

## Science and Engineering Courses, Theory and Practice; An Example

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Dr. Cheryl Xu received her Ph.D. degree in 2006 from Purdue University. Her research interests are: high temperature wireless sensing, multifunctional ceramic composites, and artificial intelligence (AI) for process modeling/control. Dr. Xu is active in conducting research in the field of materials and advanced manufacturing and has attracted a high level of research funding (\$5.5M). She has graduated six Ph.D. and five M.S. students. She has co-authored a textbook (Intelligent Systems: Modeling, Optimization and Control, CRC Press, 2008) and written four book chapters. She has published about 50 peer-reviewed journal articles and 30 refereed conference proceedings. She has nine US patent applications. Dr. Xu won the Office of Naval Research (ONR) Young Investigator Award and was awarded the Society of Manufacturing Engineering (SME) Outstanding Young Manufacturing Engineer Award in 2011. She was the only recipient of the IEEE Education Society Teaching Award in 2015, chaired NSF National Wireless Research Collaboration Workshop in 2015 and serves as an Associate Editor of ASME Transactions, Journal of Micro- and Nano- Manufacturing since 2015.

## Science and engineering courses, theory and practice: an example

**ABSTRACT.** In engineering subjects where many topics deal with theory and abstractions, it is challenging for students to fully understand and learn the concepts and apply them to solve given practical problems. As examples in classes in Systems Engineering as well as Signal Processing, Control Systems, and Electromagnetics, to just mention a few, we have found it useful to supplement lectures with examples where some solutions are presented using software packages and simulations after theory and principles are presented in detail. In fall semester we presented examples in the electromagnetics class where given problems were solved using concepts learned in the class followed by results, graphical representations obtained using modern tools for illustration and graphical representation. These software tools are available in our engineering computer Labs and students can try these solutions outside of the classroom as well. It is useful at the start of the course to show what are applications of materials they will learn in the course. One useful example is wireless communications, e.g., cellular phone system, where for example antennas are used as transmitting and receiving systems for electromagnetic waves carrying information signals. In spring semester course they will also encounter applications of digital signal processing (DSP), for example digital filters, used in smartphones. This paper will focus on the signal processing course.

**1. INTRODUCTION.** In every engineering program there are courses with high mathematical concepts and abstractions. For example in electrical/computer programs courses such as control systems, electromagnetics, signal processing and communications, students have difficulty with concepts such as transforms (Fourier, Laplace), bandwidth, signal-to-noise ratio, design of various filters, convolution, and time/frequency domain representations of signals & systems. In the signal processing course, we start the class by showing practical examples and applications of digital signal processing (DSP) systems. In Figure 1 we show a picture of a digital signal processor where students can see the actual hardware with designated input/output terminals.

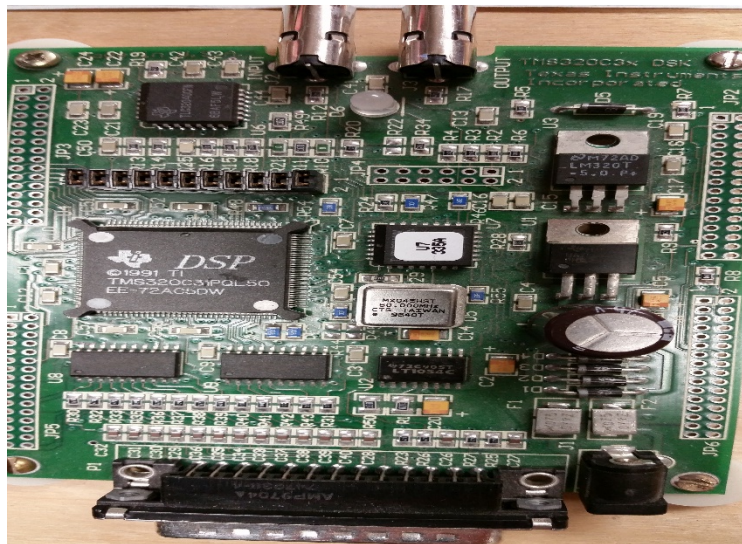


Fig. 1. Example of a digital signal processor

The signal processing course topics include: continuous-time, discrete-time signals and systems, analog processor, digital processor, design of filters, the sampling theorem, difference equation modeling of digital systems, discrete-time Fourier transform and its inverse, discrete-time Fourier transform (DFT), Fast Fourier Transform (FFT) algorithm, the z-transform, and design of digital filters (FIR, IIR). There are several textbooks available for teaching signal processing course including references [1], [2], and [3].

