. In fact, by using trim-pots, they could produce a near-perfect match.

Once the students had built their circuit to closely match the expected bandpass filter, they were paired into groups for the second part of the project. First, the students were asked to cascade one student's filter with the second student's filter, using their implementations from part one, yielding a sharpened bandpass filter with 40 dB/decade rolloffs away from the center frequency of 2.5 kHz. The students worked together to characterize the operation of the cascaded filters, and would hopefully discover that the 3 dB bandwidth was now reduced.

After they had characterized the cascaded sharpened filter, the student teams were asked to design a second filter (“the POTS filter”) that had as passband the range of speech frequencies, defined by the plain old telephone system (POTS), from 400-3400 Hz. Additionally, the filter was expected to have a passband ripple of no more than  $\pm 0.75$  dB from peak to trough and have the best attenuation possible for frequencies outside of the 400-3400 Hz range. These design specifications were intended to push the students towards varying all relevant degrees of freedom and to come up with a design wherein one filter section had a center frequency near 400 Hz and the other filter section a center frequency near 3.4 kHz, while keeping the ratio of center frequency to bandwidth of the two filter sections nearly the same and simultaneously high. Students were expected to come up with a reasonable design in MATLAB first and to then implement it on their breadboard. Once they constructed their design, students tested it using an audio file of a person speaking, i.e. with frequency components within the specified range. They were expected to not hear noticeable distortion between the input signal and the signal at the output of their POTS filter. However, this would not be the case when listening to other audio files, such as those with classical music containing upper register and/or bass notes. The frequency response results – from a typical POTS filter design and its LiaB implementation – are shown in Figure 6.



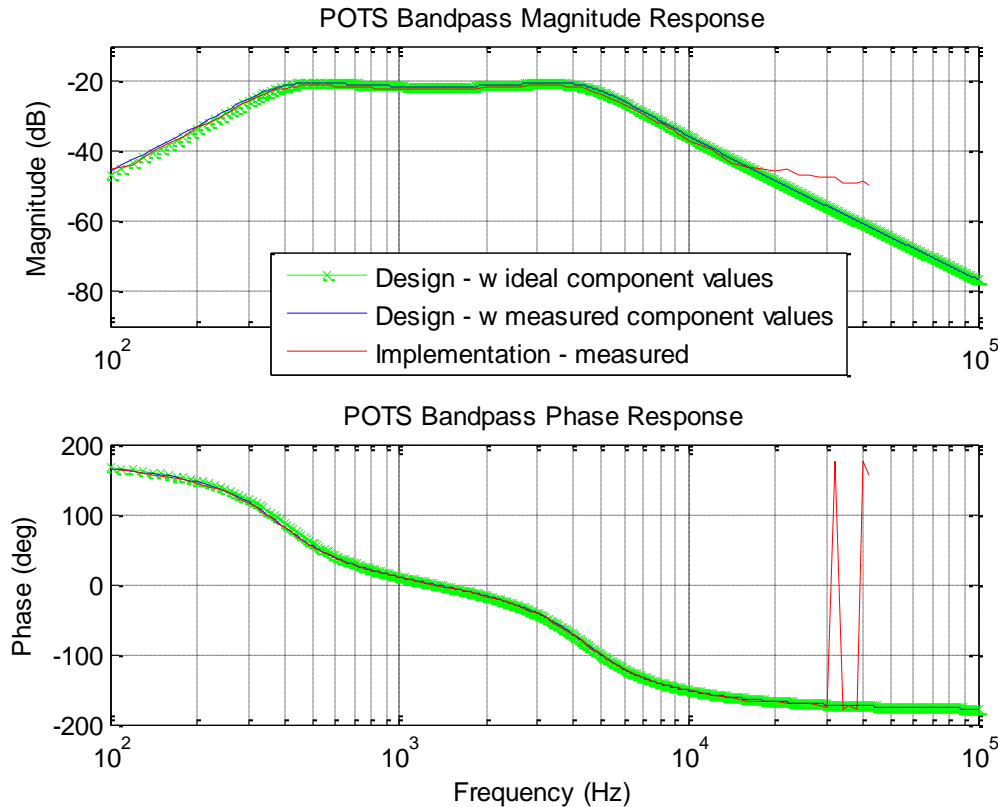


Fig. 6 Frequency responses for POTS filter.

For the final step in the characterization of the POTS filter design, students were asked to input a 400 Hz square wave and explain the observed output. Since a square wave generates odd harmonics at multiples of 400 Hz, they would be able to see the filtered version of their square wave relative to the 400 Hz input square wave. By using the magnitude as well as the phase response of their design, at the relevant harmonic frequencies, they would be able to construct a close approximation of the observed output waveform in steady state. The latter teaches that while phase is not important for the listening test, it is important for waveform fidelity.