**2. SIGNAL PROCESSING SYSTEMS, EXAMPLES.** Signal processing systems process input signals and produce an output or response signal as shown in Fig. 2.

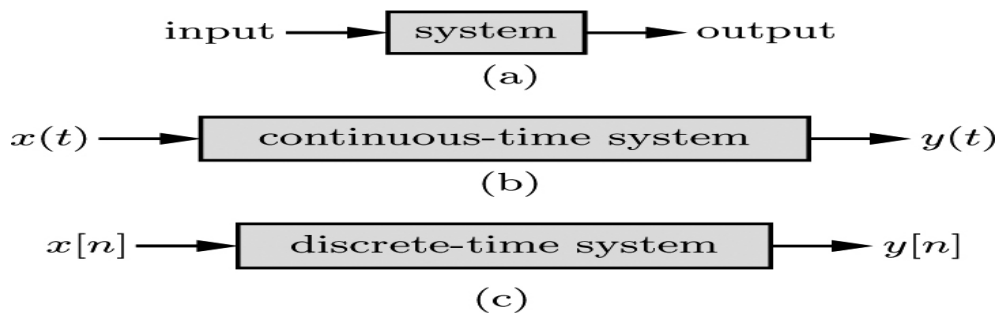


Fig. 2. Signal processing system input/output representation.

For continuous-time (analog) system, we can compute output either in time domain using differential equation model or by convolution operation. Alternatively signal processing system can be analyzed and designed in the frequency domain using transfer functions  $H(\omega)$ , Fourier transform of system impulse response  $h(t)$ , or  $H(s)$  which is Laplace transform of the impulse response. In filter problems, transfer function representation is often used. We now present a few examples showing how signal processing problems can be solved using simple calculations then showing how we can use computer information technology (CIT) tools (e.g., MATLAB or MATHCAD) to simulate these systems.

**Example 1.** (Active Analog Filter). The system is a filter circuit (system) using resistors, capacitors and an operational amplifier (OP-AMP). Input  $x(t)$  is applied as voltage source in series with resistor  $R$ , then through a capacitor  $C$  connected to inverting terminal. Resistor  $R$  is also connected (feedback) between output  $y(t)$  and the inverting terminal. Finally the capacitor  $C$  is also connected from output to the node between  $R$  &  $C$  on the input side, non-inverting terminal of the OP-AMP is grounded. At first  $R = 1 \Omega$  and  $C = 1 \text{ F}$ , students can vary these values to see the effect on the frequency response plots. The transfer function  $H(s) = Y(s) / X(s)$  can be derived by writing system equations in the frequency domain (or alternatively by transforming system's differential equation) and is given by:

$$H(s) = -s / (s^2 + 2s + 1)$$

To see what kind of filtering operation is performed on the input signal, students can plot frequency response function  $H(\omega) = H(s = j\omega)$ . This can be done in MATLAB using bode function:

```
>> % Frequency Response Plots using MATLAB
```

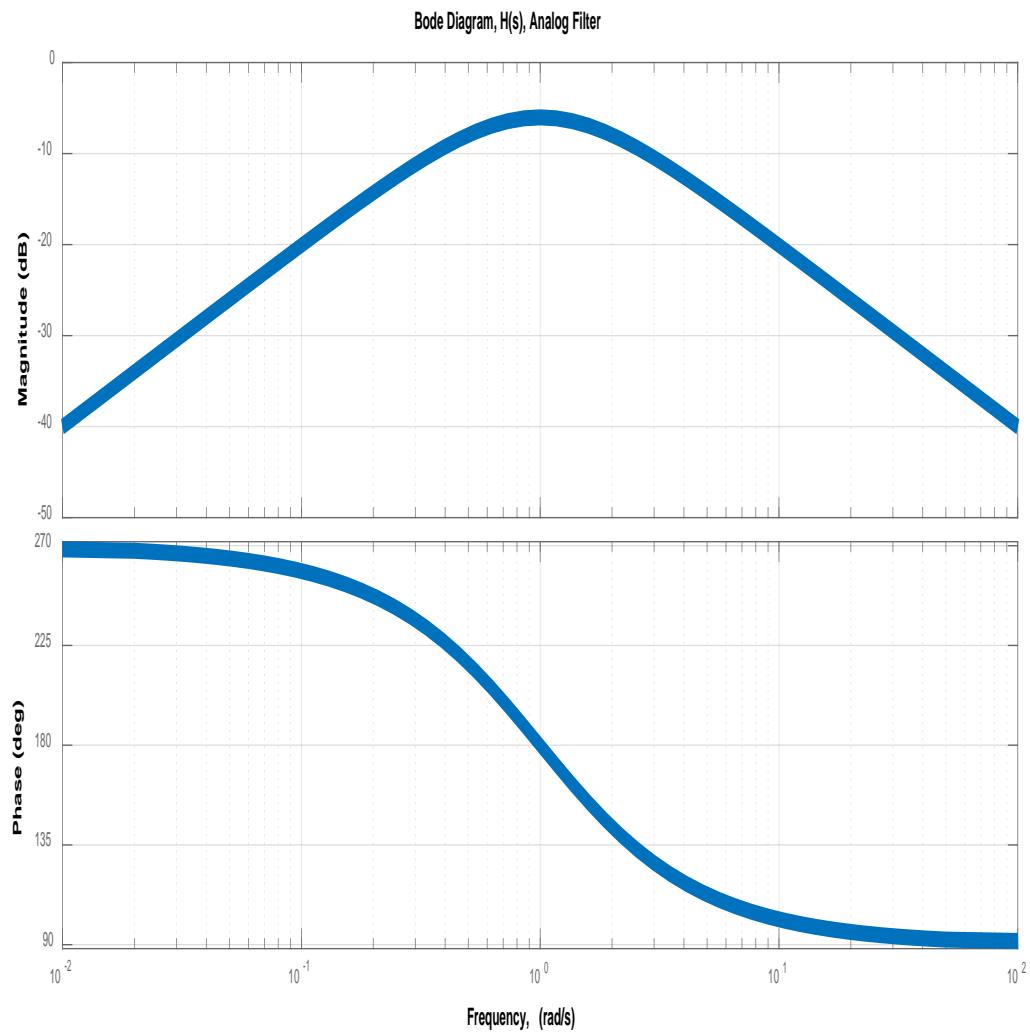
```
>> B = [-1 , 0] ;
```

```
>> A = [1 , 2 , 1] ;
```

```
>> SYS = tf (B , A)
```

```
>> bode (SYS) ;
```

```
>>
```



Next we also show the magnitude and phase response plots using MATHCAD:

## ACTIVE FILTER FREQUENCY RESPONSE PLOTS

$\omega := 0, 0.01.. 100$

$$H(\omega) := -j \cdot \frac{\omega}{-\omega^2 + 2j\omega + 1}$$

Fig. 3 (a). MAGNITUDE FREQUENCY RESPONSE

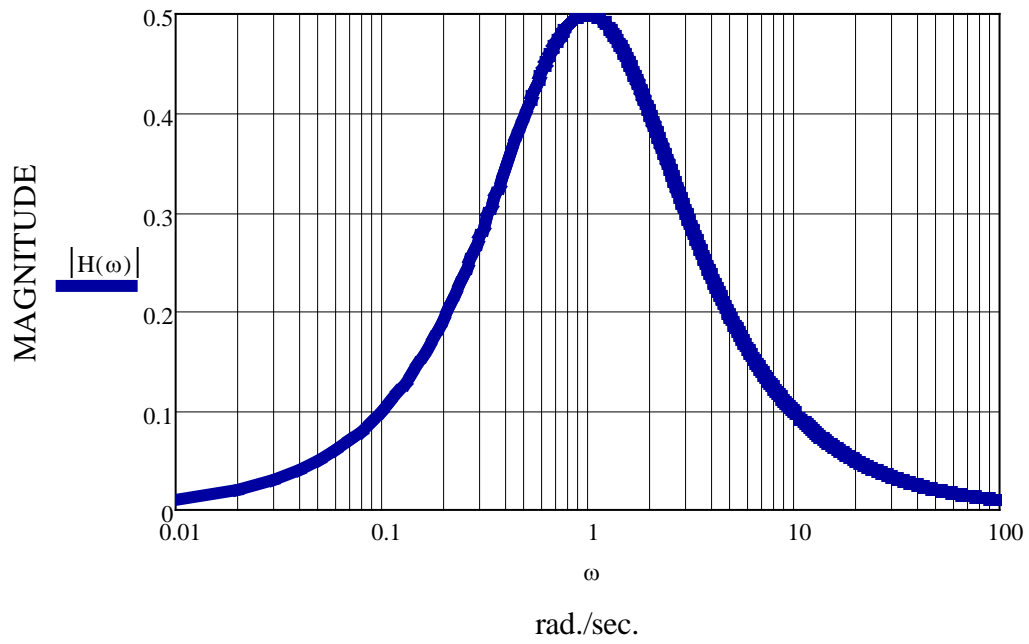
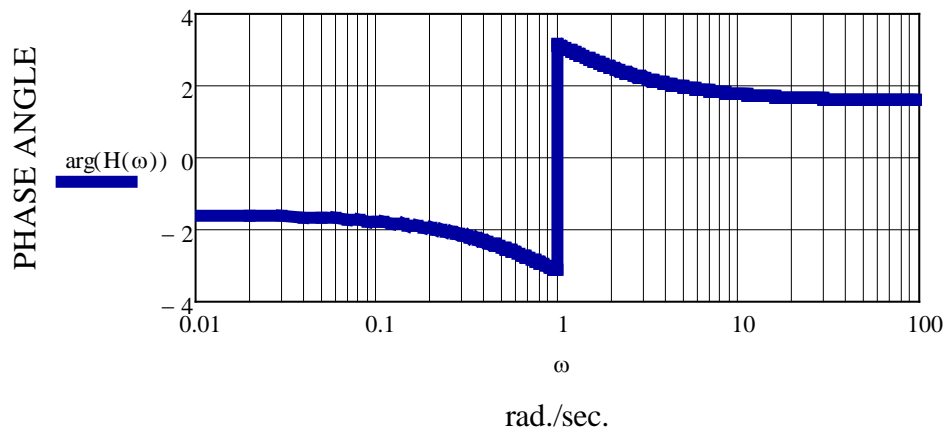


Fig. 3 (b). PHASE FREQUENCY RESPONSE



From plots it is clear that the system represents a band-pass filter. Later in the course students will study infinite impulse response (IIR) digital filters where we use, for example, bilinear transformation to get  $H(z)$  (z-transform of impulse response) from  $H(s)$ . In the time domain the system is studied using  $h(t)$ , inverse transform of  $H(s)$ , then for a given input the response is computed using the convolution operation :  $y(t) = x(t)*h(t)$ . The convolution operation is also a difficult subject for students. In the course they will encounter a few types of convolution including continuous-time, discrete-time, and periodic convolutions. Problems are assigned in the class, students can use either MATLAB or MATHCAD. Some students also may use other software packages like MATHEMATICA or MAPLE.

The following example is a convolution problem where students can use graphical method to find the results then check their answer using, for example, MATLAB.

**Example 2.** (Convolution). Given the two finite-energy signals  $x(t)$  and  $h(t)$  below, students are asked to find and plot convolution  $y(t) = x(t) * h(t)$  as a function of time:

$$x(t) = 3 ; 0 \leq t \leq 2 \text{ sec.} \quad \text{and} \quad h(t) = t ; 0 \leq t \leq 2 \text{ sec.} \ \& \ h(t) = -1 ; 2 \text{ sec.} \leq t \leq 4 \text{ sec.}$$

(both signals are zero otherwise)