**Assessment:** Informal assessment of both activities was done at the end of the semesters. A common frustration expressed by students was the lack of background in MATLAB programming. No formal classes on MATLAB are required in the BSEE degree program, though the students are required to take a course on problem solving using C and C++ and a TA is available to answer questions about MATLAB. Many commented that their limited experience with MATLAB created a barrier to their ability to complete the assigned tasks. The development of additional tutorials on MATLAB is planned to address this concern. In both courses, students stated that they obtained a deeper understanding of the design process and the theoretical concepts that were applied.

*Circuits Experiments:* While there were more students who did not answer “Yes” to the question posed about the comparison between expected and measured results, the depth of the qualitative reflection in the answers provided was still less than had been expected and few students went beyond this to identify potential causes quantitatively. We will review how to streamline the

experiments as the amount of time and effort that this level of evaluation required in addition to the self-guided learning of MATLAB may be more than what one can expect from students during a single experiment, one of 10 assigned during a semester-long, one credit hour lab course. Introduction of the MATLAB support package for the oscilloscope may also be moved earlier in the circuits laboratory course.

*Continuous and Discrete Signals Project:* Respondents to the Student Perception Of Instruction survey at the end of the semester concurred “that a deeper understanding of the subject matter was attained, that the projects helped to see how filters and signals are used in the real world, that theories and concepts were related to practical issues, that the out of class assignments were valuable, and that the projects were fun but pretty difficult.”

Respondents to the Articulated Learning Exercise focused exclusively on the hands-on projects in this class, reflected in free format on the questions: What did I learn? How specifically, did I learn it? Why does this learning matter, or why is it significant?, and In what ways will I use this learning? Students reported learning that implementation can be tedious and super-frustrating, and then rewarding when a finished product is achieved. They also learned to go all the way from concepts to implementation, and that time management is a critical skill. Students reported that they learned by doing, by trial and error, by intelligent experimentation, a constant interplay between thinking and doing. The hands-on learning led to better understanding after having to struggle from a start with cursory knowledge, it cemented the ideas taught more so than book learning had, and taught the important engineering skill of breaking a problem down into small problems, and solve them before assembling everything. Some reported that they began to see the real world applications of what they had learned so far in their curriculum, and how this could connect to employment opportunities; they had learned a lot more than just the answer to the question they set out to answer, at the expense of time.

It is difficult to directly measure the impact of having hands-on projects versus not having them; however, it is equally difficult to imagine getting responses as above without doing hands-on projects!

This brings us to the potential for improvement. Many students had trouble in designing the bandpass filter for the POTS application with a 400 to 3400 Hz passband. A good approach to this problem was to design two cascaded filters that had different center frequencies and bandwidths while keeping the Q constant (ratio of center frequency to bandwidth) of the cascaded filter sections the same; this normalization maintains the shape of the (Bode plot) magnitude response when the center frequency is varied over the (Bode plot) logarithmic frequency scale. Once students realized this, they could adjust their design until they met the specifications of their filter. In many design results, students designed for two filter sections that had center frequencies close to the cutoff frequency specifications of the filter. For instance, one sample design had two cascaded filters, one designed for a 410 Hz center frequency and a 360 Hz bandwidth and another with a 4.4 kHz center frequency and a 3.86 kHz bandwidth. However, several teams focused their efforts on minor modifications of the single filter section designed in the first part of the activity, which they would then cascade, rather than designing filters using the topography from the first part of the activity that would have two different center frequencies and bandwidths. One potential way to avoid this behavior would be to separate the class into two

halves during the first part of the activity where one half would design the original bandpass filter and a second group would design a bandpass filter using the same topography, but at a different center frequency. Formation of student teams could then result in the cascade of two similar filters or two different filters. Selected results from student work could be shown during class as a means to suggest the need for a redesign of both filters in order to better meet the specification for the POTS application.

**Summary:** Two methods have been developed to guide students to close the design cycle. In the first method, students are asked to overlay the measurements obtained from the circuits constructed to meet the experimental design specifications on top of the expected results that the students calculated in MATLAB. In the second method, students are asked to apply the results from their first experiment to meet the design specifications in a second experiment. The preliminary assessment of each method has been conducted and some of the weaknesses in each approach have been identified. The experiments are currently undergoing revisions and will be tested in the coming semester. The hands-on design project in the Signals course was successful in terms of most of the class reporting that their understanding of the basic concepts was enhanced by struggling through the implementation. The students learned how to reconcile differences between theory and measured results or performance and to work towards improvements in performance relative to requirements. A design review and subsequent re-design cycle would likely lead to a more universally satisfactory learning experience.

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