Problem is to compute the convolution integral  $y(t) = \int x(t-\tau) h(\tau) d\tau$  where integral is from  $\tau = 0$  to  $\tau = t$ . Using graphical convolution technique, students look at the following intervals (regions) of time  $t$  :

$$t < 0 , y(t) = 0 \text{ since there is no overlap between } x(t-\tau) \text{ and } h(\tau)$$

$$0 \leq t \leq 2 \text{ sec.} , y(t) = 1.5t^2 ; \mathbf{y = 3(\text{overlapping area})}$$

$$2 \text{ sec.} \leq t \leq 4 \text{ sec.} , y(t) = -1.5t^2 + 3t + 6$$

$$4 \text{ sec.} \leq t \leq 6 \text{ sec.} , y(t) = 3t - 18$$

$$t > 6 \text{ sec.}, y(t) = 0.$$

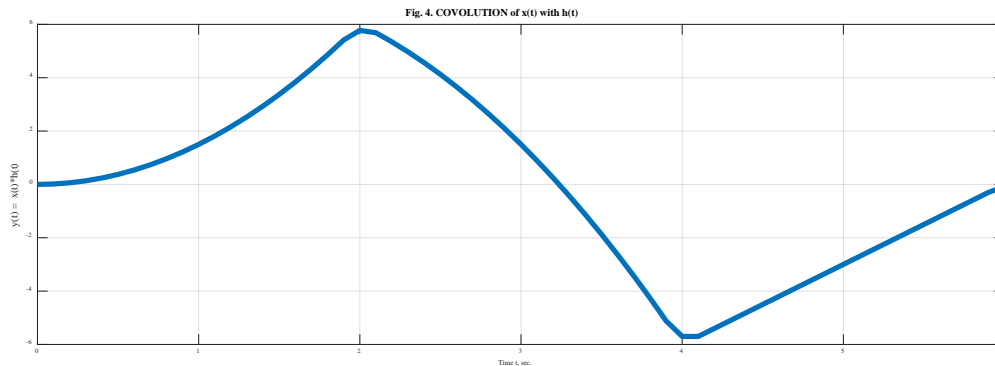
Students can use MATLAB code to plot  $y(t)$  vs.  $t$  (Figure 4) :

```
>> % Convolution of finite-energy signals x(t) and h(t)
>> x = [1.5 , 3*ones(size(1:1:19)) , 1.5] ;
>> n = 0:1:19 ;
>> h = [(ones(size(n))).*n*0.1,0.5,-1*ones(size(21:1:39)),-0.5] ;
>> y = 0.1*conv(x,h) ;
>> m = 0:1:60 ;
```

```
>> t=0.1*m ;
```

```
>> plot (t,y)
```

Note that signals change abruptly at  $t = 0, 2$  seconds, and 4 seconds, midpoints are used in the MATLAB code.



Students note that using MATLAB command CONV they need to include the sampling time (here  $T = 0.1$  sec.) to get the correct results. They can also use other programs to check the results of their graphical convolution as well.

Digital signal processing course includes designing infinite impulse response (IIR) digital filters starting with an analog filter, a problem is presented next.

**Example 3.** (IIR digital filter design). One method of designing a digital filter based on analog prototype is using the impulse invariance transformation. Basically the impulse response  $h(t)$  is sampled every  $T$  seconds, then z-transform of sampled impulse response will give us the  $H(z)$  of the digital filter. In the frequency domain poles of  $H(s)$  in the s-plane are mapped to poles of  $H(z)$  in the z-plane. The problem below will illustrate this design method and its simulation.

From analog filter  $H(s) = (4 - 8s) / (s^2 + 5s + 4)$  students perform partial fraction expansion to find:

$H(s) = 4 / (s + 1) - 12 / (s + 4)$  , now poles  $s = -1$  and  $s = -4$  are mapped to

$z = \exp(-T)$  and  $z = \exp(-4T)$  where  $T = 1 / f_s$  ( $f_s$  is the sampling frequency of the digital system)

the transfer function of the digital filter is obtained as:

$H(z) = A \{ 4z / [z - \exp(-T)] - 12z / [z - \exp(-4T)] \}$  , constant A is found from condition

$H(z=1) = 1$ , similar to  $H(s=0) = 1$  or 0 dB.

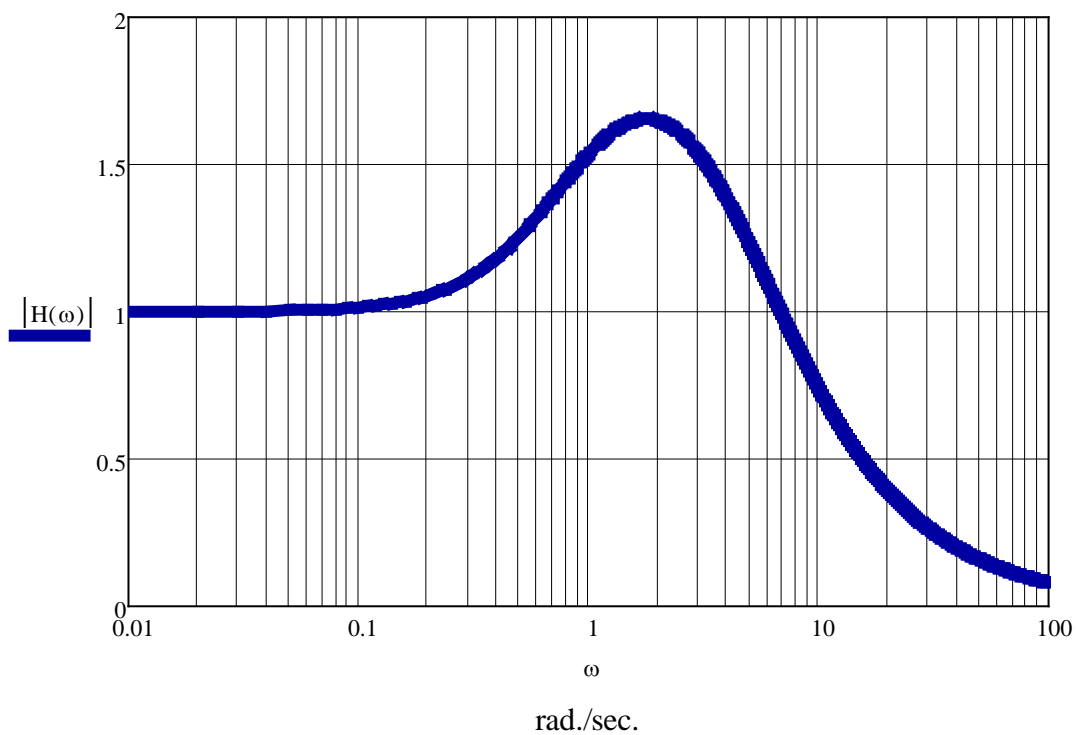
We next show a simulation with  $T = 0.01$  sec., MATHCAD plots are shown in Fig. 5.

ANALOG FILTER  $H(s)$ ,  $s = j\omega$  for frequency response

$\omega := 0, 0.01.. 100$

$$H(\omega) := \frac{4 - j \cdot 8 \cdot \omega}{-\omega^2 + 5 \cdot j \cdot \omega + 4}$$

Fig. 5 (a). Analog Filter Magnitude Frequency Response



DIGITAL FILTER  $H(z)$ ,  $z = \exp(j\Omega)$  where  $\Omega$  in radians is digital frequency

$\Omega := 0, 0.001.. \pi$

$z(\Omega) := \exp(j \cdot \Omega)$

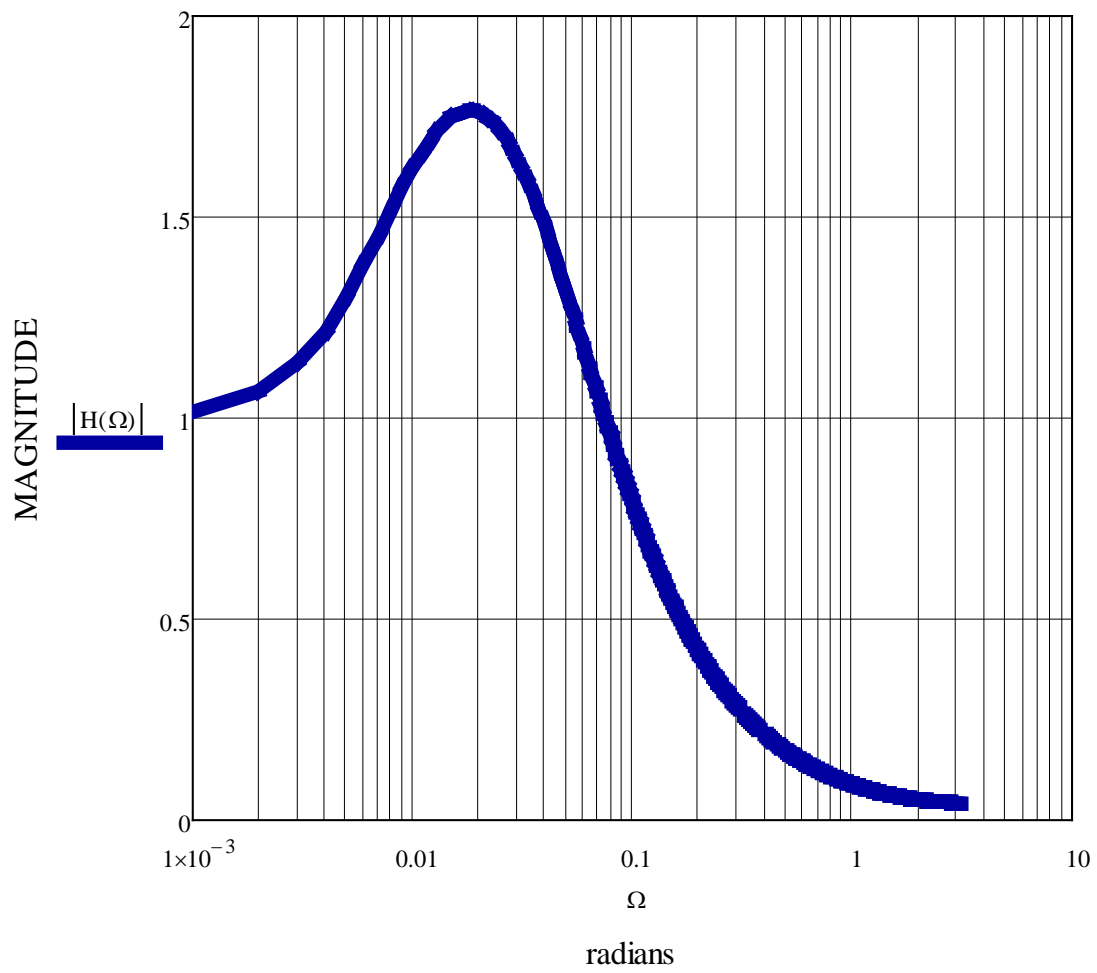
$T := 0.01$

$$A := \left( \frac{4}{1 - \exp(-T)} - \frac{12}{1 - \exp(-4 \cdot T)} \right)^{-1}$$



$$H(\Omega) := A \cdot \left( 4 \cdot \frac{z(\Omega)}{z(\Omega) - \exp(-T)} - 12 \cdot \frac{z(\Omega)}{z(\Omega) - \exp(-4 \cdot T)} \right)$$

Fig. 5 (b). Digital Filter Magnitude Frequency Response



Students learn theory and underlying principles of designing analog and digital systems in the class. Once they have gone through design problem solutions, simulations are done using software packages to verify their design. They write their own code for simulations.

**3. COURSE ASSESSMENT.** Signal processing course Student Outcomes, SOs, were:

- (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
- (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Assessment results showed that about 60% of students performed at or above expected level of achievement. Note that the course contains applications of mathematics, science, and engineering. It also includes design and ability to formulate/solve engineering problems. Finally course uses information technology tools. Without a laboratory section for the course, the design results are verified using simulations, for example using MATLAB, MATHCAD or other available programs. It is very important that students first go through problems using paper/pencil, back of envelope calculations, with use of calculator before they attempt simulations, obtaining graphical results from available computing information technology tools.

**4. CONCLUSIONS.** In this paper we have shown how computer information technology (CIT) are used at the right time, right place in an example science and engineering course. Students are encouraged to use paper and pencil, calculator to solve a given problem and do simple calculation (“back of envelope”) before using software packages for simulation and graphical representations. More information regarding challenges involved covering both theory and practice in science & engineering courses are given in a paper [4].

## R E F E R E N C E S

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